The potential of agricultural residues for energy production in Calabria (Southern Italy)

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ABSTRACT

This work aims at estimating the biomass from agricultural residues of Calabria region (Southern Italy) for possible energy conversion in combined heat and power (CHP) systems. To this purpose, attention has been focused on agricultural residues, livestock sewage, and by-products and waste of the agro-food industry. The investigation has been based on statistical information from 2015, and an extensive literature review has been performed to define proper parameters for the analysis. The study highlights that an interesting amount of biomass residues is present in the investigated area, with about 820,000 tons per year that can be conveniently used in small-scale CHP units to satisfy the thermal and electric request of regional users. Specifically, Organic Rankine Cycle (ORC) systems have been considered to exploit lignocellulosic residues through direct combustion, while anaerobic digestion and internal combustion engines (ICEs) have been adopted for the energy valorisation of the other investigated feedstock. The analysis demonstrates that the available biomass residues could satisfy the thermal request of more than 116,000 households and the electric load of about 178,000 families simultaneously.

KEYWORDS: Biomass; agricultural residues; livestock; cereal crops; energy exploitation; combined heat and power.

WORD COUNT: 7996

NOMENCLATURE

Symbols

A_c	Cultivated area (m^2 or ha)
a_f	Availability factor of residues (%)
AR	Annual available residues (kg/year)
E	Annual energy content (J/year)
H_i	Lower heating value (J/kg)
inh	Inhabitants (-)
j	Generic stream (-)
$m_{biofuel}$	Annual biogas amount (m^3/year)
N_A	Number of animals (-)
P	Power (W)
P_C	Cereal production (kg/year)
P_P	Processed product (kg/year)
R	Potential annual residues (kg/year)
RAR	Residue-to-area rate (kg/m^2-year)
RPC	Residue per capita (kg)
$RPPR$	Residue-to-processed product ratio (-)
RPR	Residue-to-product rate (-)
TS	Total solid concentration (%)
TVS	Total volatile solids (%)
$y_{biofuel}$	Digestion yield factor (m^3/kg)

Greek symbols

Δt	Annual operating time (h/year)
φ	Moisture content (%)
λ	Water latent heat of vaporisation (J/kg)
η	Efficiency (%)

Subscripts

A	Agro-food industries
B	Breeding farms
C	Cereal crops
b	Biomass
d	Dry biomass
d.b.	Dry basis
el	Electric
L	Lignocellulosic
th	Thermal

Acronyms

CHP	Combined Heat and Power
CPW	Citrus Processing Wastewater
d.b.	Dry basis
EU	European Union
ICE	Internal Combustion Engine
LSU	Livestock Units
OMW	Olive Oil Mill Wastewater
ORC	Organic Rankine Cycle
toe	Tons of oil equivalent

1. INTRODUCTION

In recent years, public sensitivity to environmental issues and energy security has increased, leading to the promotion of renewable energy resources [1,2]. Among the renewable energy sources (namely solar, wind, geothermal and marine energy, biomass, biofuels, and many others), the exploitation of biomass materials produces energy in a sustainable way to be used as replacement for fossil fuel.

However, the direct use of crops for energy production would induce competition with food use [3,4]. Therefore, to avoid this competition, the agricultural and agro-industrial residues that are not used for food production can be destined to other uses. This recycling strategy not only avoids disposal costs and environmental issues, but also brings valorisation patterns for the agricultural and agro-industrial sectors. In order to find a solution to what they call the "food, energy and environment trilemma", Tilman et al. [5] suggested alternative biomass sources - e.g. wood, forest, and crop residues as well as municipal and industrial wastes - that could together meet a substantial share of the future energy demand [6]. Waste biomass as energy source is closely related to forest, agriculture, livestock residues, and urban waste potential and availability [7]. Due to the intrinsic physico-chemical characteristics of the different biomasses, the choice of the most suitable feedstock to feed biomass-to-energy conversion plants is often a very delicate task. Furthermore, biomass is the one of the renewable energy sources, which is most closely tied to its territory [8], because the yearly amount of biomass residues depends upon several local conditions, such as climatic factors, farm production, type and variety of livestock, and crops and their yields [7]. Therefore, since one of the key barriers to biomass development is the lack of knowledge on the resource potential [9,10], accurate estimates of biomass sources and availability over a territory are important to support the policy and decision making processes [11].

In countries like Italy few detailed studies on the assessment of biomass availability for energy exploitation in individual regions have been performed [8]. To fill this gap, this study analyses the energy potential from agricultural biomass exploitation in Calabria (Southern Italy), one of the regions in Italy that are most devoted to the agricultural sector. More specifically, after giving some outlines about the main characteristics of the agriculture *sensu lato* in the region, the yearly amounts of fruit tree, crop, agro-industry and livestock residues produced in Calabria are evaluated in terms of available dry materials. This evaluation has been carried out by applying coefficients drawn from literature, giving the biomass yield from unit agricultural area or production and livestock amounts, to production statistical data.

Finally, as a possible application, the combined heat and power (CHP) production by Organic Rankine Cycle (ORC) systems (for energy conversion of pruning residues) and Internal Combustion Engines (ICE) (fed by the biogas from anaerobic digestion of agricultural and breeding residues) have been quantified.

The methodology proposed and applied in the case study of Calabria is general, since it requires input parameters that can be easily found in the literature and it is not based on assumptions or hypotheses directly linked to the specific territory. This procedure can be extended to other rural contexts at different spatial scales - ranging from agricultural districts to entire countries – and it can be used for planning activities and strategic choices in the renewable energy sector.

2. OUTLINES ON THE RENEWABLE ENERGY SECTOR IN EU-28, ITALY AND CALABRIA

The most recent statistical data, issued by EUROSTAT [12] and, at the national level, by GSEE [13] ("Gestore Servizi Energetici", the Italian agency for energy services management), show that, against a gross inland energy consumption[1] of EU-28 of about 19,000 TWh per year, the 28 countries have a primary production of energy[2] lower than 50% of this demand (about 9,000 TWh per year); the national production of renewable energy[3] (2,400 TWh per year) covers only 12.6% of this share. In Italy, the self-sufficiency of the energy sector is lower (that is, the internal production of energy, 420 TWh per year, covers only 23.1% of the gross inland energy consumptions, equal to 1,800 TWh per year), but the incidence of the renewable energy production on the total national need is higher than EU (15.1%, for a yearly amount of 274 TWh).

In the Calabria region, the latest available data regarding the gross inland energy consumption report a yearly total need of 28.3 TWh for 2015, of which 37.6% (10.7 TWh per year) is represented by a consumption of renewable energy [13]. In this region, the production of renewable energy concerns mainly hydropower (1.404 TWh/year) and wind energy (1.866 TWh/year); about 10% of the hydro-electrical energy produced is exported to other regions, while wind energy is fully

[1] "Gross inland energy consumptions is the energy demand of a country or region and represents the quantity of energy necessary to satisfy inland consumption of the geographical entity under consideration" [12].
[2] "Primary production of energy is any extraction of energy products in a useable form from natural sources" [12].
[3] "Renewable energy sources are energy sources that replenish (or renew) themselves naturally and include *hydropower* (the electricity generated from the potential and kinetic energy of water in hydroelectric plants), *tide, wave, ocean energy* (mechanical energy derived from tidal movement, wave motion or ocean current and exploited for electricity generation), *geothermal energy* (the energy available as heat from within the earth's crust, usually in the form of hot water or steam), *wind energy* (the kinetic energy of wind converted into electricity in wind turbines), *solar energy* (solar thermal energy, radiation exploited for solar heat, and solar photo-voltaic for electricity production, *biofuels* (fuels from biomass) *and renewable municipal waste"* [12].

consumed on site. No geothermal neither tide, wave, ocean energies are produced in Calabria, while electric production from solar energy (615 GWh/year) and biofuels (977 GWh/year) is much less than what is needed in the region (1,010 and 6,490 GWh/year, respectively) (Figure 1). The regional thermal energy production from biomass is equal to 5,466 GWh/year, while solar thermal production corresponds to only 35 GWh/year.

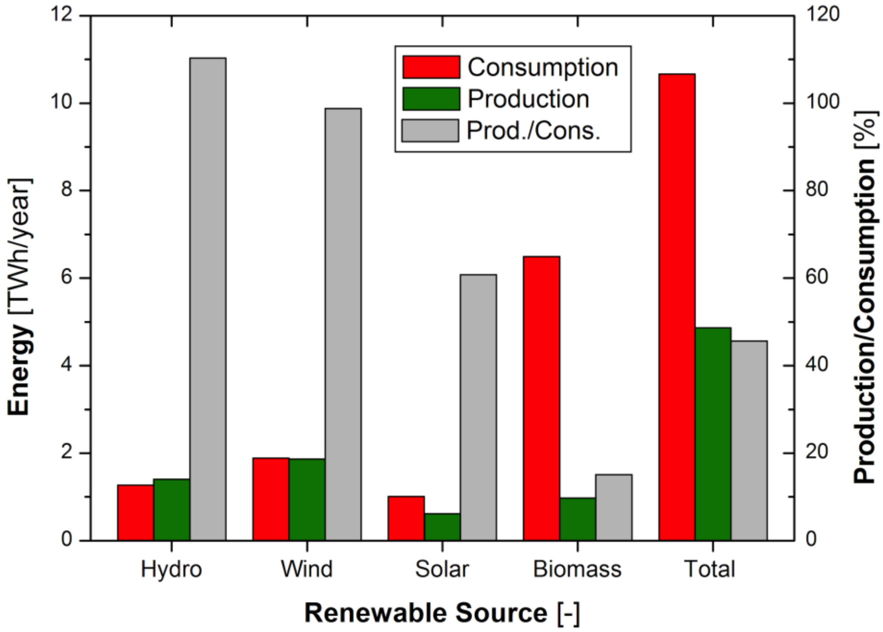


Figure 1 *- Yearly energy consumption and production from renewable sources in Calabria [13].*

In Calabria, the highest share of renewable energy is produced by 176 wind plants with a total power output of 1,025 MW (average size of 5.8 MW); 52 hydropower plants, of mean power equal to 14.2 MW, guarantee a total electric power of 740 MW, while solar energy production (total power of 484 MW) is fragmented in more than 20,000 plants of very small size (23 kW, most of them for family production and on-site consumption). Finally, 37 plants producing biofuels from biomass operate with total and mean unit power output of 195 and 5.3 MW, respectively (Figure 2). Figure 3 reports the geographical distribution of renewable energy production among the provinces of Calabria region.

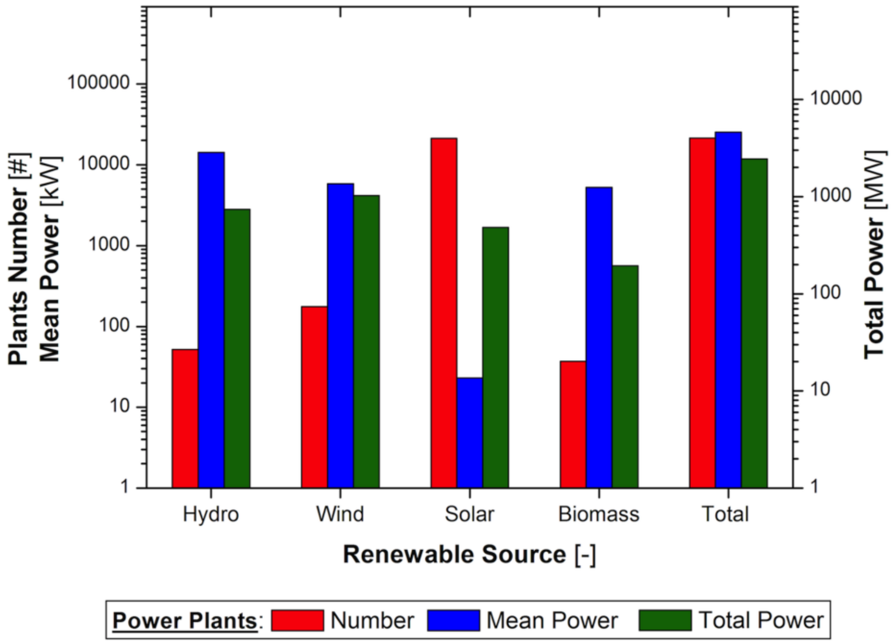


Figure 2 *- Number and power output of renewable energy plants in Calabria [13].*

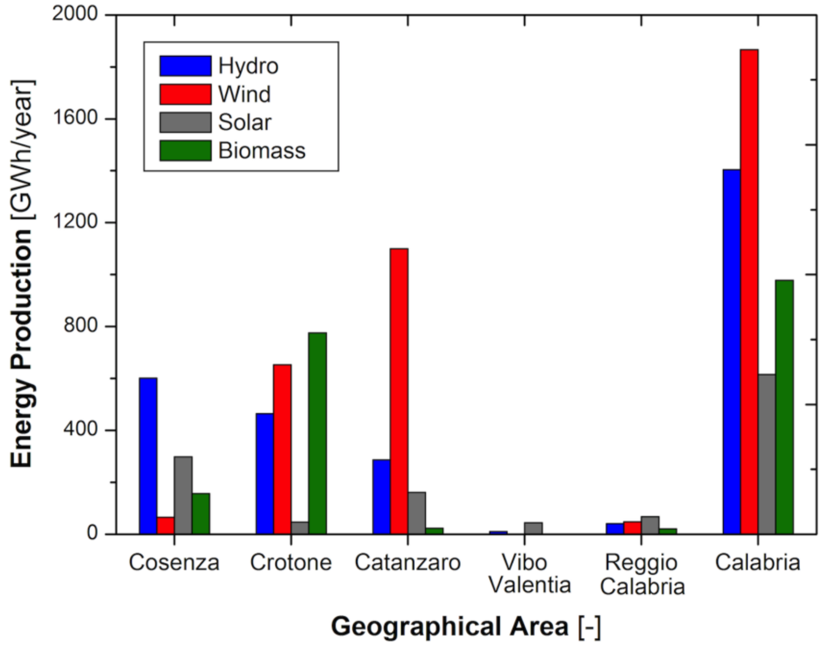


Figure 3 *– Energy production from renewable sources per province in Calabria [13].*

3. BIOMASS AND ENERGY PROCESSES

Several definitions of biomass are found in scientific and legal literature [14,15]. Specifically, in the European Union (EU) biomass represents the "*biodegradable fraction of products, waste and* *residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste*", according to the Directive 2009/28/EC of the European Parliament and Council [16]. At the same time, different criteria can be adopted to classify biomasses, considering characteristics, composition, and origin [17-22]. As an example, when the origin is analysed, it is possible to distinguish between vegetable- and animal-derived biomass, between energetic crops, natural and residual biomass, according to Figure 4. Specifically, the energy exploitation of biomass residues represents an important chance to diversify the energy mix, reduce dependence on traditional fossil fuels, and mitigate the environmental problems of residues disposal. To that purpose, this paper will focus on the share of agricultural and agro-industrial residues (the highlighted feedstock of Figure 4) that is not used for other applications (i.e., food, feedstuff, animal bedding, soil protection, fertiliser, etc.).

