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Novel Methodology to Assess Advanced Biofuel Production at Regional Level: Case Study for Cereal Straw Supply Chains

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Abstract: Nowadays, there is an urgent necessity for breakthrough technologies able to reduce process complexity and to lower costs to make the biomass-based biodiesel supply chain competitive. This paper presents an innovative methodology for the identification of secondary biomass potentials for biofuel production. The methodology, divided into four steps, defines the criteria that allow identification of promising scenarios of biomass supply chains for commercial application of innovative technologies. The model set up a scoring procedure based on carbon emission avoidance, efficient resource exploitation and sustainability indexes. Applying the four levels of analysis (biomass availability, suitability analysis, regionalization and multi-criteria analysis), the cereal straw supply chains in four European districts (Scandinavian, Hanseatic, Central European and Mediterranean) have been identified and grouped in 18 biomass supply regional clusters (BSRCs). The clusters represent the most promising hotspots where biomass availability, logistics and feedstock requirements for a novel conversion technology meet. Central European and Mediterranean districts are those with the highest cereal straw bioeconomic potentials which allow mono-feedstock supply chains and relatively high capacity of a conversion technology at 200 MW_{th} and beyond. Central Europe has an overall bioeconomic potential of 16.249 kt (232.359 TJ) distributed over 36 regions and organized in 12 BSRCs. The Mediterranean district has an overall bioeconomic potential of 3541 kt (50.630 TJ) distributed over nine regions and organized in four BSRCs.

Keywords: agricultural residues; cereal straw; biomass supply chains; bioeconomic potential; biomethanol



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1. Introduction

During recent decades, the EU policy has strongly promoted bioenergy chains, starting from liquid biofuel certification with the aim to reach the CO_{2,eq} reduction targets. In order to endorse better environmental performances, the RED II promotes a gradually increasing sub-target for advanced biofuels (see Annex IX, Part A of RED II) up to at least 3.5% by 2030.

Chiaramonti et al. [1] highlight that biofuels and advanced biofuels together will constitute more than 17% of the fuels by 2050 and advanced biofuels are expected to be the majority of the total biofuel volume by 2040.

The Directive introduced a methodology for evaluating the environmental sustainability of the biofuels, considering the biomass sources and all the biofuel production steps. The environmental sustainability is mainly measured in terms of CO_{2,eq} savings calculated versus the reference fossil energy scenario. Therefore, the biofuels have to guarantee at least the CO_{2,eq} savings required to access the EU energy market and the design of the biomass supply chain is a critical step that determines the convenience of the energetic production system.

According to Guo [2], the biomass supply chain has to be optimized by reducing costs and environmental impacts and ensuring continuous feedstock supply. In practice, the identification of a general and optimal solution for the biomass supply chain, that is usually designed and set up according to specific and complex needs, is not straightforward.

Indeed, the relatively low energy density and the bulky, distributed nature of the feedstock require a tailored-made analysis [3]. For these reasons, it is important that comprehensive planning of the supply chain accounting for the energy conversion technology is carried out [4].

The review paper of Wang et al. [5] indicates that the Life Cycle Assessment (LCA) methodology is the most implemented approach for evaluating the environmental performances of the bioenergy chains, but a more appropriate focus is needed for estimating the land availability and its potential as biomasses sources.

Focusing on specific geographical areas with high diversification level of feedstock is important for improving local energy security, supporting the local economy and increasing the regional stability of the energy market [6]. Locally produced biofuels can reduce the energy import, exploiting the environmental, economic and social sustainability of the energy system.

In this framework, this paper proposes a new methodology for the identification of the optimal advanced biomass supply chain at a regional level. The methodology will account for biomass availability, suitability class allocation, regional cluster identification and Multi-Criteria Analysis (MCA) for identifying the most promising scenarios for biomass supply chains in different EU regions, under different conditions and environmental constraints.

The proposed methodology has been designed for the comparison and the selection of the most profitable biomass supply chain for feeding a flexible and not feedstock-specific bioenergy conversion technology. In the present paper, the case study of cereals' straw will be implemented as it is a residual biomass available in all the EU regions and feasible supply chains will be identified. In fact, this biomass allows mono-feedstock supply chains with relatively high capacity for large conversion plants of 200 MW_{th} and beyond.

The supply chain is applied here to an innovative process that is part of advanced biodiesel production, making it more efficient and less expensive than current technologies, developed within the CONVERGE project [7].

The development of a proper methodology for biomass supply represents a very important key aspect of the CONVERGE project, with the available feedstock being fundamental in defining plant capacity and costs. These studies and research on the biomasses are conducted at early stage together with the deployment of the biomass conversion technologies to TRL 5. The process involves an indirect gasification step, followed by syngas conditioning and methanol synthesis through five innovative integrated solutions. This process scheme is very flexible and not feedstock-specific, allowing a wide range of biomass feedstock to be considered for processing, e.g., ligno-cellulosic residues from agriculture, forestry and industrial activity, or waste. Hence, the selection of the most promising location for implementing a full-scale technology at the demonstration stage, not commercially available, is quite challenging.

In general, the existing studies focus on net availability of a single investigated biomass as technical potential, excluding the comparison of different biomass supply chains and their logistical aspects and/or local factors such as settlement structure, etc.

Indeed, studies that use consistent data and methodology to estimate total technical availability of cereal straw or other ligno-cellulosic residues from agro-forestry sectors for bioenergy uses are quite common. Additionally, GIS-based assessment of cereal straw energy resources in the European Union has been widely applied in the field of bioenergy installations [8–11].

In the presented methodology, the use of different biomass types with different seasonalities and multi-feedstock supply chains is considered for a certain technology, such as the CONVERGE process. The application of the MCA approach takes into consideration factors beyond the technical potential of the biomasses, their seasonality and the logistic complexity of the related supply chains, as detailed in the following paragraphs. The MCA's results, when combined with techno-economic evaluation of the technology under investigation, can be useful decision tools for the selection of the most profitable solution.

2. Methodology for the Enhanced Biomass Availability Assessment

The proposed methodology for the assessment of the biomass supply chains applied to a selected technology at a commercial level consists of four steps (Figure 1):

- first level availability assessment of the bioeconomic potential;
- second level availability assessment for the suitability class allocation;
- spatial distribution at regional level;
- MCA identifying the most promising supply chains and locations for a specific technology.

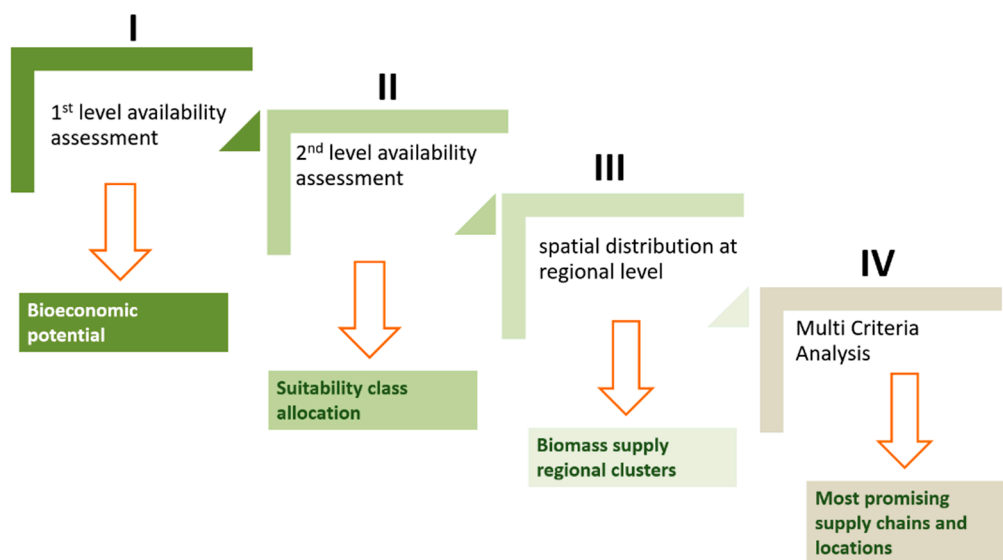


Figure 1. Methodology scheme for country-specific supply chains.

2.1. First Level Availability Assessment

The first level availability is defined as the amount of each biomass in a specific district, taking into account limitations due to technical accessibility, ecological share for primary residues and competing uses.

To have homogeneous and standardized information, the basic data (cultivation surfaces, primary productions and related residue productions) are preferably collected from statistical database (i.e., EUROSTAT) primary sources. At least four years of data are included in order to mitigate the effect of annual fluctuations of agricultural land use, climate factors and market conditions.

A distinction between three levels of biomass potential is applied: theoretical, technical and bioeconomic [12,13].

Theoretical potential (TrP) includes all parts of the total harvested biomass (H) that have no direct use in food, feed or industrial production and that is considered as gross residue:

$$TrP = H - PP, \quad (1)$$

where PP is the primary production. According to art. 3, paragraph 17, of Regulation EC 178/2002, primary production is intended here as the yield of the main product of the agriculture production cycle for which the crop is cultivated, for example, in the case of cereals, grains.

Technical potential ($TchP$) is the amount of residue that can be removed from the field or forest or collected without any technical, legislative and sustainability constraints (R):

$$TchP = TrP - R. \quad (2)$$

$TchP$ is the net residue, that is effectively exploitable for individual and alternative uses.

Bioeconomic potential (*BeP*) is the share of technical potential that is not necessarily used in competing applications (*Ca*) with respect to a specific purpose.

$$BeP = TchP - Ca \quad (3)$$

The last contribution to bioeconomic potential evaluation is the assessment of competing applications, which is affected by lack of reliable data, resulting in the most critical step of the methodology. Data for competing conventional uses, potential novel competitors and technical constraints or ecological issues present high levels of uncertainty. This uncertainty is managed by the introduction of a precautionary reduction factor for biomass availability. The use of agricultural biomass in the industrial sectors of biochemicals, bioplastics and, in general, bio-based materials is still one of the major data gaps. Therefore, if detailed regional data are available, the bioeconomic potential might be further split into high value added bioproduct potential and advanced biofuel potential. Although precious information is missing, it has been assumed that the quantity of biomass at stake is small. Anyway, if this flux of biomass materials is material, the broad picture of inter-sectorial biomass flows is not distorted [8].

2.2. Second Level Availability Assessment: Suitability Class Allocation

The second level availability assessment identifies the biomass bioeconomic potential with respect to the plant feedstock requirements. This allows classification of each considered area (EU country or region) by means of suitability categories. In particular, four different categories are identified:

1. **no operational limit:** the bioeconomic potential of a mono-feedstock supply chain is beyond the amount needed to run a selected plant capacity of a certain technology;
2. **operational limit:** the bioeconomic potential of a mono-feedstock supply chain is only enough to cover the amount needed to run one selected plant capacity of a certain technology;
3. **operational risk:** the bioeconomic potential of a mono-feedstock supply chain is not enough to cover the amount needed to run one selected plant capacity of a certain technology, therefore a multi-feedstock supply chain is necessary to operate the plant at full capacity;
4. **no suitability:** the bioeconomic potential of the biomass is not enough to operate the plant capacity of a certain technology.

2.3. Spatialization at Regional Level

This step considers a site-specific analysis to assess feedstock availability and accessibility assessment, conventional biomass uses and feedstock competition, logistics, etc. A regional breakdown allows assessment of whether the biomass availability (kt/y) in a given area is able to supply a commercial-scale conversion plant [8]. For each type of biomass, the regional bioeconomic potential and the feeding needs of the technology for different nominal capacities of the commercial plant are investigated and described.

The data at a regional level can be collected from a statistical database (i.e., EURO-STAT), from relevant projects (i.e., S2BIOM, BIORAISE, AGROCYCLE) or from specific works [14,15]. When the quantitative data are collected, the use of GIS tools is considered the proper solution for analyzing in detail the biomass supply [16], optimizing the transportation costs [17] or determining locations, sizes and number of bioenergy facilities [18]. In particular, in this work, spatialization deals with the analysis of site-specific non-technological barriers, as mentioned before, resulting in a quantitative ranking of possible regions to collect biomass for a given plant capacity.