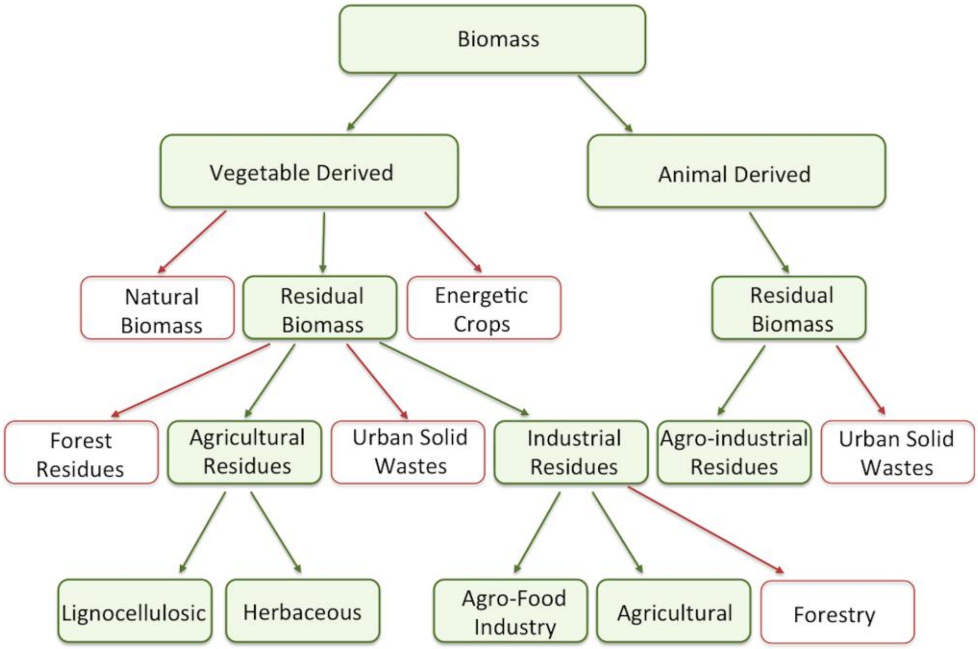


Figure 4 *– Biomass classification based on feedstock origin [17,22].*

Several processes and conversion systems can be adopted for biomass energy valorisation as a function of the characteristics of the available raw material [18-21]. To this purpose, Figure 5 shows the main conversion routes, based on thermochemical, biochemical, and mechanical processes [15,22-24]. Specifically, feedstock with high moisture content ($\varphi > 50\%$) is usually exploited by biochemical conversions adopting anaerobic digestion and fermentation (with distillation) processes [25,26]. Thermochemical conversions are used for low-moisture biomass ($\varphi < 50\%$) and are based on direct combustion, gasification, or pyrolysis [27,28]. Mechanical extraction with transesterification represents another way to produce biofuel from oleaginous plants, vegetable oils, and fatty acids [29-31].

Different small-scale energy systems are available on the market for the biomass energy exploitation: internal combustion engines, steam engines, steam turbines, gas turbines, Organic Rankine Cycles, Stirling engines, and fuel cells [32-34]. In particular, thermal energy from direct combustion of solid, liquid, or gaseous biofuel is usually employed to generate steam from water or other working fluids and feed steam engines, steam turbines, ORCs or Stirling engines [35,36]. Gaseous fuel from digestion and gasification processes can be used in gas engines, gas turbines, or fuel cells [15,21,37]. Finally, liquid biofuels (ethanol and bio-diesel) drive internal combustion engines [30,38]. Detailed information on the different processes and energy systems are available in literature [32,34,39-41].

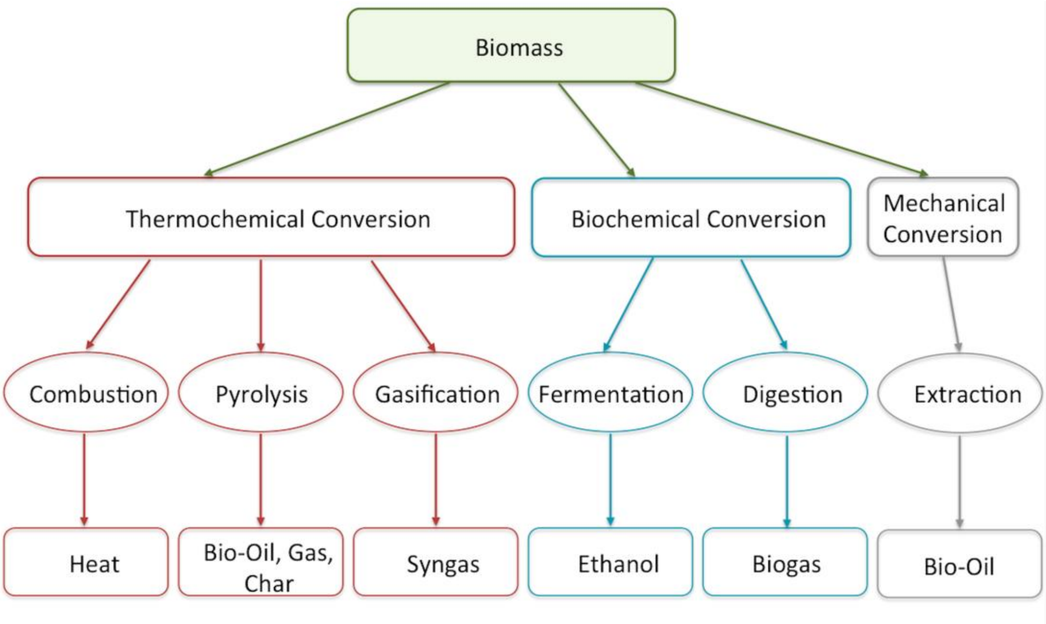


Figure 5 *– Scheme of main conversion processes for the energy exploitation of biomass [15,22].*

4. MATERIALS AND METHODS

4.1 Data sources and collection

Since this investigation aims at evaluating the residual biomass amount in Calabria (Southern Italy) for possible exploitation as an energy source, attention has been focused on agricultural residues, by-products and waste of the agro-food industry, and livestock sewage (Figure 4).

Preliminarily, a quantitative investigation has been carried out to identify the most important agricultural sectors in Calabria. To this aim, the agricultural areas and yearly productions of tree and cereal crops, as well as the number of livestock animals in this region have been drawn from statistical data provided by Italian National Institute of Statistics (ISTAT). Specifically, the Sixth Agricultural Census and the last annual report give detailed information on the cultivated areas, agricultural yields, and geographic location of the different products [42,43].

Based on the processed data regarding agricultural areas and yearly production of tree and cereal crops, as well as the number of livestock animals in Calabria, the prominent agricultural sectors have been defined.

Given that agricultural production often is destined for both markets and processing industries (e.g. table olives and olive oil), the mean amounts processed in agro-food industries have been quantified from the same data source. Furthermore, an extended literature review has been performed to define proper methods for the evaluation of energy potential production from biomass.

4.2 Assessment of biomass potential

A comprehensive literature analysis has been carried out to establish suitable procedures for the evaluation of the biomass potential. Starting from agricultural and livestock data [42,43], it is possible to calculate the amount of residues produced per year. This has been done by applying coefficients drawn from literature, giving the biomass yield from unit agricultural area or production and livestock amount.

4.2.1. Residues of fruit tree pruning

The potential annual amount of lignocellulosic residues R_L (t/year) from periodic pruning operations of tree crops has been evaluated as the product of the cultivated area A_c (ha) by the "residue-to-area rate" *RAR* (t/ha-year) - that is, the yearly specific production rate of fresh pruning residues per cultivated area unit - according to the following equation [22,44-47]:

$$R_L = A_c \ RAR \qquad (1)$$

while the corresponding dry amount of lignocellulosic biomass $R_{L,d}$ (t/year) is a function of the moisture content φ (%) of the fresh residues:

$$R_{L,d} = R_L\,(1 - \varphi / 100) \tag{2}$$

A lot of experimental investigations have been carried out in the last decades to define the residue-to-area rate of different agricultural tree crops and their relative moisture content [48-51]. The analyses demonstrate that water content and pruning yield are significantly influenced by several factors, i.e., the geographic location, climate conditions, irrigation frequencies, soil characteristics, local agricultural practices, etc. [52-54]. As an example, in Calabria and Italian Southern regions the high temperatures and local soil characteristics favour the growth of vines and citrus orchards with respect to other parts of the Italian peninsula [54,55], whereas the moisture content is significantly lower.

4.2.2. Residues of cereal crop harvesting

For cereal crops residues consist of straw after grain harvesting. The straw quantity produced yearly R_C (t/year) has been estimated by multiplying the crop production P_C (t/year) - referred to grain - by the “residue-to-product rate” *RPR* (-), i.e. the dimensionless ration between straw and grain mass, according to [11,56-58]:

$$R_C = P_C \; RPR \tag{3}$$

Given the amount of residues, the related dry biomass production $R_{C,d}$ has been evaluated by their average total solid concentration *TS* (%), that is, the quantity of feedstock that can be theoretically converted into energy, excluding water:

$$R_{C,d} = R_C \; TS / 100 \tag{4}$$

RPR, *TS* coefficients have been drawn from literature; as for the other agro-food industry and breeding farm residues, the related variability, depending on factors such as physical and chemical composition of residues and production processes, has not been taken into account; only the mean values have been considered.

4.2.3. Residues of agro-food industries

Furthermore, the annual amount of residues generated by agro-food industries R_A (t/year) has been estimated, based on the "residue-to-processed product ratio" *RPPR* (-), that is the dimensionless biomass yield from unit treated product, as follows [8,59]:

$$R_A = P_P \ RPPR \tag{5}$$

where P_P is the amount of processed products by agro-food industries annually (t/year).

For example, the amount of olive oil mill wastewater (OMW) produced from olive oil extraction has been assessed by a coefficient that gives the weight of OMW (in tons) per unit weight of olives processed. For this coefficient, the average value found in literature has been assumed; however, it should be considered that biomass yields show a considerable variability, since they depend on several factors. In more detail, in the case of tree fruit processing (i.e., olives, citrus and grapes), the agro-food industries produce wastewater (OMW and CPW for olive oil mills and citrus processing facilities, respectively) and solid residues (pomace, citrus peel, and marc, for olive oil mills, citrus processing facilities, and wineries, respectively). Wastewater consists of a blend of water produced by fruit, machine, and plant washing and fruit processing (that is, water contained in fruits and used for their processing); moreover, citrus processing plants produce also wastewater in machines that extract essential oils and dry peel [60,61]. Solid residues consist of a blend of fruit organic residues and other compounds used for processing (e.g. sulphites in wineries).

Composition of agro-industries residues, whose physical and chemical characteristics show a very large variability [62,63], depends mainly on the processing technology (e.g., in the case of olive oil production, on extraction for pressure or for centrifugation by 2-phase or 3-phase cycles) and secondarily on olive species, level of fruit ripening, etc. [64].

The *RPPR* and *TS* coefficients have been taken from the literature.

4.2.4. Residues of breeding farms

Concerning residues of livestock, the amounts of annual biomass R_B (a blend of wastewater and manure) have been estimated as a function of the number of animals (*capita*) N_A and the produced residue per capita *RPC*, i.e. the mass of excrement generated yearly by each animal [11,59,65]:

$$R_A = N_A \ RPC \tag{6}$$

In order to compare differences in excrement production among different animals, density of farm animals has been taken into account by livestock units (LSU). LSU is a reference unit that facilitates the aggregation of livestock from various species and age as per convention using specific coefficients established initially on the basis of the nutritional or feed requirement of each type of animal.

The different parameters have been drawn from the literature. Specifically, Eurostat "Thematic Glossary" has been used for LSU units [66].

4.3 Energy and power potential of agricultural residues

In order to evaluate the energy and power potential associated with agricultural residues, the available amount of biomass has been quantified. In fact, the theoretical biomass potential is subject to limitations, owing to alternative uses of residues [11,23,24]. For this purpose, an availability factor a_f is adopted to take into account the biomass already used for other purposes (i.e., animal bedding, soil protection, fertiliser, etc.) and not available for energy exploitation.

Available residues AR_j (t/year) from the generic stream j (pruning operations: $j = L$, cereal crops: $j = C$, agro-food industries: $j = A$, and breeding farms: $j = B$) are evaluated as [30,57,67]:

$$AR_j = R_j \ a_{f,j} / 100 \tag{7}$$

where R_j (t/year) is the potential biomass (wet or dry), evaluated according to the previous sub-sections, and $a_{f,j}$ is the availability factor (%) of the generic residues j.

The corresponding energy content E_j (MJ/year) is [67]:

$$E_j = AR_j \ H_{i,j} \tag{8}$$

where $H_{i,j}$ is the lower heating value of the generic wet biomass j (MJ/kg) that is calculated as

$$H_{i,j} = H_{i,j\,d} \, (1 - \varphi / 100) - \varphi / 100 \ \ \lambda \tag{9}$$

Here $H_{i,j\,d}$ is the lower heating value of the dry biomass j (MJ/kg) and λ is the water latent heat of vaporisation (MJ/kg).

The corresponding power potential P_j that could be installed for the energy exploitation of the available biomass residues is defined as [57]:

$$P_j = E_j \ \eta / \Delta t \quad (10)$$

where η represents the electric, thermal, or global efficiency of the selected conversion energy system and Δt corresponds to the annual operating time.

When biomass is transformed in liquid or gaseous biofuel (i.e., through digestion, gasification, pyrolysis, fermentation, etc.) the yield of the conversion process should be considered to evaluate the biofuel amounts and the corresponding energy availability. As an example, for anaerobic digestion the biogas amount $m_{biofuel}$ (m^3/year) is evaluated considering the available total volatile solids AR_{TVS} (t/year) and the digestion yield factor $y_{biofuel}$ (m^3/t) [68]:

$$m_{biofuel} = AR_{TVS} \ y_{biofuel} \quad (11)$$

with

$$AR_{TVS} = AR_d \ TVS / 100 \quad (12)$$

where TVS (%) represents the concentration of total volatile solids (the biodegradable dry biomass excluding ash) while AR_d is the global amount of available dry residues (t/year).