Due to the intrinsic presence of local peculiarities, the involvement of stakeholders from the investigated districts is fundamental to verify and validate the actual potential and the statistically based estimates.

2.4. MCA of the Biomass Supply Chains

The selection of the most promising supply chain for biomass, considering a specific industrial-scale conversion technology as an application, is performed through an approach based on MCA. This tool is indeed able to manage large variability and complexity of possible scenarios [19]. The MCA is implemented considering the following steps: (i) scenario definitions for each type of supply chain, (ii) decision criteria identification, (iii) criteria weight definition, (iv) MCA result interpretation. Technical feasibility, cost/effectiveness analysis and environmental pressure are collected from literature reviews and experimental data collections, allowing for the definition of state-of-the-art supply chains to be used in operative scenarios.

For each criterion, measurable indicators are identified and for each indicator three different levels of performance are defined and scored. The indicators are set for evaluating environmental, economic and logistic aspects; specific weights are already applied in order to highlight the most important objectives to be primarily reached. In fact, some indicators may support the judgment concerning different aspects; for instance, the GHG emissions calculated for a supply chain allow assessment of the environmental sustainability, but also the economic value of the biofuel or bioproduct (i.e., the lower the emissions, the higher the market value). The selection of indicators provided in Table 1 is based on the over ten years of experience of the authors in supply chain analysis, applied to the goals foreseen for the specific task of the CONVERGE project. Anyway, they can be adapted according to the specific target of the analysis.

Table 1. MCA indicators and relative scores.

Indicator	Weight	High (3)	Score Medium (2)	Low (1)
Second level availability	1	no operational limit	operational limit	operational risk
No. of regions	1	>8	4–8	<4
Transport complexity	0.3	by-product	residue	waste
Production seasonality	0.3	<8 months	4–8 months	<4 months
Storage complexity	0.3	MC < 20%	MC 20–50%	MC > 50%
Biomass competition	0.6	low market demand	medium market demand	high market demand
Supply chain complexity	0.3	low no. of processes	medium no. of processes	high no. of processes
Standardization of supply chain	0.3	low no. of solutions	medium no. of solutions	high no. of solutions
Nominal plant capacity	0.6	>200 MW	100–200 MW	<100 MW
Transport distance	0.6	<50 km	50–100 km	>100 km
Pre-treatment necessity	0.3	No	size and M reduction	size or M reduction
Traceability complexity	0.3	1 operative subject	2–3 operative subjects	>3 operative
GHG emissions	1	transport	collection and transport	collection, transport and pre-treatments

The unit weight (1) has been applied to the regional availability of the biomass and the GHG emissions of the supply chain indicators since they are assumed to be the most important aspects to be considered in this analysis. The reduced biomass competition or transport distances, high levels of chain standardization, limited number of chain processes, low traceability complexity and adequate biomass characteristics for facilitating the logistics have been assigned lower weights according to their estimated importance as reported in Table 1. The numerical scores and their ranges have been chosen on the basis of the literature analysis for the MCA and for the investigated supply chains (see comments

on MCA in the Introduction and Methodology sections) in addition to the answers to questionnaires received as a result of the stakeholder engagement activity of the authors.

In this work, Multi-Criteria Analysis (MCA) and Life Cycle Assessment (LCA) approaches are integrated, the first for the identification of the more profitable solutions, the second for further assessing the environmental pressure more deeply and for defining the associated business cases. The preliminary classification based on MCA significantly reduces the effort and the time needed for the LCA and business case implementation, since they have to be performed on a reduced number of pre-selected scenarios.

3. Case Study for Cereal Straw Supply Chains

In this work, the methodology is implemented for the cereal straw supply chain in Europe and concerns biomethanol production with the process developed within the CONVERGE project [7]. Straw from cereals has been identified as one of the best potential biomass feedstocks in Europe [20] and it may play an important role in advanced biofuels in the future. The use of straw is considered to be an environmentally beneficial and socially acceptable option for bioenergy provision; there is low competition with other land uses and thus comparably low corresponding land use change effects. Nevertheless, there are a number of uncertainties with regard to the actual potential of agricultural residues such as straw that could be used for the production of bioenergy in a sustainable manner [21].

3.1. Biomass Characterization and Logistics

Straw is an agricultural residue consisting of the dry stalks of cereal plants after the grain has been harvested [22]. According to the definitions indicated in the Directive (UE) 2018/2001, straw is classified as residue and is listed in Part A of Annex IX under point “e” *Straw*. The cereal straw physical–chemical characteristics have been collected from the literature [23,24] as illustrated in Table 2.

Table 2. LHV, moisture (MC), ash and ultimate analysis for cereal straw.

LHV	MC	Ash	C	H	O	N	S	Cl
MJ/kg_{dm}	%	$%_{dm}$	$%_{wb}$	$%_{wb}$	$%_{wb}$	$%_{wb}$	$%_{wb}$	$%_{wb}$
18.5	15	11.4	43.2	5.0	39.4	0.61	0.11	0.28

Concerning the primary production, the harvestable residues of cereal crops in Europe have been retrieved from EUROSTAT 2019—cereals for the production of grain (including seed), harvested production in EU standard humidity (1000 t) during the period 2015–2018. Data set from Eurostat 2019 is reported in Table A1 (Appendix A).

The data refer to fifteen different kinds of cereal crops (Figure 2) and the main assumptions concern the grain maize:

- grain maize harvested by hand, corn-picker, corn-sheller or combine harvester, regardless of the use, including grain for silage, is considered. Grain harvested together with parts of the cob, but with humidity higher than 20% and used for silage (so-called corn-cob-mix, MC 30–35%) is included, too;
- sweet corn cobs for human consumption are included in “Other vegetables cultivated for fruit n.e.c.” (V3900);
- maize harvested green for fodder or renewable energy use (moisture between 65 and 70%) is accounted for within “Green maize” maslin (G3000) and neglected for this calculation. It presents different yield and residue-to-crop ratio in comparison to other crops, and it is a crop with very low sustainability (super intensive, depletion of soil fertility).

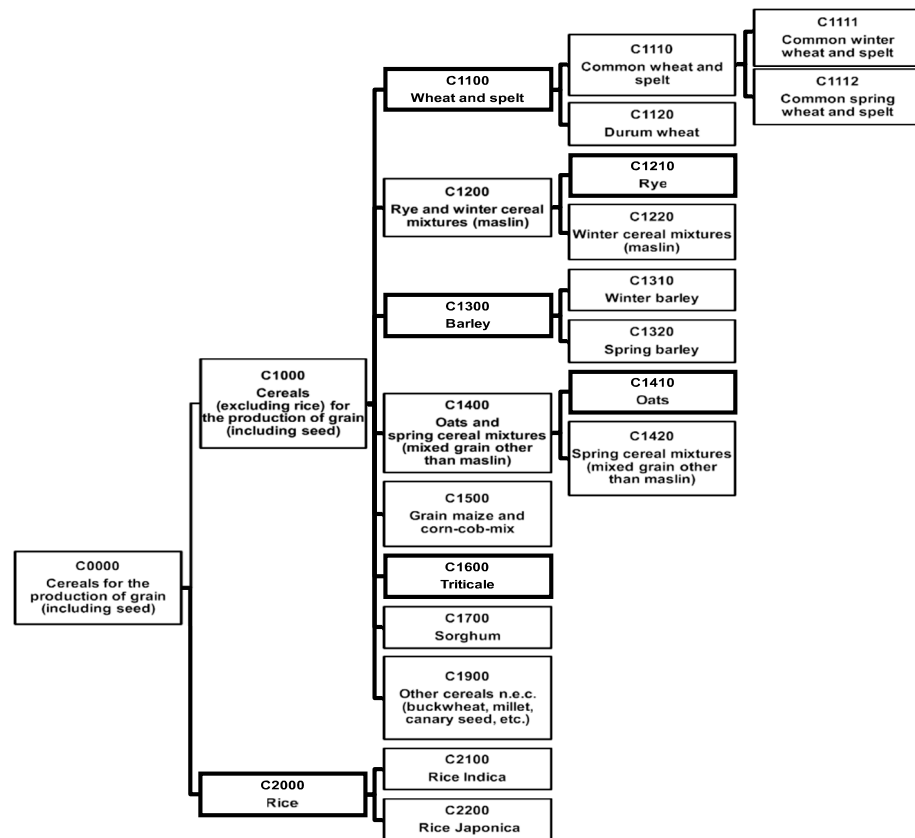


Figure 2. Hierarchy of cereal crops from [25]. Code C refers to classes of cereals, as labeled in the boxes.

Classes include all cereals harvested dry for grain, regardless of the use (including cereals used for renewable energy production). It is assumed that cereal grains are harvested just before maturity. Primary production is obtained for each EU country by EUROSTAT as yield data (kt/y) and data extraction was carried out at 2 different statistical levels, NUTS0 (Table A1 in Appendix A) and NUTS2. In any case, the primary production (cereal grains) and the theoretical potential sum to the total biomass.

The analysis of the logistics of supply chains is necessary to apply properly and with awareness the multi-criteria analysis and its scores. In Figure 3, the fundamental steps of cereal straw supply chain are briefly presented. Harvesting of straw does not present any particular technical and operational difficulty; it takes place from June–July after the grain is harvested.

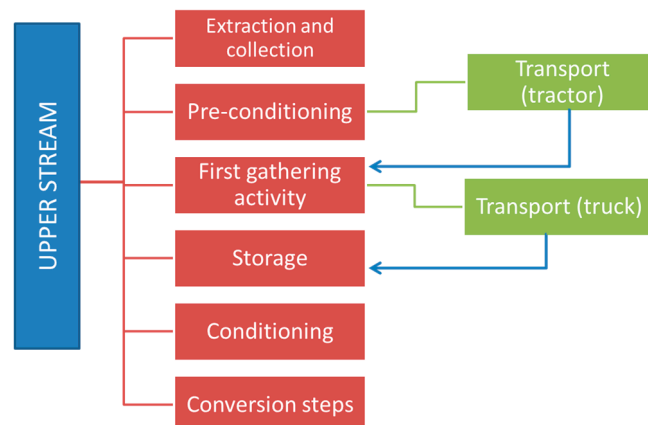


Figure 3. Operational phases of the cereal straw supply chain.

The operating machines are ordinarily kept in the machinery park by the cereal and forage producing companies: baling pickers (parallelepiped bales with 1 m side) or packing roto (cylindrical bales 1.5 m \varnothing). The only limitation is the reduced period for collecting straw (usually 3 days) in the case of second-crop growing. After baling, straw should continue to have moisture contents below 20 percent for storage. Storing at moisture contents above 20 percent will result in some molding and heating, as well as dry matter and component loss (Table 3). Pre-treatments of sizing (e.g., shredding) are necessary. Additionally, drying could be needed if the moisture content is not adequate for the conversion plant (moisture content >25%). The range of full costs and CO₂ emissions for the preparation and supply of cereal straw depends on transport distance and means of transport (Table 4).

Table 3. Dry matter (DM) loss and storage moisture direct relation [26].

Storage Moisture Content	Dry Matter Loss
11 to 20%	4.50%
20 to 25%	7.90%
25 to 34%	10.90%

Table 4. Costs and CO₂ emissions regarding the supply of cereal straw (DM content 86%; bulk density 0.13 mg/m³—square bales) [27].