In this case the available energy is the product of the biofuel amount by the relative lower heating value:

$$E_{biofuel} = m_{biofuel} \ H_{i,biofuel} \quad (13)$$

and the corresponding power potential that could be installed for the relative exploitation is:

$$P_{biofuel} = E_{biofuel} \ \eta / \Delta t \quad (14)$$

5. RESULTS AND DISCUSSIONS

5.1. Outlines on the agricultural sector of Calabria

Calabria is the southernmost region of Italian peninsula (Figure 6) with an area of 15,222 km^2. It is located between latitudes 38° and 40° N and is surrounded by the Tyrrhenian and Ionian seas. The region consists of five provinces: Cosenza, Catanzaro, Reggio Calabria, Crotone, and Vibo Valentia, with about 2 million inhabitants.

In Calabria, the extended agricultural area (706,931 ha) covers 46.4% of the total regional area [43]. As a consequence, the possible energy exploitation of agricultural residues represents an important option to reduce the regional dependence on traditional fossil fuels, to integrate the economic revenue of the agricultural sector, and to reduce the environmental pressure linked to agricultural residues management.

Productive areas are equal to 549,158 ha and consist mainly of tree crops (45.7%) and cereal crops (on arable lands) (28.4%), as shown in Table 1. Permanent pasture and meadow cover 25.6% of the regional productive area, whereas domestic gardens are less than 1%.

Figure 6 *– Investigated area: Calabria (Southern Italy).*

Table 1 – *Productive agricultural area in Calabria [43].*

Land use	Area [ha]	[%]
Tree crops	251,229	45.7
Cereal crops	156,034	28.4
Permanent pasture and meadow	140,357	25.6
Domestic gardens	1,577	0.3
All land uses (productive areas)	**549,198**	**100.0**

5.1.1. Fruit tree crops

The most important tree crops in Calabria are olives (89% of the-agricultural area and 50% of the production of fruit trees) and citrus (8% and 33% respectively). Grapes, peaches, kiwi fruit, and nectarines cover much lower areas and productions, while the other fruit tree crops (such as plums, apples, pears, and apricots) represent negligible shares of the total area and production (less than 1.5% and 3%, respectively), as visible in Figure 7. Consequently, for the following analysis the attention has been focused on olive, citrus, and grapevine, because of the higher cultivated area (larger than 96% of the total) and production (more than 87% of the total harvested amount) in Calabria. Moreover, the fruits produced by these tree species are destined for agro-industries, thus assuring the availability of additional biomass from their processing with possible exploitation for energy production.

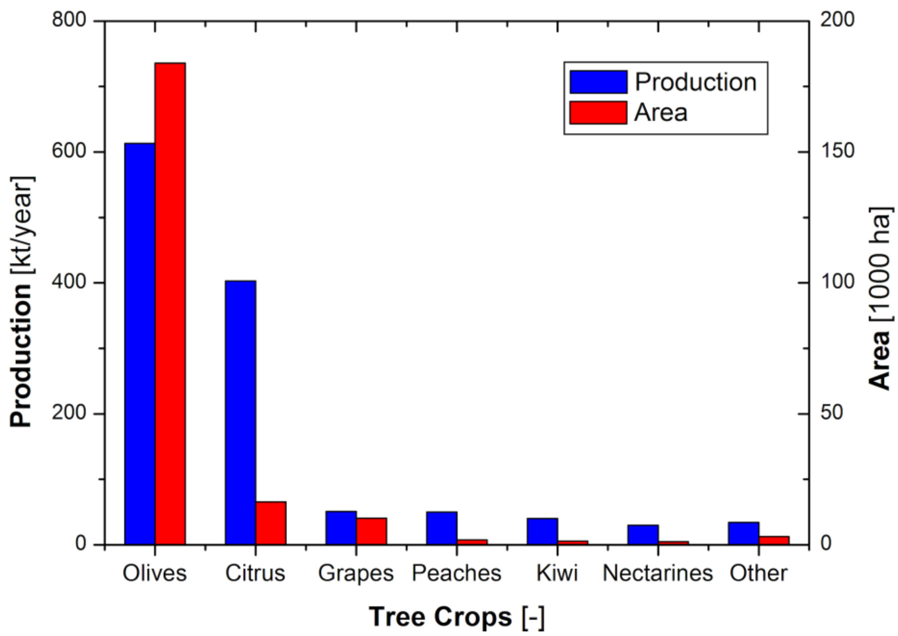


Figure 7 *- Cultivated areas and yearly production of fruit tree crops in Calabria.*

Among these most important fruit crops, about 98% of olive and grape production is destined for industrial processing (respectively for oil extraction and wine production). Only 36% of citrus is processed for marmalade and juice production, with the remaining share designated as marketable fruit (Figure 8).

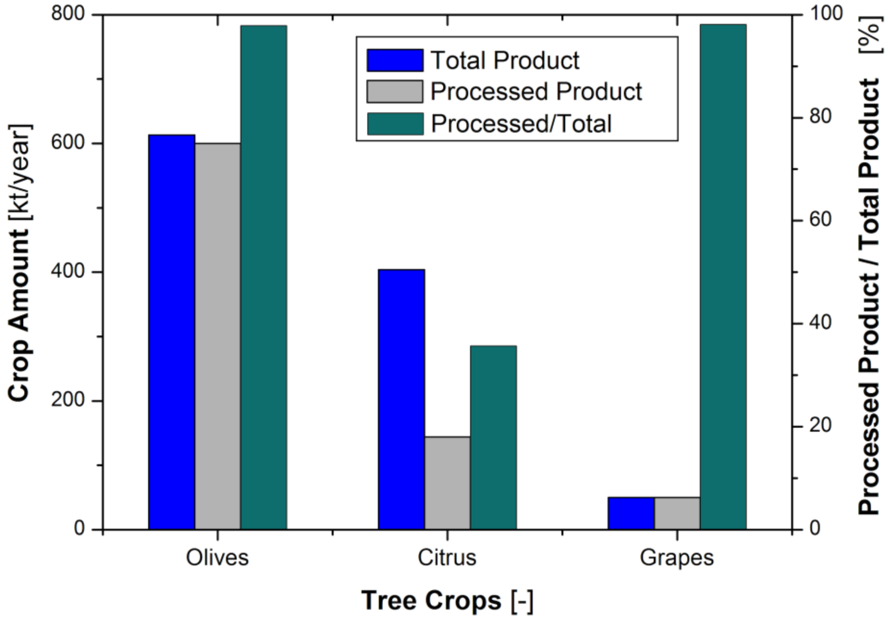


Figure 8 *- Produced and processed tree fruits in Calabria.*

Table 2 reports the experimental values of the residue-to-area rate (*RAR*) parameter, the moisture content φ, the availability factor a_f and the lower heating value of dry biomass $H_{i,d}$ for the investigated tree crops (olives, vineyards, and citrus). Data refer to experimental campaigns performed in the last decades in the Italian peninsula, adopting local pruning and cultivation practices. The specific production rates from olive groves at the national level range from 0.6 to 4.3 t/ha-year [48,49,69-71], while the corresponding values from vineyards and citrus orchards are 2.0 ÷ 3.1 t/ha-year [49-51,72,73] and 0.7 ÷ 1.9 t/ha-year [54,55,69], respectively. In particular, in Calabria and Southern regions the high temperatures and local soil characteristics favour the growth of grapevines and citrus orchards, with large residue yields (2.8 and 1.9 t/ha-year, respectively), whereas the specific production rate of olive groves corresponds to intermediate value (2.1 t/ha-year) [55].

The moisture content of lignocellulosic residues in Italy usually ranges between 35% and 55% [48,72-77]. Specifically, intermediate values have been adopted for the Calabria region (40% for olives, 50% for vineyards, and 40% for citrus residues [74,79]). Furthermore, literature review highlights the significant regional pruning availability, net of lignocellulosic residues already used for other purposes (i.e., fertiliser, soil protection, etc.), with percentages higher than 90% for all three of the species [79].

Table 3 summarises the biomass yields, specific total solids (*TS*), total volatile solids (*TVS*), and the availability factor of prominent agro-food industries residues in Calabria. Particularly, the average values found in literature have been assumed, as stated above [62,63,80-88].

***Table 2** – Residue-to-Area Rate, moisture content, availability factor, and lower heating value of fresh pruning residues for the investigated fruit tree species.*

Species	*Residue to Area Rate* [t/ha-year]	*Moisture content* [%]	*Availability factor* [%]	*Lower heating value* [$MJ/kg_{d.b.}$]
Olive	2.1 [55]	40 [74,78]	90 [79]	18 [74]
Grapevine	2.8 [55]	50 [78,79]	95 [79]	18 [74,77]
Citrus	1.9 [55]	40 [74,79]	95 [79]	18 [74]

***Table 3** – Specific biomass yields, total solids (TS), total volatile solids (TVS), and availability factor of residues of some types of agro-food industries.*

Species	*Residue*	*Residue to Processed Product Ratio [-]*	*TS* [%]	*TVS* [%]	*Availability factor* [%]
Olive	OMW	0.56 [80]	7 [81]	82 [81]	80 [79]
	Pomace	0.45 [80]	22 [82]	97 [83]	80 [79]
Citrus	CPW	1.00 [62]	2 [63]	96 [84]	80 [79]
	Peel	0.59 [85,86]	13 [86]	96 [87]	80 [79]
Grape	Marc	0.20 [88]	61 [88]	91 [88]	75 [79]

Notes: OMW = Olive Oil Mill Wastewater; CPW = Citrus Processing Wastewater.

5.1.2. Cereal crops

The most important cereal crop in Calabria arable lands is wheat, whose cultivated area and production are more than 50% and 63% of the total, respectively. Other significant crops are barley and maize, whose cultivated areas and productions are 12% and 13% (barley) and 6% and 12% (maize), respectively. Figure 9 illustrates that agriculture in Calabria also produces other cereal crops, whose total cultivated area is not negligible (about 28%), but whose production is much lower than other cereal crops mentioned above (less than 13%). Specific residue-to-product rates of the main cereal harvests are highlighted in Table 4.

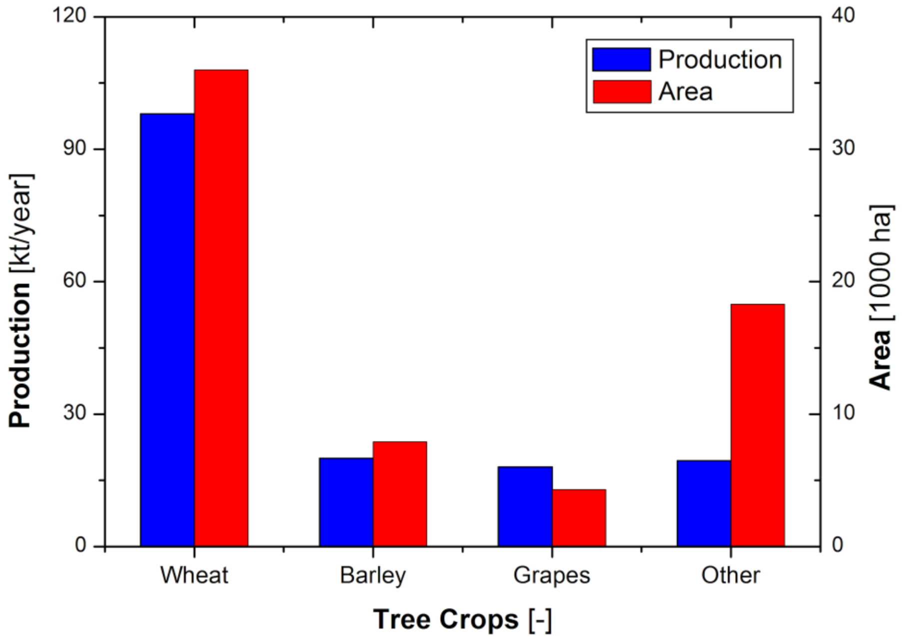


Figure 9 *- Cultivated areas and yearly production of cereal crops in Calabria.*

Table 4 *– Specific biomass yields, total solids (TS), total volatile solids (TVS), and availability factor of some cereal crop species.*

Species	*Residue to Product Rate [-]*	*TS* [%]	*TVS* [%]	*Availability factor* [%]
Wheat	2.15 [89]	91 [90]	81 [91]	80 [79]
Barley	1.31 [89]	91 [88]	94 [88]	80 [79]
Maize	1.00 [92,93]	78 [94]	88 [95]	50 [79]

5.1.3. Breeding farms

Animal breeding in Calabria is carried out both in sheds and in open air. In general, sheep and goats are bred in open air, while poultry, bovines, and pigs in sheds. The latter method allows for livestock concentration in buildings, which makes the harvest of manure and wastewater produced by animals easier.

Poultry shows the largest number of animals (about 70% of the total number) and their breeding is usually practised in sheds. Sheep and goats, bred in open air, cover shares of 14% and 8% respectively, while bovines and pigs (about 6% and 3% of the total livestock number) breeding is practised in sheds of large farms. Other species cover a limited share (no more than 1.4% of the total number of animals). To calculate the livestock territorial density, the following coefficients of LSU have been adopted: 0.03 (poultry), 0.1 (sheep and goats), 0.84 (bovines), 0.32 (pigs) and 0.21 (other animal species). In terms of LSU, bovines show the largest territorial density (about 83,000 LSU). Poultry and sheep cover about 36,000 and 25,000 LSU, while pigs and goats 16,000 and 13,500 LSU, respectively. The livestock of other species are less than 5,000 LSU.

As expected, specific biomass yields of residues from breeding farms reveals large differences between bovines, pigs, and poultry (Table 5). Residue per bovine is about 2.5 times the specific yield from pigs, whereas TS and TVS contents are similar for the three species investigated [96-102].

It is worthy to notice that the adoption of the anaerobic digestion process does not create any competition with the present use of breeding farm residues as fertilisers. The anaerobic digestion guarantees, in fact, the availability of a highly nutrient and odourless by-product (the digestate) that can be adopted as substitute of manures and traditional fertilisers in agriculture [11,15,37,104-105].

In Calabria (and more in general in many regions of Southern Italy) the traditional use of livestock residues (soil fertilisation and conditioning) have been increasingly discouraged by a number of factors, such as strict land spreading limits (with regard to the risks of soil as well as surface and ground water pollution), competition with higher-income uses (e.g., composting, energy conversion), low availability of receiving fields, high costs of possible pre-treatments and so on. Furthermore, fields amended with anaerobic digestate guarantee lower CO_2 emission with respect to soils amended with manures [106].

Table 5 *– Specific biomass yields, total solids (TS), total volatile solids (TVS), and availability factor of residues of some types of breeding farms.*

Species	*Residue*	*Specific residue yield* [t_b/*capita*]	*TS* [%]	*TVS* [%]	*Availability factor* [%]
Bovine	Manure + wastewater	13.3 [96,97]	15 [98]	75 [99]	80 [103]
Pigs	Manure + wastewater	5.2 [96,97]	16 [98]	75 [100]	80 [103]
Poultry	Manure	0.04 [101]	34 [102]	68 [102]	80 [103]

5.2. Biomass potential for energy production in Calabria

5.2.1. Pruning and harvesting residues

Table 6 highlights the potential annual quantity of biomass on dry basis (d.b.) from the three main woody crops in Calabria. The investigation reveals that an interesting biomass amount exists in the investigated area; consequently, lignocellulosic residues can be conveniently used for sustainable energy production in the region. Potential dry lignocellulosic residues reach about 290 ktons per year. Specifically, olive groves guarantee the largest biomass quantity with more than 230 ktons. Residues from citrus trees reach 40 ktons per year, while the biomass from grapevines is lower than 14 ktons. The Cosenza and Reggio Calabria provinces provide the largest contribution, with 31.7% and 28.5%, respectively. On the other hand, percentages from the Vibo Valentia and Crotone districts are lower than 12%.

Table 6 *– Potential annual amount of dry lignocellulosic biomass in the regional area.*

	Potential lignocellulosic biomass			
	Olive	*Citrus*	*Grapevine*	*Total*
	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]
Calabria	**232,591**	**39,822**	**13,799**	**286,213**
Cosenza	70,026	14,971	5,903	90,900
Catanzaro	48,031	3,989	1,023	53,043
Reggio Calabria	62,562	16,800	1,873	81,235
Crotone	29,026	1,599	4,494	35,118
Vibo Valentia	22,946	2,464	506	25,916

5.2.2 Cereal crop harvesting

The cereal crop producing most of harvesting residues in arable lands is by far wheat; this is due not only to the largest crop production in the region (about 2-fold the sum of the other cereal crops, Figure 9), but also to the highest specific yield in straw (2.15 t/t, 2-fold the straw produced by barley and maize, Table 4). Thanks to the very low water content (9-22%) and high TVS concentration (from 81% of wheat to 94% of barley) (Table 4), the cereal crop represents a suitable substrate for energy production (for instance, for anaerobic digestion with dry processes, requiring substrates with TS higher than 25% [107]) or for direct combustion plants, requiring as little water as possible [108].

At a geographical level, straw from wheat and barley is mostly produced in the provinces of Cosenza and Catanzaro (and Crotone for wheat); conversely, production of maize straw is limited in all provinces (Table 7).

Table 7 *– Potential annual amount of dry cereal crop residues in the regional area.*

	Potential cereal crops residues			
	Wheat	*Barley*	*Maize*	*Total*
	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]
Calabria	**135,569**	**24,117**	**14,134**	**173,819**
Cosenza	57,884	12,365	3,490	73,739
Catanzaro	26,327	8,156	4,992	39,475
Reggio Calabria	8,217	0,424	1,408	10,050
Crotone	37,663	1,919	2,169	41,751
Vibo Valentia	5,478	1,252	2,075	8,805

5.2.3 Agro-food industry residues

It must be noticed that the solid residues of agro-food industries yield much more TVS (that is, the substrate able to be converted into energy) than wastewater. In spite of the larger production of solid residues compared to liquid effluent (production of OMW is 24% more than pomace and citrus wastewater is about 2-fold the amount of citrus peel amount), the concentration of TS is much lower (one third in OMW and one sixth in citrus wastewater compared to the related solid residues). Wineries show the lowest production of residues (grape marc, a blend of solid and liquid biomass) - 20% (w/w) of the processed fruit, - but contains the highest TS concentration among the agro-industrial residues considered in this study (Table 3). TVS content is always high (from 82% of OMW to 96% of citrus processing residues, Table 3), thus demonstrating the suitability of these residues to energy conversion thanks to the high concentration of organic matter.

In relation to both the physical characteristics of agro-industrial residual biomasses and the distribution of fruit tree crops in Calabria, it has been found that olive oil mills produce the largest amounts of processing residues, in relation to the wider diffusion of olive crops (85% of the total agricultural area of the region, Figure 7) and the larger quantity of fruits destined to transformation compared to the other agro-industrial crops analysed in this study (98% against 36% of citrus fruits, Figure 8). Conversely, residues from wineries show a quite limited availability in the region. However, it should be noted that the use of these residues as substrate for energy plants is limited by the substantial presence of inhibiting compounds, which are toxic for the microbial populations degrading substrates in biological plants [109]. As a matter of fact, olive oil mill residues (pomace and wastewater) citrus processing waste (wastewater and peel) and grape marc contain polyphenols, essential oils and tannins respectively, whose typical concentrations after fruit processing are always higher than the inhibition limits of the biological processes producing energy. For example, OMW contains a polyphenol concentration between 0.5-24 g/L [110,111] that is also 10-fold the inhibition limit of the anaerobic digestion processes (about 0.5 - 2 g/L [111,112]). Moreover, the high presence of essential oils (over 1,000-1,200 ppm [60]) has been found to be a problem even in in the most efficient and robust biological processes in citrus wastewater depuration by aerobic-anaerobic lagooning, which tolerates essential oil concentrations up to 600 ppm [61,113].

This drawback may be overcome by the removal of the inhibiting compounds prior to biological processing, but this technique requires additional costs, which can lower the energy conversion profit. The most suitable practice is blending the residues of olive oil mills, citrus processing plants, and wineries with other substrates (generally, straw or animal effluents), in order to lower the concentration of inhibiting compounds under a limit assuring a regular biological process and appreciable energy yields. For example, in anaerobic digestion, OMW should be used at concentrations not higher than 20-30% [114], while a volume of citrus processing residues below 60-70% should not fed to biogas plants [109].

Finally, since pH values of the substrates must be in certain optimal ranges for balanced biochemical processes (e.g. 6.5-8.5 for anaerobic digestion [83,115,116]), the high acidity of these biomasses must be contrasted by supplying additives or by blending with other substrates.

Table 8 *– Potential annual amount of dry biomass from agro-food industries in the regional area.*

	Potential agro-food industry residues					
	OMW	*Pomace*	*CPW*	*Peel*	*Marc*	*Total*
	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]
Calabria	**23,515**	**59,388**	**2,882**	**11,051**	**6,044**	**102,880**
Cosenza	6,898	17,421	0,598	2,292	2,357	29,567
Catanzaro	2,352	5,940	0,476	1,825	0,817	11,411
Reggio Calabria	9,680	24,447	1,496	5,738	0,917	42,278
Crotone	1,588	4,010	0,151	0,580	1,818	8,146
Vibo Valentia	2,998	7,571	0,160	0,615	0,134	11,478

Notes: OMW = Olive Oil Mill Wastewater; CPW = Citrus Processing Wastewater.

Regarding the local availability of agro-industrial residues in Calabria (Table 8), olive oil mill residues are mostly abundant in the provinces of Reggio Calabria (34,127 t/year) and Cosenza

(24,319 t/year); the first province also shows the highest production of citrus processing residues (7,234 t/year), which are distributed quite similarly among the other provinces. The provinces producing the largest quantities of winery residues are Cosenza and Crotone (2,357 and 1,818 t/year, respectively). On the whole, residues of oil extraction are about 6-fold and 14-fold the volumes of residues produced annually by citrus processing industries and wineries, respectively.

5.2.4 Breeding farm residues

Among the analysed animal residues, poultry manure shows the highest content of TVS per unit weight (about 2-fold the TVS of bovine and pig manures, Table 5), and thus appears to be the most suitable substrate for biochemical energy conversion processes. However, since bovine and pig breeding farms are widely diffused in the regional territory, the total annual amount of organic matter from excrements produced by bovines and pigs is about 13-fold and 3-fold the production of poultry factories, respectively.

One must take into account the main physico-chemical properties of animal manure, which is often alkaline (pH over 7.9) and rich in nitrogen [98], but lacks inhibiting compounds (differently from agro-industrial residues). These peculiar characteristics let these substrates be suitable as single feedstock for some types of energy conversion processes (e.g. biogas plants); moreover, they can be blended with other substrates (for example, with agro-food industry residues, showing unbalanced C/N ratios and high acidity) to correct the related peculiar characteristics in the case of strict process requirements.

Another important consideration relates to the breeding tethering: if additional shares of goats and sheep - matching the best sanitary and breeding conditions - were bred in a shed instead of in open air (however, without harmful effects in their health and welfare), their manure would be easily collectable and, given the quite large diffusion of these livestock, may represent an additional feedstock for energy plants at a provincial scale. In any case, the present work does not consider the energy exploitation of goats and sheep residues.

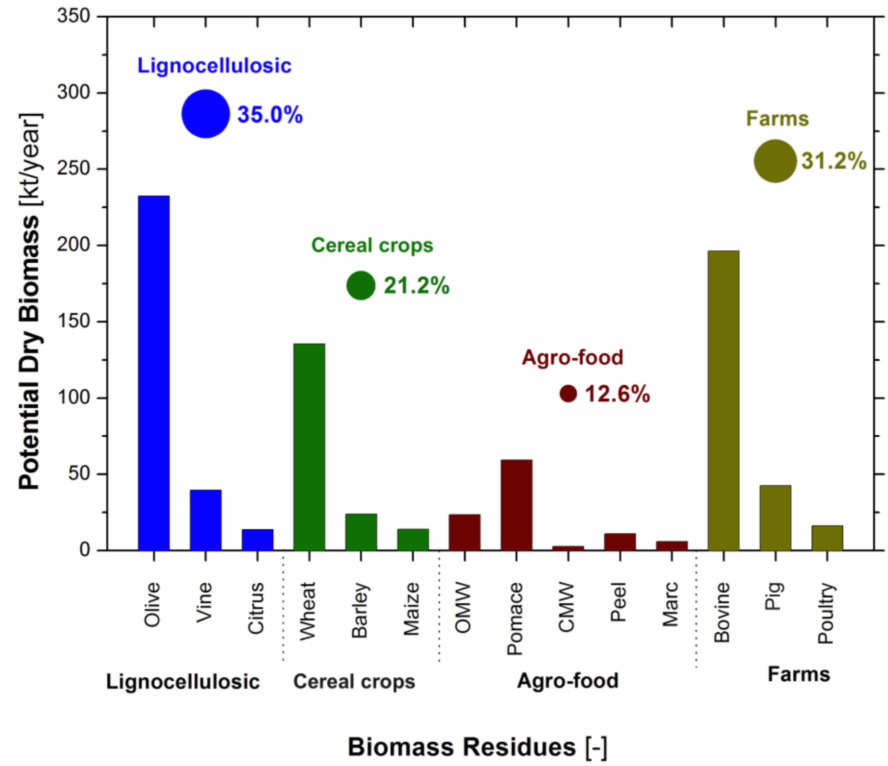
The estimation of the provincial distribution of breeding farm residues in Calabria shows that the province of Cosenza produces by far the largest amounts of bovine, pig, and poultry manure. Large quantities of bovine manure are also produced in the provinces of Reggio Calabria and Crotone, while the poultry manure is practically negligible in the province of Catanzaro (Table 9).

Table 9 – *Potential annual amount of dry biomass from breeding farms in the regional area.*

	Potential breeding farms residues			
	Bovine	*Pig*	*Poultry*	*Total*
	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]	[$t_{d.b.}$/year]
Calabria	**196,380**	**42,610**	**16,298**	**255,288**
Cosenza	93,200	22,772	6,250	122,222
Catanzaro	20,327	4,213	0,217	24,758
Reggio Calabria	35,369	8,674	3,027	47,070
Crotone	29,496	5,534	3,438	38,468
Vibo Valentia	17,987	1,417	3,366	22,770

5.2.5 Global amount

Figure 10 summarises the potential annual amount of dry residues from the four investigated feedstock. The analysis reveals that Calabria guarantees about 820 kt/year, with higher shares from lignocellulosic residues and breeding farms wastes (35.0% and 31.2%, respectively). Lower quantities are obtained from cereal crops (21.2%) and agro-food industries (12.6%).



Figures 10 – *Potential annual production of dry biomass from fruit tree crop pruning, cereal crop harvesting, agro-food industries, and breeding farms in Calabria.*

The comparison across the five provinces highlights that Cosenza offers the largest biomass potential in the region, with more than 315 kt/year, due to the city's significant production of pruning operations, livestock activities, and cereal crop harvesting (Tables 6 to 9). Significant biomass residues are also located in Reggio Calabria province (180.6 kt/year), while Vibo Valentia presents the lowest amount with 69.0 kt/year. Crotone has the highest biomass density (71.1 t/km^2), compared to the regional average concentration of dry residues of 53.7 t/km^2.

5.3 A possible application

The previous analysis has demonstrated that an interesting amount of biomass residues is available in Calabria; as a consequence, the possible energy exploitation in combined heat and power (CHP) systems appears extremely interesting. To this purpose, different processes and cogeneration systems can be adopted as a function of the characteristics of the available biomass. For lignocellulosic residues, the thermochemical conversion based on the combustion process appears as the most mature technology for the energy exploitation of pruning residues [15,27]. In this case, biomass boilers can be coupled with Organic Rankine Cycle (ORC) systems owing to their higher performance and lower costs with respect to other technologies (i.e., steam turbines, gas turbines, and steam engines) for decentralised and small-scale combined heat and power applications [117,119]. It is worthy to notice that natural drying (on field or at storage plant) is usually adopted in Southern Italy for pruning residues of fruit trees [21,120]. As a consequence, the expensive active drying is not strictly necessary to fed modern boilers that can work with 40% moisture content [51]. For the other investigated agricultural residues (from cereal crops, agro-food industries, and breeding farms), the biochemical conversion based on anaerobic digestion is considered the proper solution to obtain biogas and feed internal combustion engines (ICEs) according to the literature [11,39].

To this purpose, Figure 11 illustrates the considered energy conversion chains for the exploitation of the investigated agricultural residues, while Table 10 highlights the typical performance of production small-scale CHP units based on ORC [121-124] and ICE [125-128] technologies. Tables 11 and 12 summarise the potential energy content in terms of tons of oil equivalent (toe[4]) associated with pruning and wet agro-industrial residues, respectively. For the latter, the energy content is based on the methane production from anaerobic digestion, adopting specific yields of Table 13 [85,87,129-136].

[4] 1 toe = 41.868 GJ [130-131].