Transport Distance ^{a)} (km)	Means of Transport	Supply Costs (€/Mg DM)		CO ₂ Emissions (kg CO ₂ ,eq/Mg DM)	
		<i>a Total of</i>	<i>Thereof for Transport</i>	<i>a Total of</i>	<i>Thereof for Transport</i>
10	Tractor	65	12	11	3
30		71	18	14	6
30		75	22	16	8
100	Truck	87	34	29	21
250		110	57	58	50
100		Rail ^a	113	60	21
250	134		81	28	20
100	Ship ^a	97	44	26	18
250		105	52	33	25
800		134	81	59	51

^a This includes a pre-carriage with truck: for rail 30 km; for ship 50 km.

3.2. Bioeconomic Potential Assessment

Theoretical potential of cereal straw is calculated from a non-linear variation in straw/grain ratio [9], as Figure 4 illustrates. The higher the yield, the lower the straw/grain ratio depending on the concept of biophysical maximum of a plant.

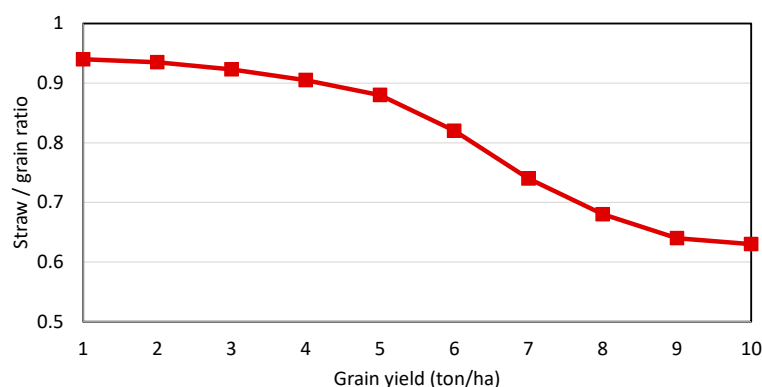


Figure 4. Straw-to-grain ratio for wheat and barley production [9].

With a precautionary approach adopted in the CONVERGE project, the residue-to-crop ratio of 0.625 has been considered. Only the technical potential, as a fraction of the straw theoretical potential, is accessible for further utilization, due to factors such as affordability, sustainable harvesting practices, e.g., balancing humus quality [28,29], and legislation [21].

The estimation of a potential supply of removable straw is obtained by reducing the quantity of harvestable straw by a coefficient of sustainability (to maintain the soil carbon balance and soil fertility) which defines, in holistic approaches, the level of removable straw compatible with maintaining the rate of Soil Organic Matter (SOM): it varies from 20 to 50% and usually 33% is adopted [20]. Bioeconomic potentials of cereal straw have been estimated on the basis of the JRC Policy and Science Report [8] that indicates the share of collected crop residues and allows estimation of the competing applications for straw according to the following equation:

$$S_{bp} = S_{tep} \frac{kt}{y} - (S_{thp} \times 0.25) \quad (4)$$

where

S_{bp} = Straw bioeconomic potential;

S_{tep} = Straw technical potential;

S_{thp} = Straw theoretical potential;

0.25 = Crop-type residue collection coefficients.

Competing applications further restrict technical potential; for cereal straw, they are:

- conventional uses (livestock littering, industrial, green building, etc.);
- energy production (heat and power).

For cereal straw, an in-depth understanding of each value chain and of current concepts for managing residues is needed. In addition, analysis of statistical data for competing applications (e.g., livestock littering in a certain region) and review of the literature and industry reports are required. Moreover, according to [30], in order to allocate straw demand of competing applications to a regional level, different scenarios should be analyzed to reflect changing demand patterns as a result of different conditions such as legislation, prices or subsidies. Straw for litter is used for animal bedding; this application accounts for the largest straw demand [9] and is expensive and labor-intensive. The amount of straw used for litter (or bedding) can significantly vary due to the type of livestock and the country (Figure 5).

The major straw-consuming livestock are dairy cows, other cows, buffaloes, goats, sheep and horses for an overall amount of about 61 million metric tons of dry matter. Horses have been identified as a significant competitive user, but no statistical data are available in EUROSTAT databases. Straw mulching is relevant in the field of ecological farming. Interviews with farmers revealed that up to 100% of the produced straw on the farm is used for surface mulching. Straw delivers important nutrients, improves humus development, prevents soil erosion and reduces the use of artificial fertilizers. Energy is the main non-agricultural competitive use for straw. According to Helin et al. [20], Denmark, Hungary, Sweden, Spain and the United Kingdom are the most advanced countries in terms of use of straw for energy (Table 5).

All the EU power plants using straw to produce energy consume about 2 million metric tons of straw which represents about 1% of the annual quantity of harvestable straw in Europe and up to 30% of the harvestable straw at a regional scale (NUTS2). Agro-industrial applications are also relevant: mushroom and strawberry cultivation needs straw previously composted or directly incorporated into the soil, respectively. Moreover, natural materials are becoming increasingly important in modern times, especially in the context of construction material, even if, compared to the other alternative uses, the building sector absorbs minor amounts [31].