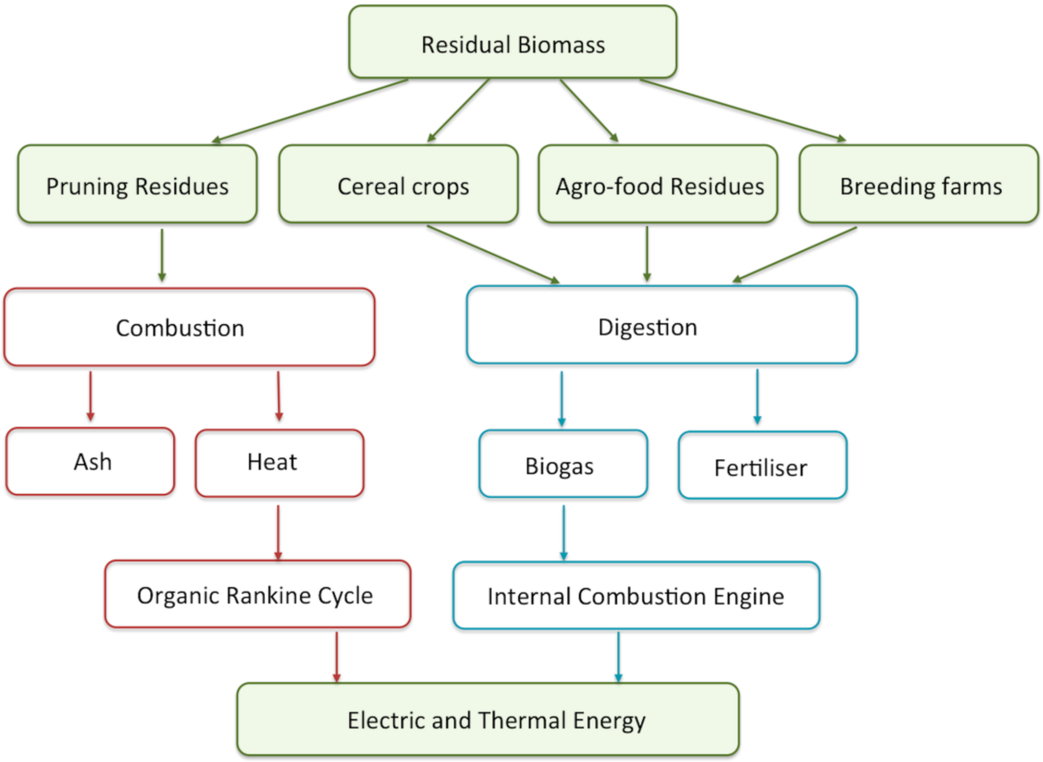


Figure 11 *– Energy conversion pathways for the investigated biomass residues.*

Table 10 *– Electric and thermal power, electric and total efficiency of production Organic Rankine Cycle (ORC) and Internal Combustion Engine (ICE) systems.*

Technology	**Manufacturer**	**Power [kW]**		**Efficiency [%]**	
		Electric	Thermal	Electric	Total
ORC	Adoratec [121]	300 - 1,000	1,350 - 4,270	18.1 - 19.0	98.8 – 98.9
biomass fuelled	Siemens [122]	400 - 1,000	1,740 - 4,050	18.4 - 19.6	92.0 – 98.1
	Triogen [123]	100 - 170	400 - 680	15.4 - 18.1	84.7 – 90.4
	Turboden [124]	200 - 1,016	1,402 - 4,081	12.3 - 19.9	97.3 – 99.3
ICE	2G Energy [125]	50 - 1,067	70 - 1,089	35.3 - 42.5	81.1 – 88.4
biogas fuelled	Jenbacher [126]	249 - 1,067	275 - 1,179	37.8 - 44.1	78.6 – 87.3
	MWM [127]	400 - 800	393 - 827	41.4 - 43.3	81.8 – 86.3
	PowerLink [128]	50 - 1,000	72 - 1,091	36.0 - 38.7	80.9 – 88.8

Investigated agricultural biomasses guarantee about 185,000 toe per year (101,550 toe from lignocellulosic residues and 83,171 toe from cereal crops harvesting, agro-food industries, and breeding farms), that corresponds to 18.1% of the annual petroleum product used in the region for energy purposes in 2015 [13,43]. Specifically, the anaerobic digestion of wet biomasses produces about 110 million m^3 per year of methane, 32.7% of the Calabrian natural gas used for energy purposes [13].

Table 11 *– Potential energy content (toe) of lignocellulosic biomass residues.*

	Lignocellulosic Residues
	[toe]
Calabria	**101,550**
Cosenza	32,299
Catanzaro	18,752
Reggio Calabria	28,928
Crotone	12,399
Vibo Valentia	9,172

Table 12 *– Potential methane yield (1,000 m^3) and energy content (toe) of cereal crop, agro-food, and breeding farms residues.*

	Cereal crops		*Agro-food industries*		*Breeding farms*	
	[1,000 m^3]	[toe]	[1,000 m^3]	[toe]	[1,000 m^3]	[toe]
Calabria	**54,883**	**41,497**	**22,109**	**16,717**	**33,009**	**24,957**
Cosenza	23,630	17,866	6,303	4,766	15,963	12,069
Catanzaro	12,278	9,283	2,506	1,895	3,221	2,436
Reggio Calabria	3,085	2,332	9,129	6,902	6,135	4,638
Crotone	13,282	10,042	1,773	1,341	4,910	3,712
Vibo Valentia	2,609	1,973	2,397	1,813	2,780	2,102

Table 14 shows the electric and thermal power that could be installed in the region, taking into account the biomass energy potential. To this purpose, the CHP electric efficiency of ORC systems (for the exploitation of pruning residues) has been fixed to 17%, while the electric efficiency of ICE units (for the exploitation of biogas from digestion) has been considered equal to 40%, according to the typical performance of production cogeneration units for small-scale applications (Table 10) [121-128]. Total efficiency has been set to 85% and 7,000 operating hours per year have been imposed, in line with the literature [32,34,137]. Specifically, the analysis highlights that the electric power is equal to about 81 MW_{el}, whereas thermal power is larger than 165 MW_{th}. Cosenza province guarantees the largest potential value (P_{el} = 31.3 MW_{el} and P_{th} = 58.8 MW_{th}) while Vibo Valentia offers the lowest power (P_{el} = 6.2 MW_{el} and P_{th} = 13.7 MW_{th}), according to residual biomass quantities available in the investigated areas.

Table 13 *– Specific methane yield of cereal crop, agro-food, and breeding farms residues.*

Origin	**Residue**	**Methane yield** [m^3/t_{TVS}]
Agro-food industries	OMW [129]	350
	Pomace [132]	250
	CPW [85]	350
	Peel [87]	350
	Marc [133]	350
Breeding farms	Bovine manure and wastewater [134]	200
	Pig manure and wastewater [134]	300
	Poultry manure [135]	200
Cereal crops	Wheat [136]	500
	Barley [136]	450
	Maize [136]	450

Notes: OMW = Olive Oil Mill Wastewater; CPW = Citrus Processing Wastewater.

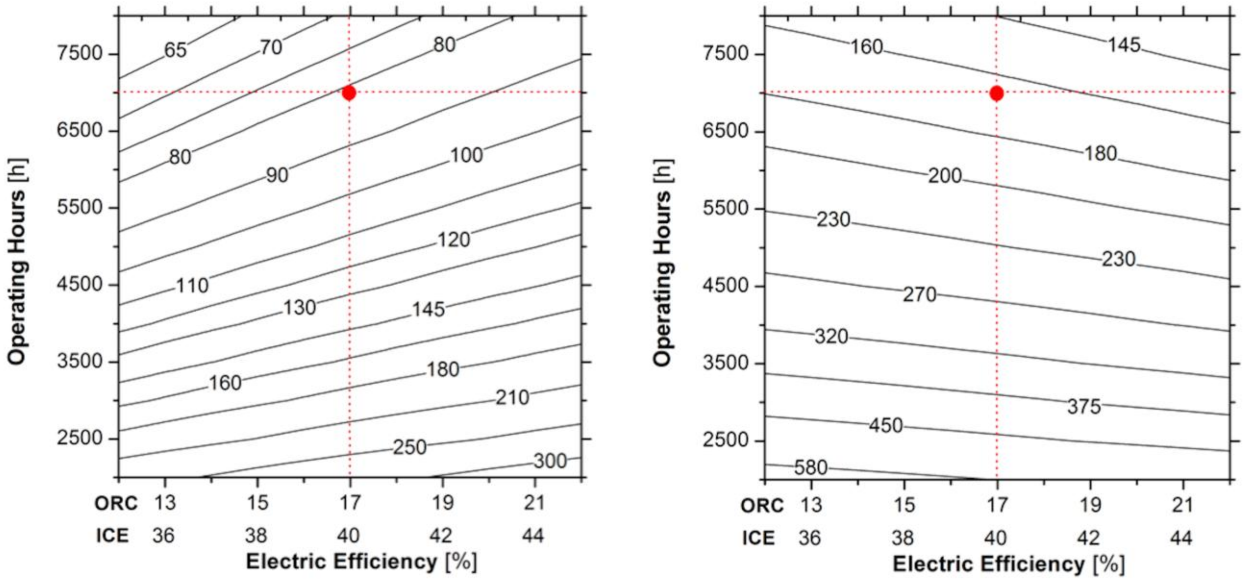
Table 14 *– Potential CHP installations for the energy exploitation of biomass residues.*

	Electric Power [MW_{el}]	*Thermal Power* [MW_{th}]
Calabria	**81.1**	**165.4**
Cosenza	31.3	58.8
Catanzaro	13.8	29.2
Reggio Calabria	16.6	39.8
Crotone	13.2	23.9
Vibo Valentia	6.2	13.7

The analysis has been repeated in order to define the influence of the CHP characteristics and annual operating hours on the electric and thermal power that could be installed in the region. To this purpose, the electric efficiency has been varied from 12% to 22% for the ORC systems, and from 35% to 45% for ICEs (±5% with respect to reference values). Lower efficiencies refer to typical performance of production micro-scale CHP systems while the higher efficiencies represent modern small-scale units. The total efficiency has been maintained equal to 85%.

Figure 12 summarises the main results in terms of power maps. Here red circles correspond to the hypotheses previously adopted ($\eta_{el,ORC}$ = 17%, $\eta_{th,ORC}$ = 68%, $\eta_{el,ICE}$ = 40%, $\eta_{th,ICE}$ = 45%, and Δt = 7,000 h). The plot depicts the significant effect of the CHP performance on the global power plant size. As an example, the potential electric and thermal power reaches 96 MW_{el} and 151 MW_{th} when energy systems with the highest electric efficiency are adopted and the operating hours are 7,000. For the same operating time, the power capacity passes to 67 MW_{el} and 180 MW_{th} when the systems with the maximum thermal performance are selected.

Furthermore, the figure depicts the influence of the annual operating time on the global CHP size. As expected, the lower the operating hours, the higher the potential power. Specifically, a 40% increase in the installed power is registered when the operating time decreases from 7,000 to 5,000 hours per year. The increase is larger than 55%, reducing the operating time from 7,000 to 4,000 hours.



a) b)

Figure 12 *– Influence of the CHP performance and operating hours on the global electric (a) and thermal (b) power plant size.*

Finally, the annual electric and thermal energy provided by the energy exploitation of the regional agricultural residues has been estimated both in terms of total and specific production (i.e., the energy production per number of inhabitants). In particular, Table 15 shows the minimum and maximum values corresponding to different CHP electric efficiencies (low performance units: $\eta_{el,ORC}$ = 12% - $\eta_{el,ICE}$ = 35% and high performance units: $\eta_{el,ORC}$ = 22% - $\eta_{el,ICE}$ = 45%). The electric energy ranges between 466 and 669 GWh_{el} while the corresponding thermal energy moves from 1,056 to 1,259 GWh_{th}. The regional specific electric production is always higher than 236 kWh_{el} per inhabitant and reaches about 340 kWh_{el} when the CHP units with the highest electric efficiencies are considered. The corresponding thermal production per number of Calabrian citizens moves from 639 to 536 kWh_{th}/inhabitants.

The results reveal that Calabrian agricultural residues could be properly adopted to satisfy part of electric and thermal loads of the region. Specifically, when the CHP electric and thermal efficiency are equal to the reference values ($\eta_{el,ORC}$ = 17%, $\eta_{th,ORC}$ = 68%, $\eta_{el,ICE}$ = 40%, $\eta_{th,ICE}$ = 45%), the investigated biomass residues could provide an electric and thermal energy per inhabitant equal to 288.0 kWh_{el} and 587.6 kWh_{th}, satisfying the thermal request of more than 128,000 households and the electric load of about 215,000 families, considering the average annual request of domestic users in Southern Italy (2,616 kWh_{el} and 9,029 kWh_{th}) [138,139].

Table 15 *– Annual energy production from the exploitation of biomass residues. Influence of CHP performance: low ($\eta_{el,ORC}$ = 12% - $\eta_{el,ICE}$ = 35%) and high ($\eta_{el,ORC}$ = 22% - $\eta_{el,ICE}$ = 45%) electric efficiencies.*

	Annual energy production							
	Low CHP electric efficiencies ($\eta_{el,ORC}$ = 12% $\eta_{el,ICE}$ = 35%)				***High CHP electric efficiencies*** ($\eta_{el,ORC}$ = 22% $\eta_{el,ICE}$ = 45%)			
	Total		*Specific*		*Total*		*Specific*	
	Electric	*Thermal*	*Electric*	*Thermal*	*Electric*	*Thermal*	*Electric*	*Thermal*
	[GWh_{el}]	[GWh_{th}]	[kWh/inh]	[kWh/inh]	[GWh_{el}]	[GWh_{th}]	[kWh/inh]	[kWh/inh]
Calabria	**466.0**	**1,259.3**	**236.5**	**639.1**	**669.0**	**1,056.4**	**339.5**	**536.1**
Cosenza	181.8	448.5	254.5	627.8	255.9	374.3	358.3	524.0
Catanzaro	79.0	222.4	217.5	612.6	114.4	187.0	315.1	514.9
Reggio Calabria	92.8	301.7	166.9	542.7	139.2	255.2	250.4	459.2
Crotone	77.0	182.5	440.7	1,044.5	107.5	152.0	615.5	869.7
Vibo Valentia	35.5	104.3	218.3	641.8	51.9	87.9	319.5	540.6

Note: inh = inhabitants.

6. CONCLUSIONS

The work focused on the assessment of biomass availability in Calabria, the southernmost region of the Italian peninsula. To this purpose, attention was concentrated on agricultural residues from fruit trees and cereal crops, livestock sewage, waste and by-products of the agro-food industry.

The analysis highlighted that an attractive amount of dry biomass residues (818,200 t/year) is available in the region, with an average concentration equal to 53.7 t/km^2. Lignocellulosic residues from pruning operation of fruit trees offer the highest quantity, with 286,213 t/year. Specifically, olive groves guarantee more than 230,000 t/year, whereas vineyards and citrus provide lower quantities. Also, breeding farms offer an important contribution (255,288 t/year), mainly due to bovine livestock (76.9% of animal farm residues).