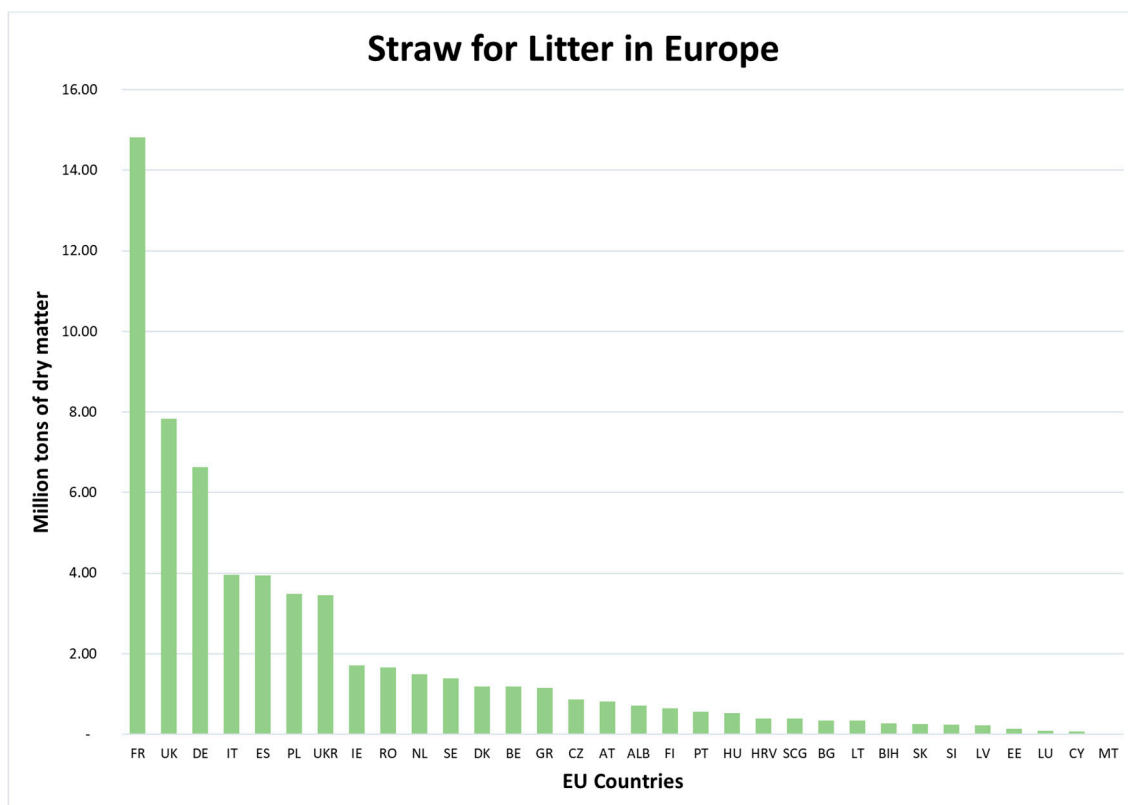


Figure 5. Distribution of cereal straw for litter in the EU countries [21].

Table 5. Straw for energy, power plants and quantity of straw (kilotons). CHP means combined heat and power [20].

Countries	Straw (kt)	Plants
Denmark	110	55 district heating and CHP plants
Sweden	135	8 district heating and CHP plants + 1 large power plant
Spain	160	1 large power plant
Poland	5	2 boilers
Hungary	270	1 large power plant
UK	200	1 large power plant
France	6	2 boilers
Total	1900	

At a national level (NUTS0 area), the bioeconomic potentials of cereal straw residues seem to be largely widespread in most of the countries. Three countries produce 46% of the biomass potential for straw: France, Germany and Poland. France is the top producer of straw, particularly of wheat and maize. Germany is the next biggest producer of straw, mainly wheat and barley. Poland's production of straw is largely oilseed rape, wheat and triticale. Romania is dominated by maize and wheat, while the top producers of rice in Europe are Italy, followed by Spain, Greece, Portugal, France, Romania, Bulgaria and Hungary.

The cereal straw potentials are shown in Figure 6.

Moreover, to account for the use of agricultural biomass in the manufacture of bio-based chemicals and bio-based plastics (high added value bio-based materials), which remains one of the major data gaps, a precautionary scenario has been considered by a reduction factor to assign the share of biomass available as feedstock for advanced biofuel

production. It considers the biomass potential for advanced biofuel between 45 and 10% of the bioeconomic potential.

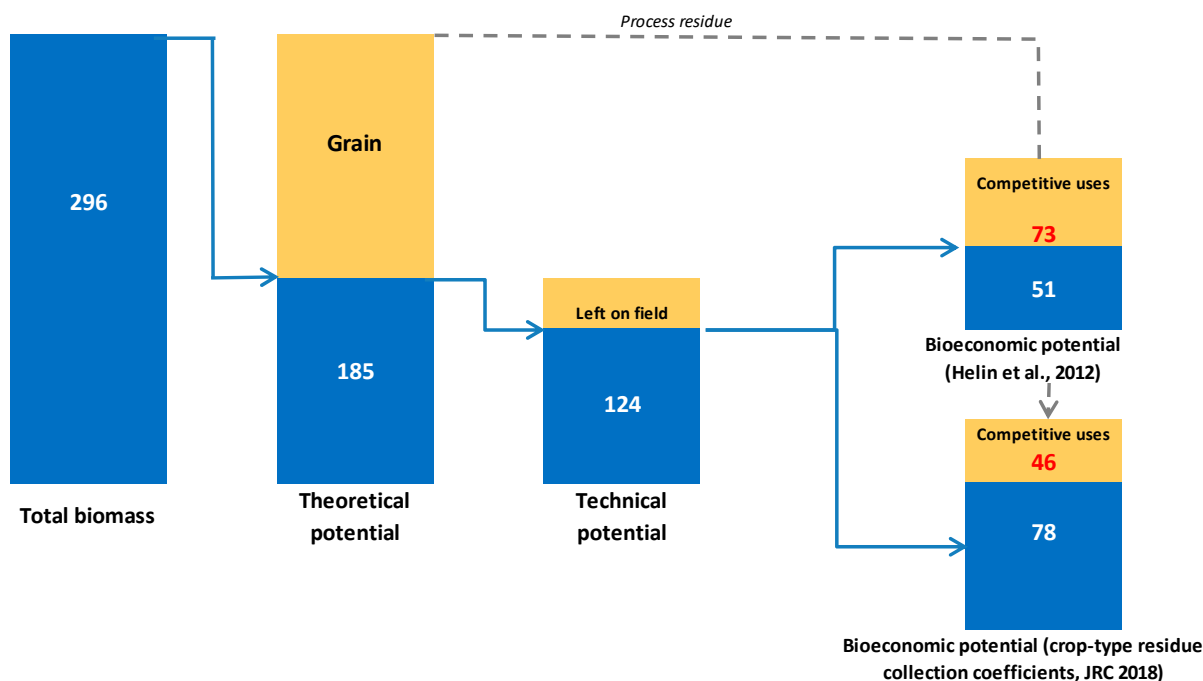


Figure 6. Scheme of the biomass potentials for cereal straw (Mt/y) (data from [8,20,30]).