Furthermore, the possible energy exploitation of the available biomass in combined heat and power (CHP) systems was investigated, and the annual electric and thermal energy production were estimated considering the typical performance of production small-scale cogeneration units. For lignocellulosic residues, the thermochemical conversion based on the combustion process coupled with Organic Rankine Cycle (ORC) systems was considered. For the other investigated agricultural biomass, the biochemical conversion based on anaerobic digestion was evaluated as the proper solution to obtain biogas and feed internal combustion engines.

The investigation demonstrated that the energy valorisation of the available regional residues assures an electric production between 466 and 669 GWh_{el}/year, depending on the efficiency of selected CHP units (last value refers to the highest efficiency systems). The corresponding thermal energy ranges from 1,056 to 1,259 GWh_{th}/year. In this way, it is possible to fulfil the thermal requests of at least 128,000 families and the electric load of more than 215,000 households in the region. The Calabrian specific electric and thermal production corresponds to 288.0 kWh_{el} and 587.6 kWh_{th} per inhabitant, respectively.

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DECLARATIONS OF INTEREST

Declarations of interest: none.

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Table 15 *– Annual energy production from the exploitation of biomass residues. Influence of CHP performance: low ($\eta_{el,ORC}$ = 12% - $\eta_{el,ICE}$ = 35%) and high ($\eta_{el,ORC}$ = 22% - $\eta_{el,ICE}$ = 45%) electric efficiencies.*

Figure 1
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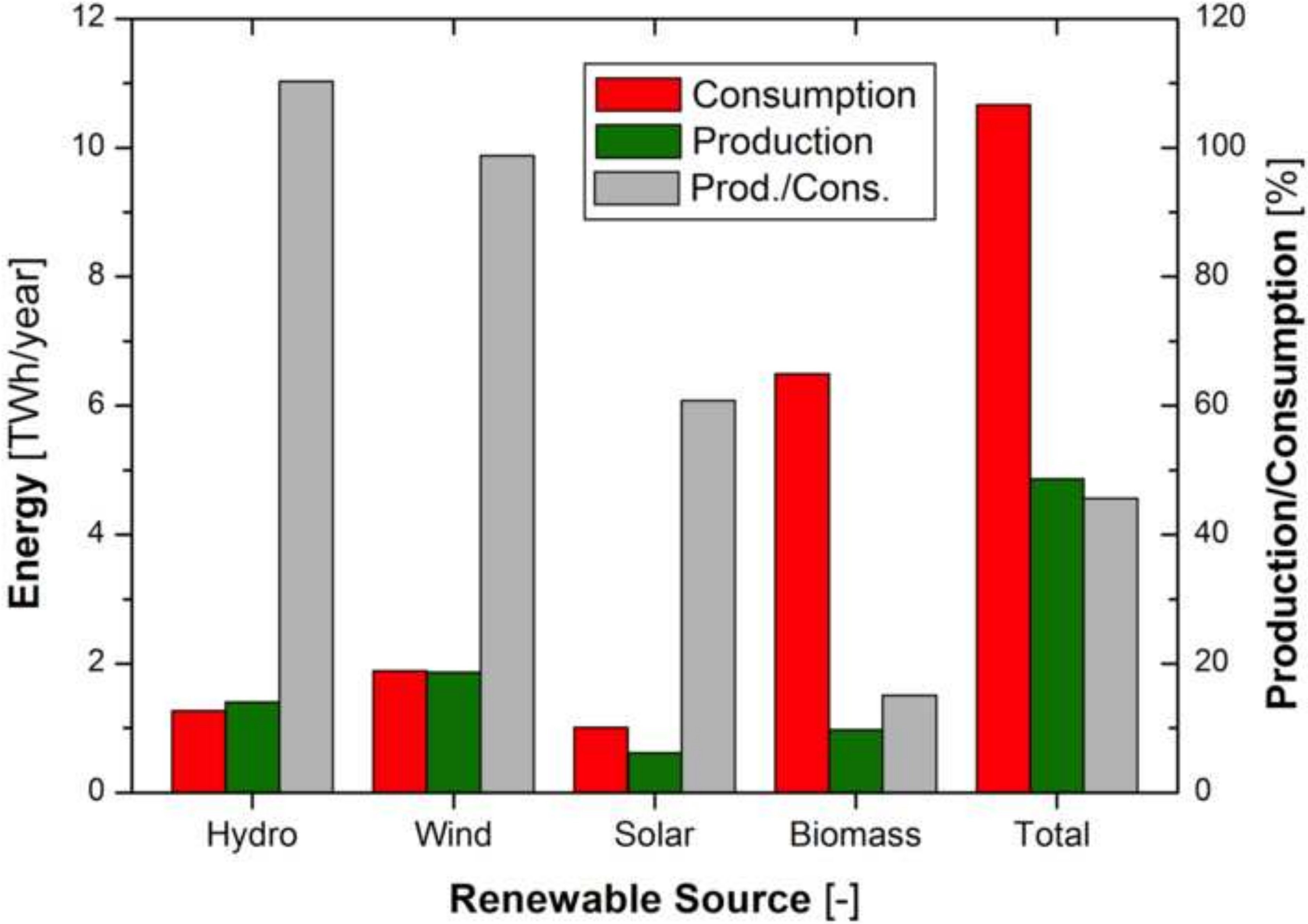

Figure 2
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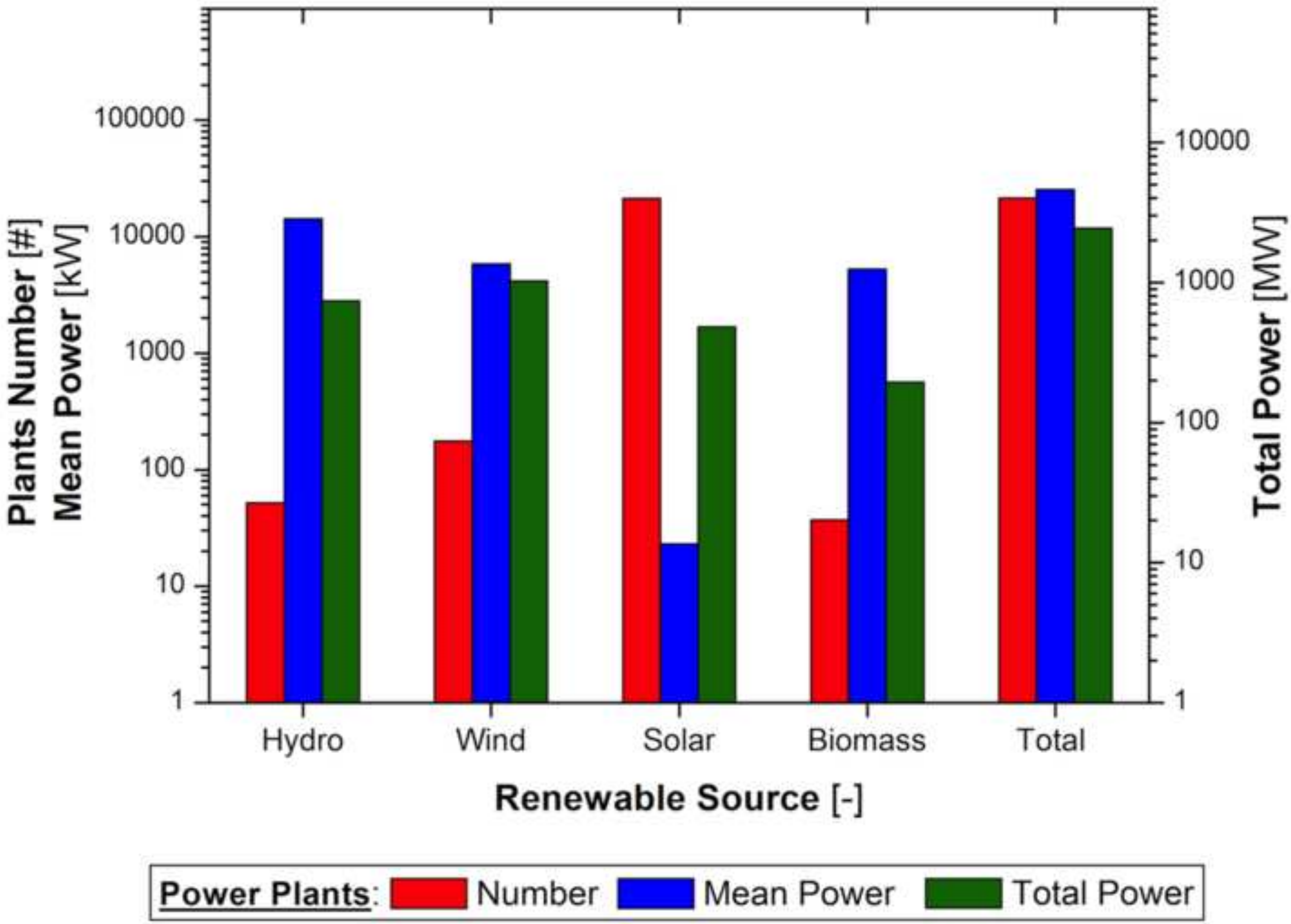

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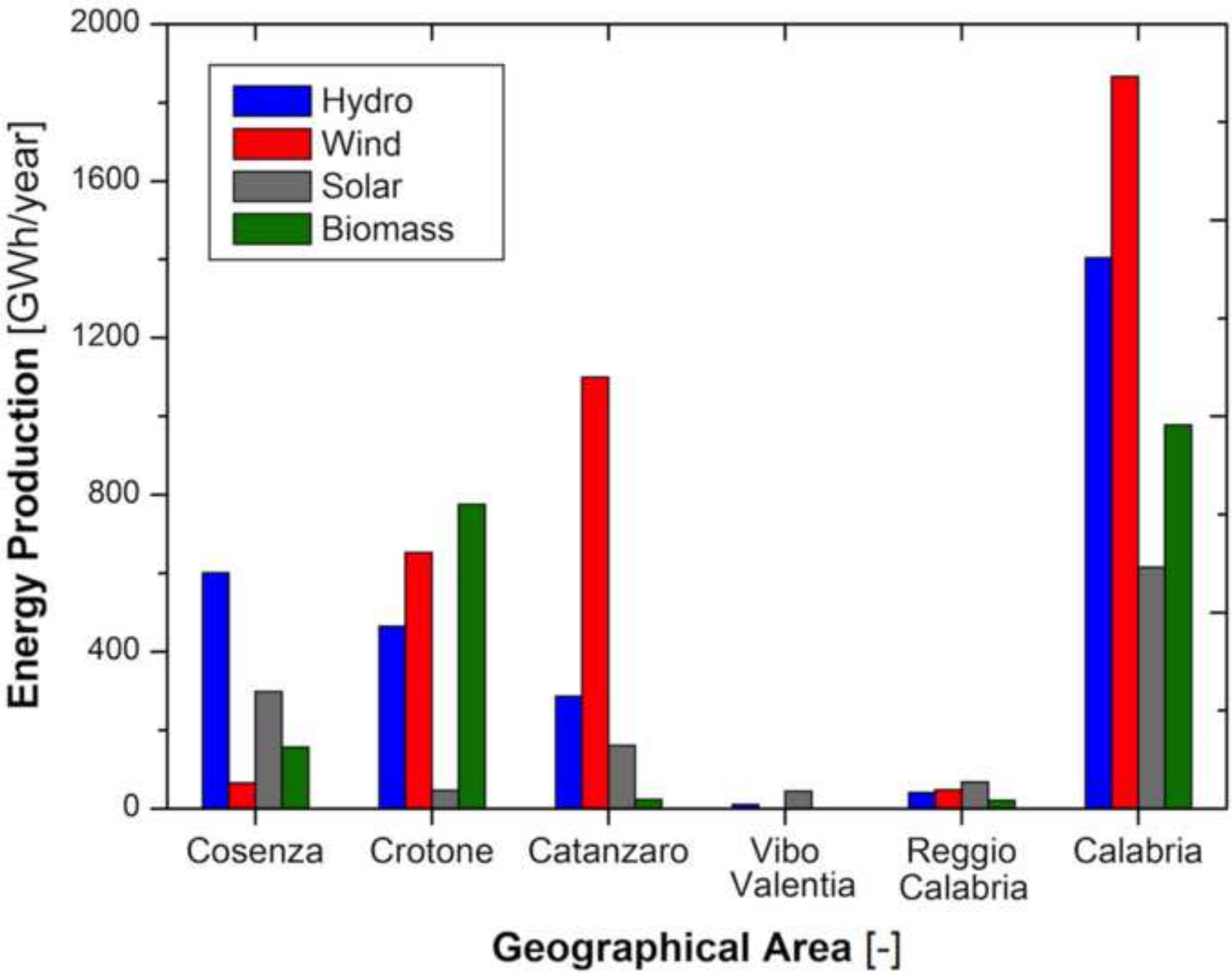