The distribution of the cereal straw in the EU countries according to the precautionary scenario is shown in Table 6.

3.3. Suitability Class Allocation

The biomass is converted into methanol in an innovative process developed within the CONVERGE project. The plant is modeled in ASPEN modeling, determining the mass and energy balances of the integrated plant for a given capacity of biomass input (i.e., 100 MWth). The results (i.e., mass flows and thermal duties) can be linearly scaled to other biomass inputs. For instance, for CONVERGE technology, the hypothesis of 100 MWth and 200 MWth plant capacity allows the assessment of the plant feedstock requirements for a preliminary speculation (Table 7). For cereal straw, the specific conversion concept requires 138 and 275 kt/y of biomass for a plant thermal capacity of 100 and 200 MWth, respectively. Figure 7 shows the cut-off for a plant of 200 MWth.

3.4. Data Spatialization for Cereal Straw

Afterwards, the spatialization of the data was completed for every EU-27 country and the data collection at the European regional level (NUTS2) was conducted with statistical database EUROSTAT. Moreover, in the CONVERGE project a specific questionnaire composed of 5 sections and containing 40 description fields was provided to producers, first gathering entities and industrial and research institutions (in total 43 entities) able to give back localized information about the current flows of residual biomass treated or studied by them.

The regional data, available in EUROSTAT as NUTS2 data, were analyzed by QGIS v3.8-Zanzibar. The adoption of GIS solutions provides the distribution of bioeconomic potential of biomass in the European administrative units (NUT32) at a glance.

The most conservative precautionary bioeconomic potential (45% scenario) has been arranged by an ordinal scale on the basis of the availability of data amplitude (Figure 8).

Table 6. Synthesis of the results for cereal straw potentials.

Cereal Straw	Country	Theoretical Potential	Technical Potential	Bioeconomic Potential JRC	Precautionary Scenario (45%)	Precautionary Scenario (10%)
Central Europe	France	39,833.85	26,688.68	16,730.22	7528.60	1673.02
	Germany	27,794.80	18,622.51	11,673.81	5253.22	1167.38
	Poland	17,873.15	11,975.01	7506.72	3378.03	750.67
	Romania	15,592.16	10,446.74	6548.71	2946.92	654.87
	Hungary	9308.02	6236.37	3909.37	1759.22	390.94
	Bulgaria	5862.80	3928.08	2462.38	1108.07	246.24
	Serbia	5437.14	3642.88	2283.60	1027.62	228.36
	Czechia	4876.19	3267.05	2048.00	921.60	204.8
	Austria	3145.51	2107.49	1321.11	594.50	132.11
	Slovakia	2532.56	1696.81	1063.67	478.65	106.37
	Bosnia and Herz.	901.47	603.98	378.62	170.38	37.86
	Switzerland	549.53	368.19	230.80	103.86	23.08
	Slovenia	375.90	251.85	157.88	71.05	15.79
Mediterranean Europe	Spain	13,794.66	9242.42	5793.76	2607.19	579.38
	Italy	10,652.26	7137.02	4473.95	2013.28	447.4
	Greece	2129.84	1426.99	894.53	402.54	89.45
	Croatia	1905.32	1276.56	800.23	360.11	80.02
	Portugal	726.38	486.68	305.08	137.29	30.51
	Albania	435.59	291.85	182.95	82.33	18.29
	North Macedonia	339.18	227.25	142.45	64.1	14.25
Scandinavia	Denmark	5584.18	3741.40	2345.35	1055.41	234.54
	Sweden	3260.59	2184.60	1369.45	616.25	136.94
	Finland	2120.25	1420.57	890.51	400.73	89.05
	Norway	803.85	538.58	337.62	151.93	33.76
North Seas	Lithuania	3168.68	2123.02	1330.85	598.88	133.08
	Latvia	1636.64	1096.55	687.39	309.33	68.74
	Belgium	1630.59	1092.49	684.85	308.18	68.48
	Ireland	1363.55	913.58	572.69	257.71	57.27
	Netherlands	884.26	592.45	371.39	167.12	37.14
	Estonia	734.55	492.15	308.51	138.83	30.85
	Luxembourg	97.73	65.48	41.05	18.47	4.10
TOTAL		185,351.18	124,185.29	77,847.49	35,031.37	7,784.75

Table 7. Straw feedstock requirements on the basis of types of biomass and plant capacity.

Parameter	Unit	System Simulation	Case 1	Case 2
Plant power	MWth	10	100	200
Plant operation	h	8400	8400	8400
Energy requirements	TJ/y	197	1969	3937
Straw MC	%	35	35	35
LHV	MJ/kg	13.11	13.11	13.11
Feedstock	kt/y	15	150	300