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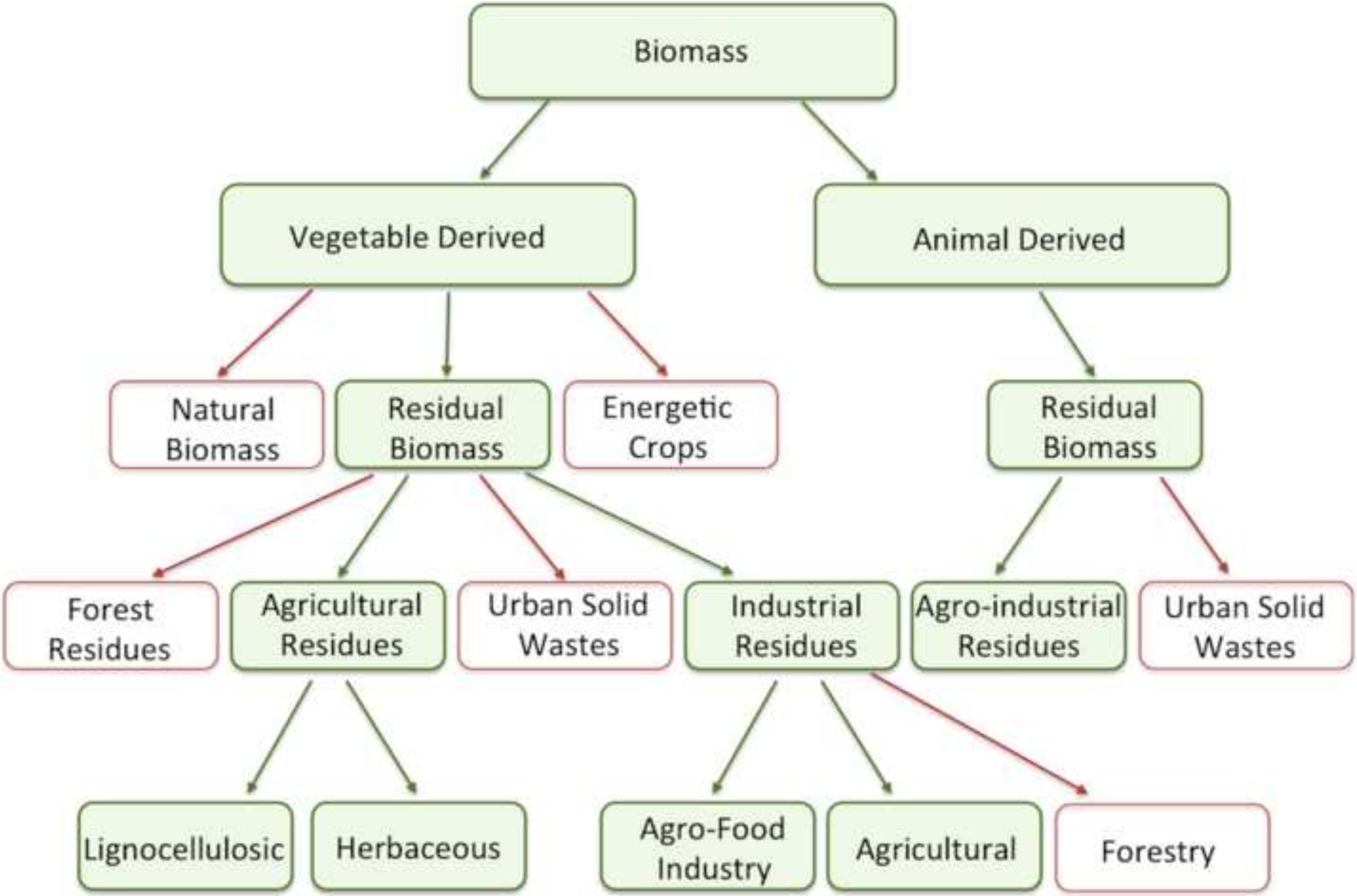

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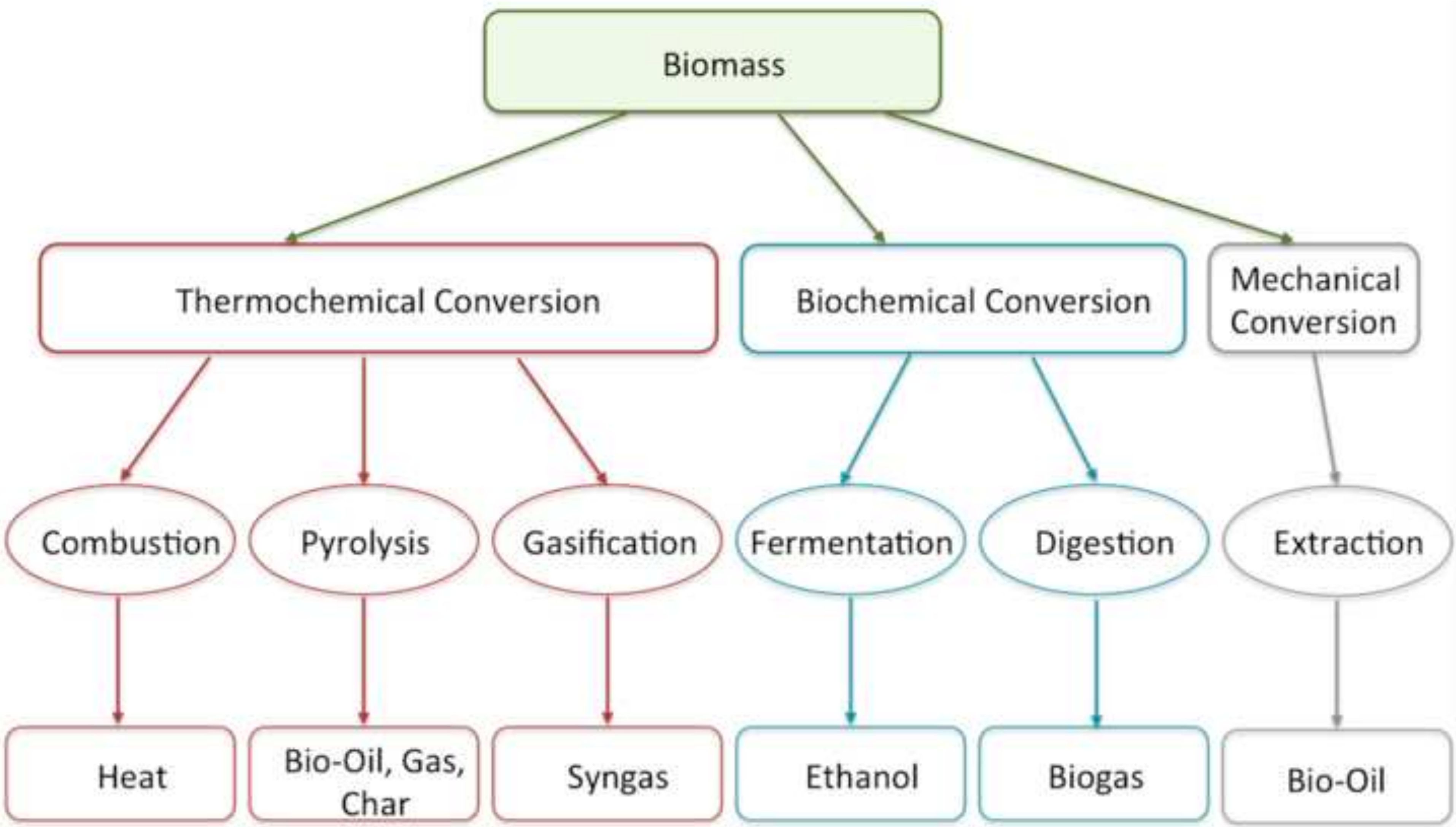

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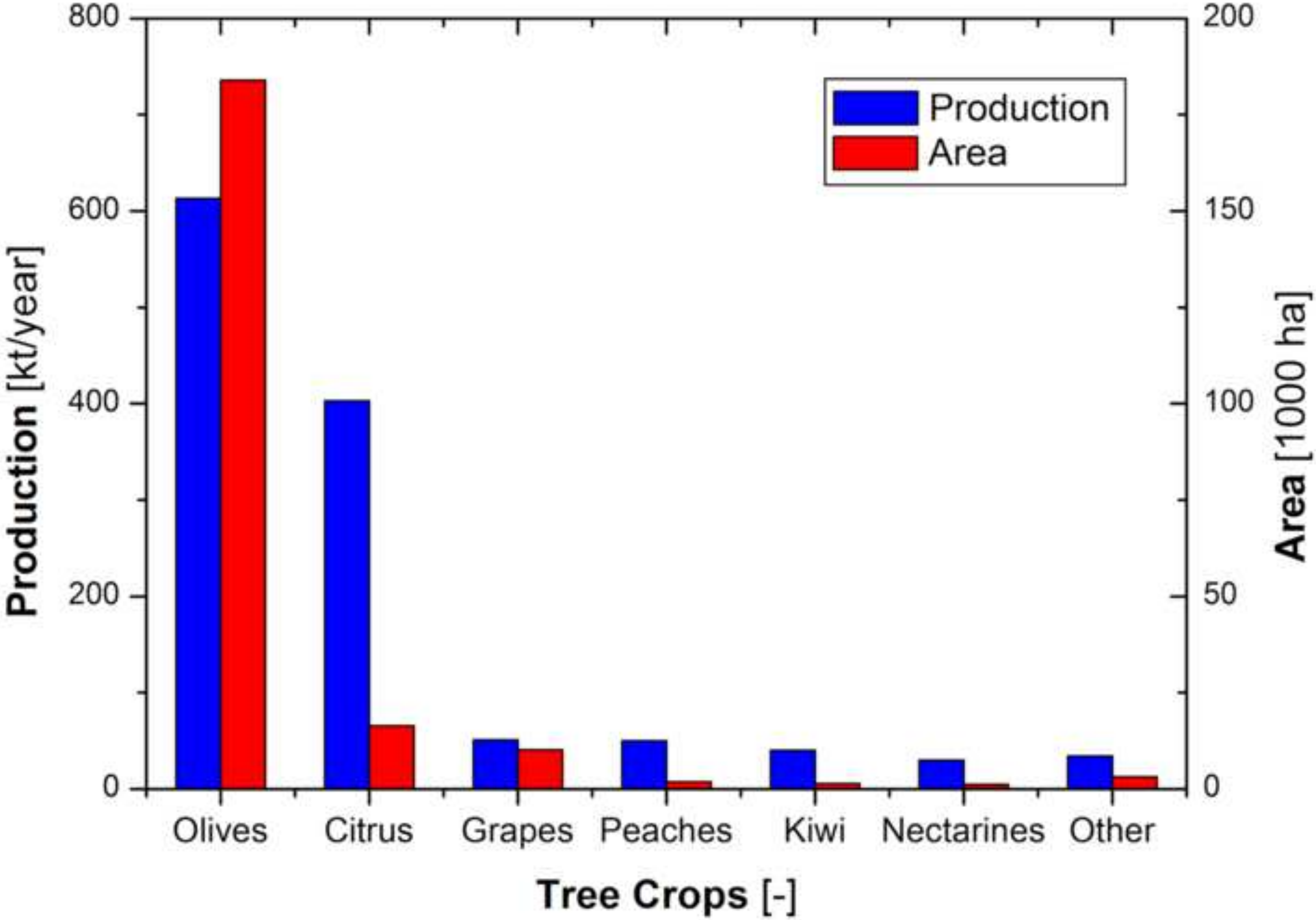

Figure 8

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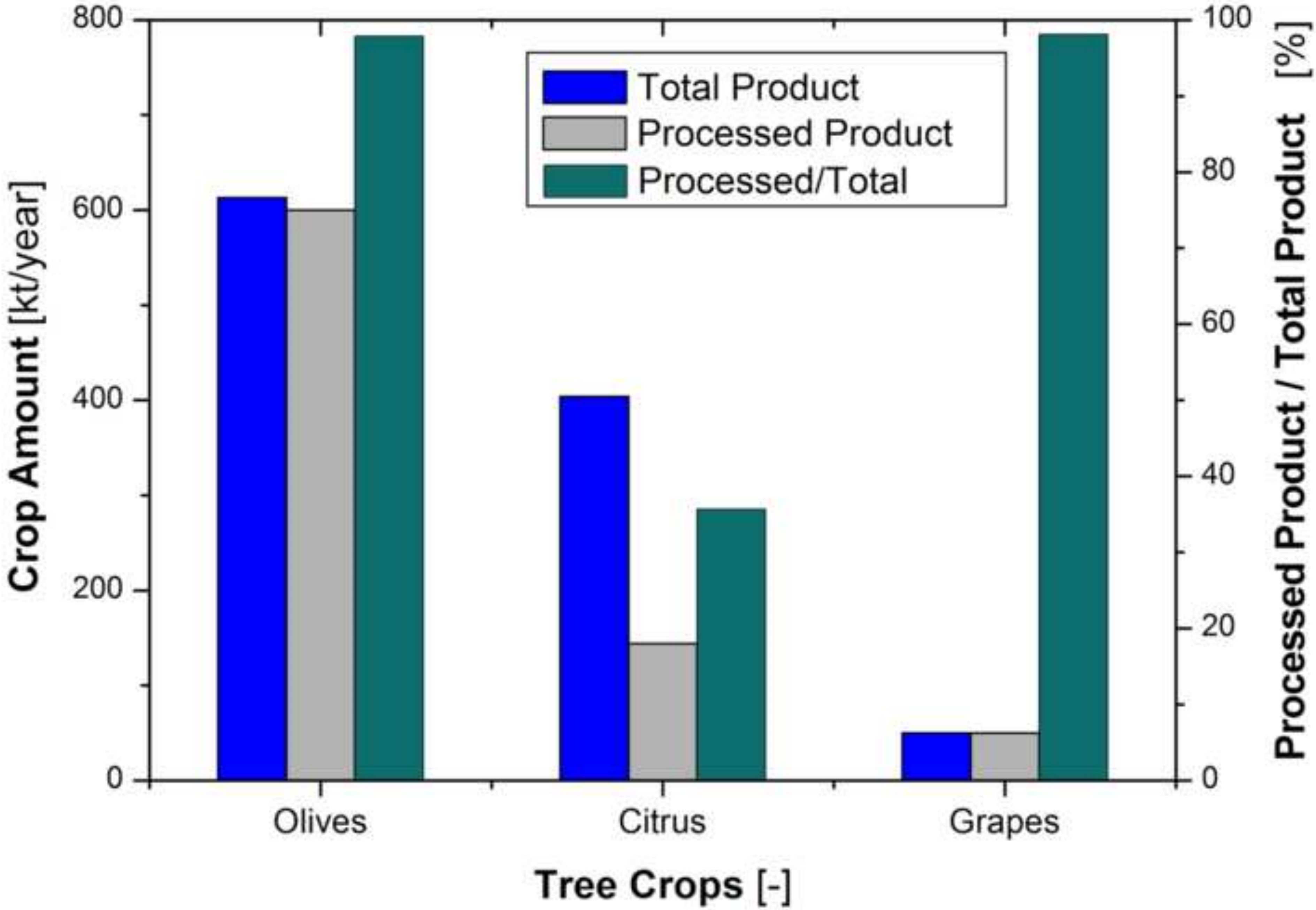

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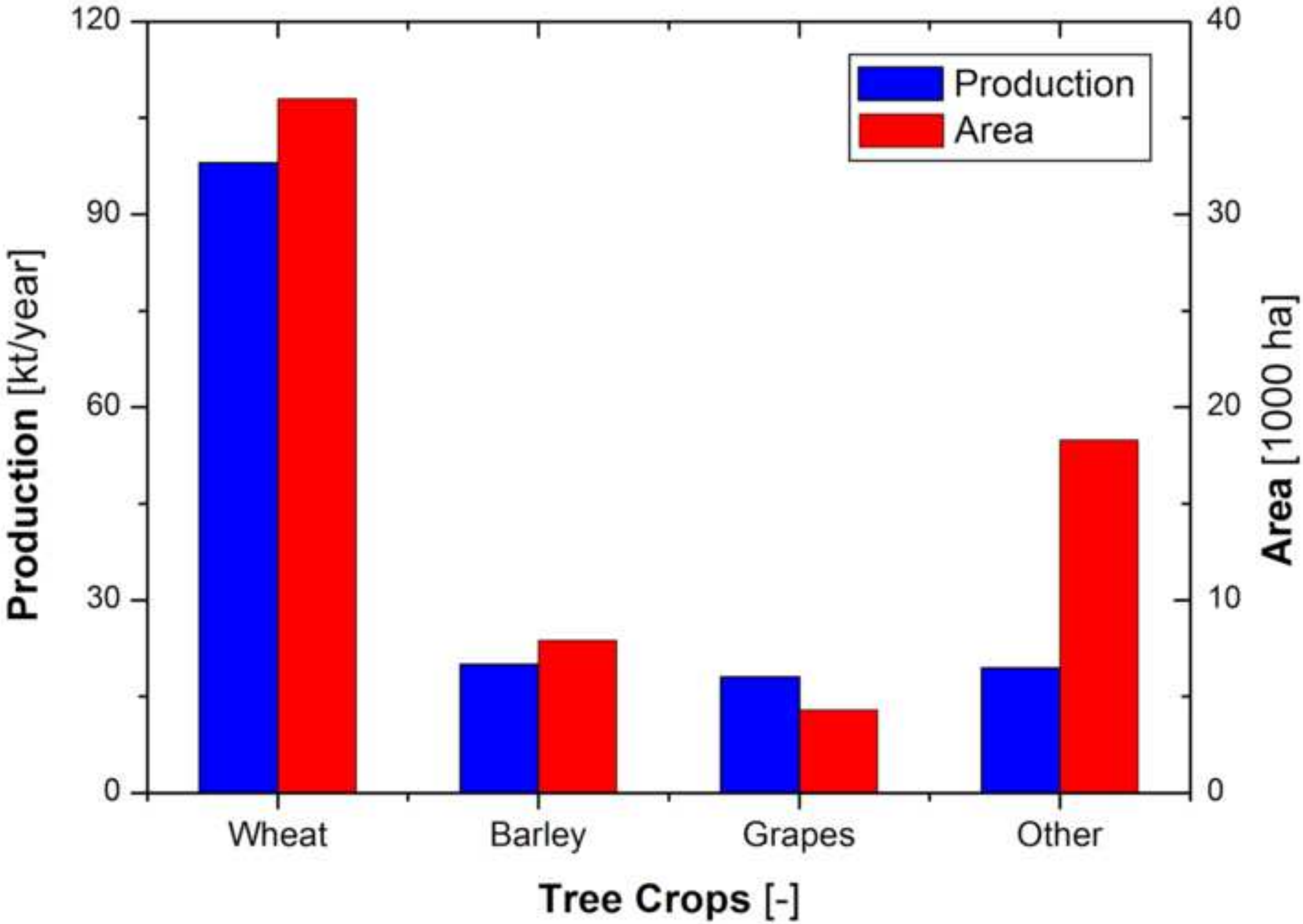

Figure 10
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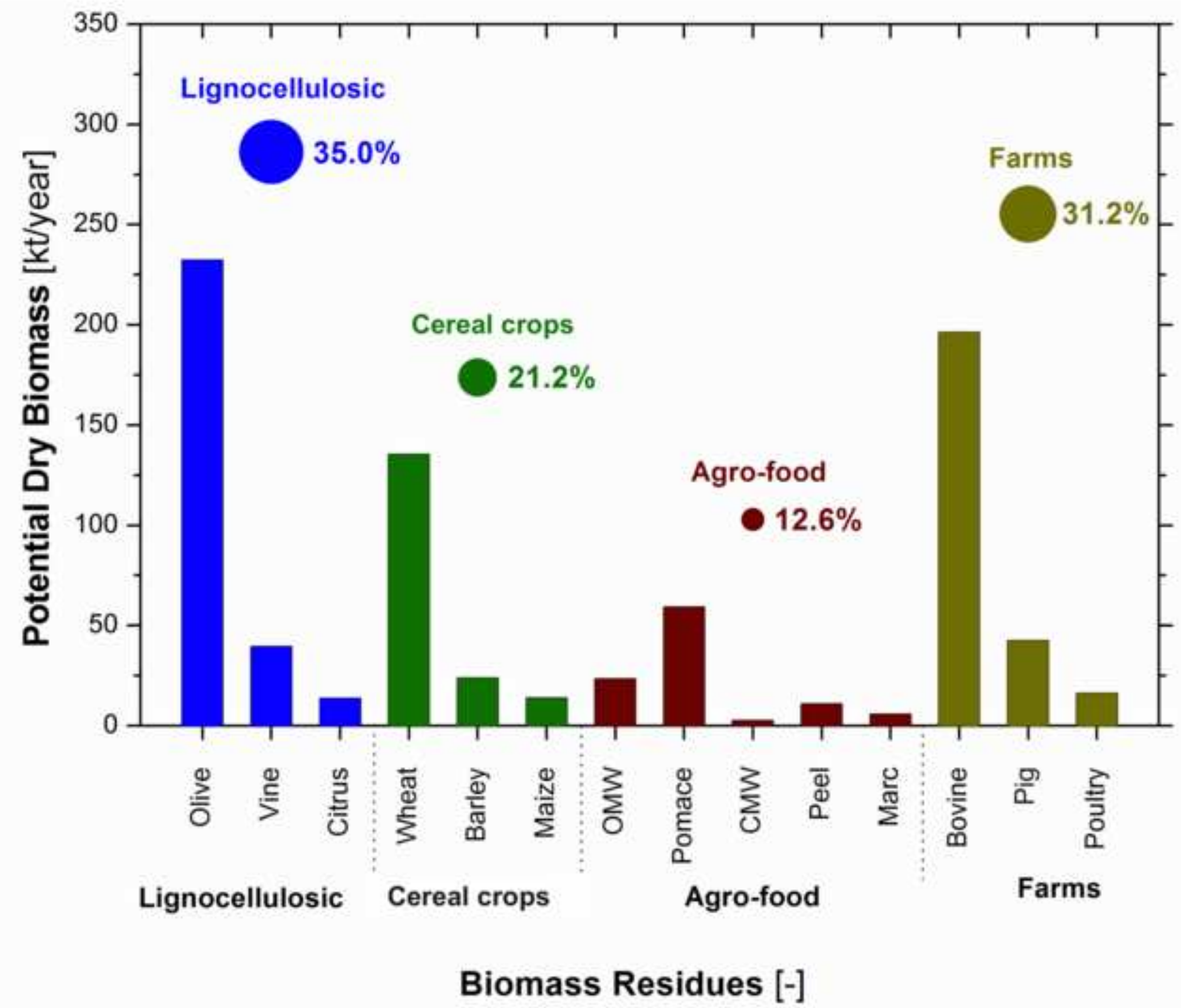

Figure 11
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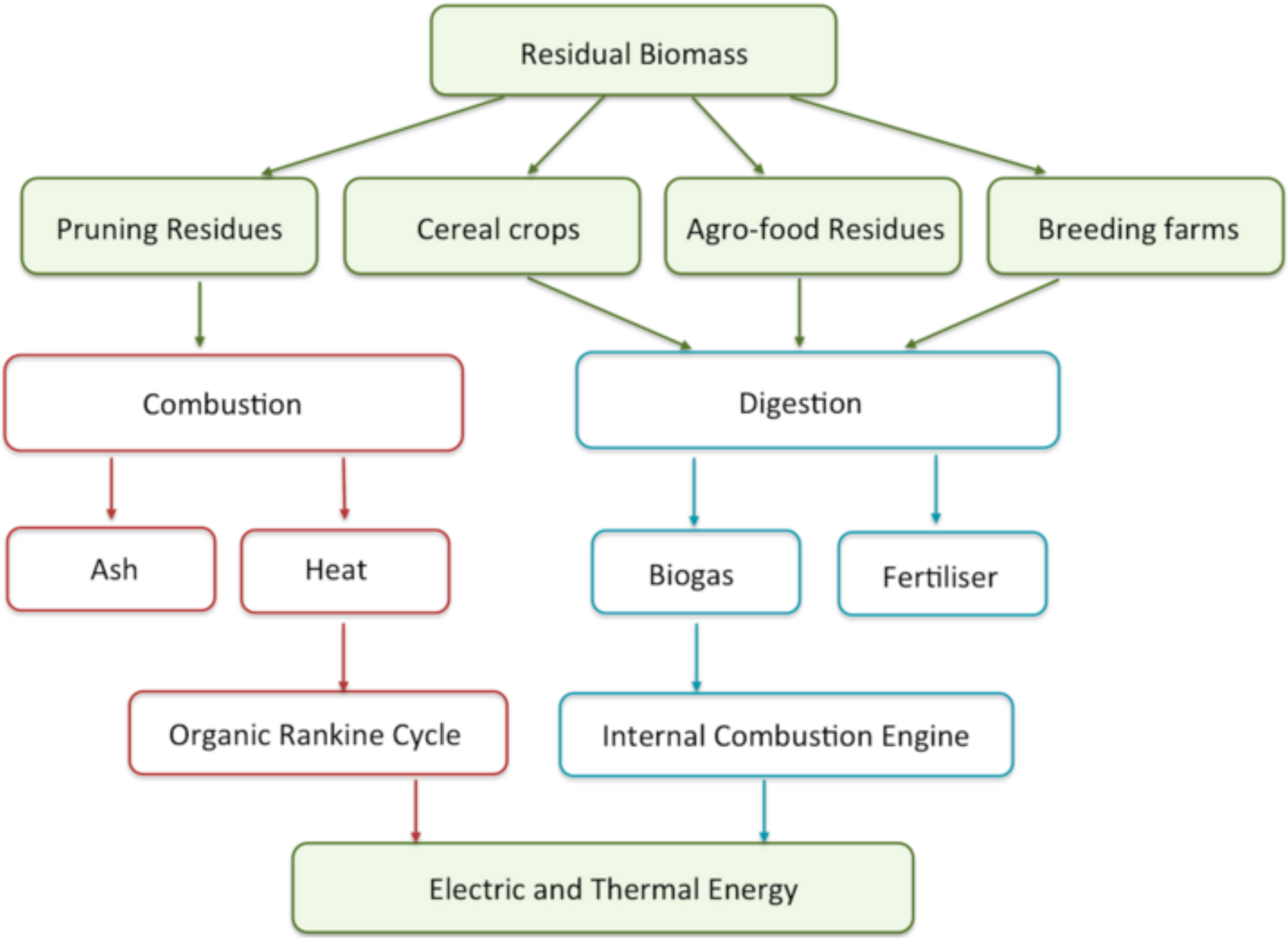

Figure 12

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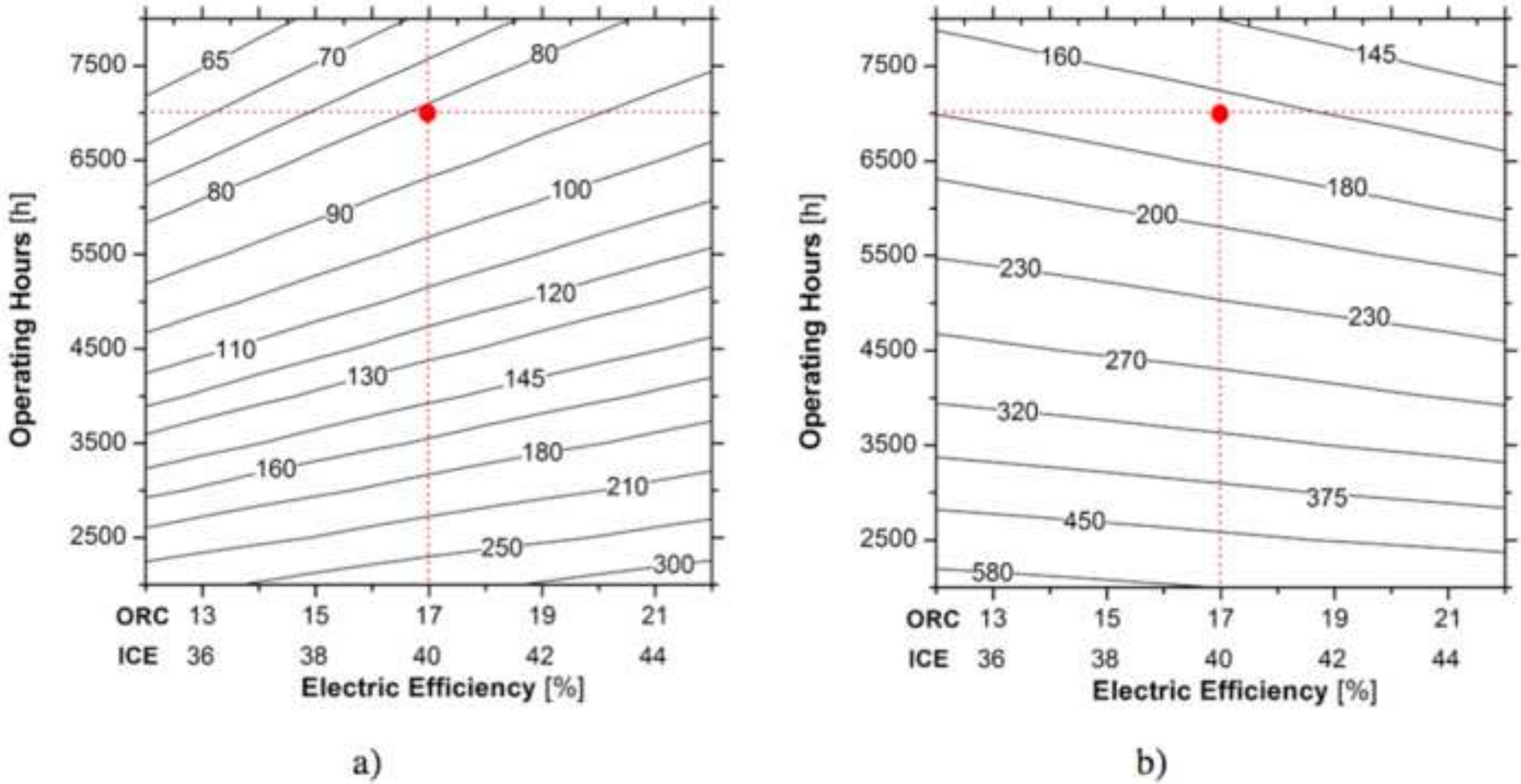

HIGHLIGHTS

- Biomass residues in agricultural areas can be exploited in CHP systems
- Statistical and literature data allow assessment of biomass territorial availability
- In Calabria (Italy) about 820,000 tons per year can be used in small-scale CHP units
- The energy demand of 116,000 households and 178,000 families can be satisfied
- The methodology can be extended to other rural contexts at different spatial scales