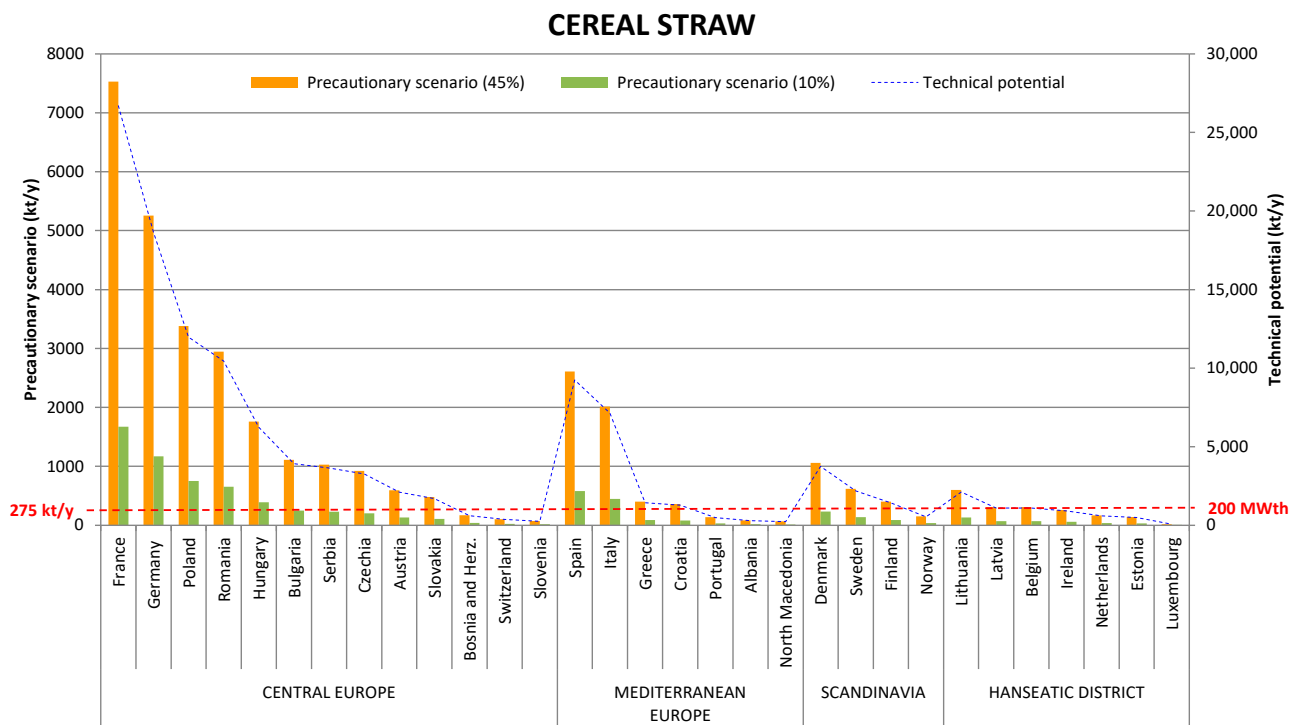


Figure 7. Cross checks of bioeconomic potential and the thresholds (cut-off) of the plant feeding requests for cereal straw. Red line (275 kt/y) is the required amount to steady operate a 200 MW_{th} conversion plant, for reference.

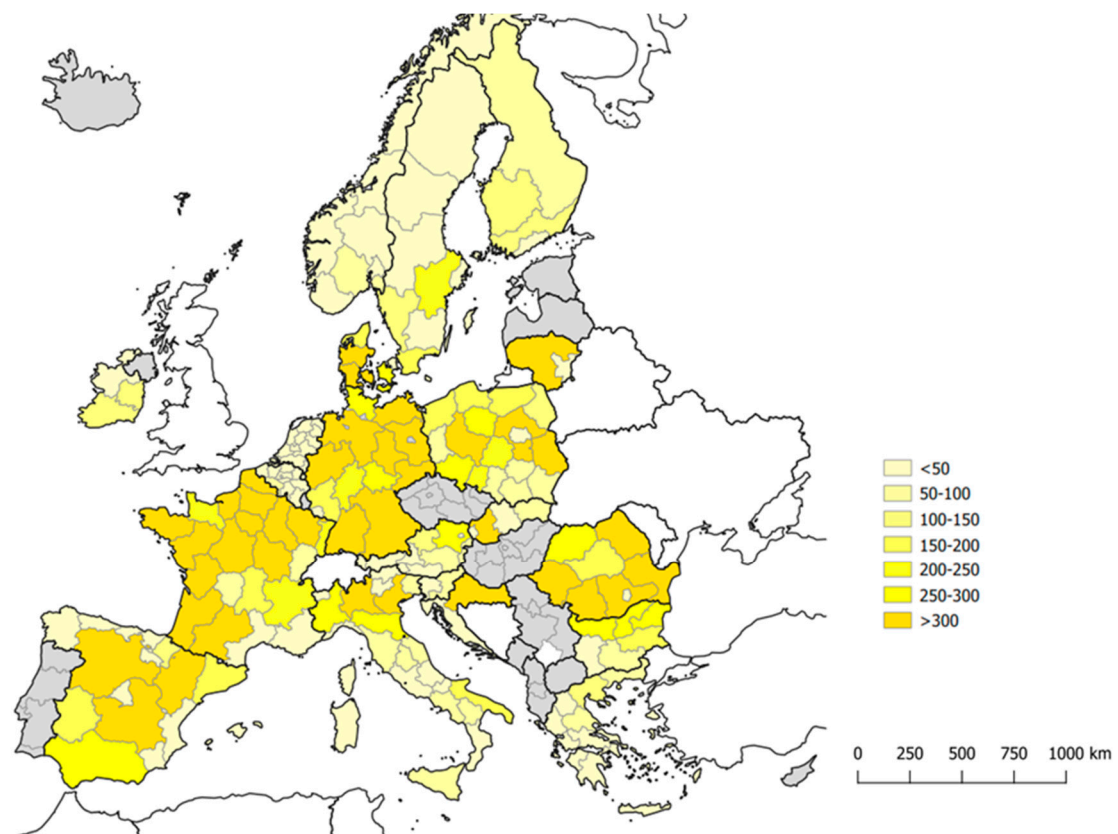


Figure 8. Regional breakdown of the bioeconomic precautionary potential (kt/y) for cereal straw.

The area around Paris (Centre—Val de Loire) is one of the most promising regions. Regions with an undersupply of straw tend to import such biomass to satisfy straw demand. This happens, for example, for some regions in the Netherlands [32]. Moreover, the introduction of suitability classes gives additional details with respect to the regional breakdown maps, scoring the different regions according to their potential in scaling up the proposed conversion solution at commercial size. In fact, this solution matches the cereal straw bioeconomic potential and the feeding request of the conversion technology, identifying potential biomass supply bottlenecks (Figure 9). Forty-eight regions belong to the class “No operational limit” where the biomass can be used for mono-feedstock supply of plants with over 200 MW_{th} of capacity (Table A2 in Appendix A). These regions were grouped in eighteen biomass supply regional clusters (Table A3 in Appendix A). In each of the four EU districts, several clusters are present, representing the hotspots for commercial scaling up of the CONVERGE technology. Actually, these regions are able to provide a sufficient amount of mono-feedstock to plants over 200 MW_{th}, without limitations from the upstream logistics.

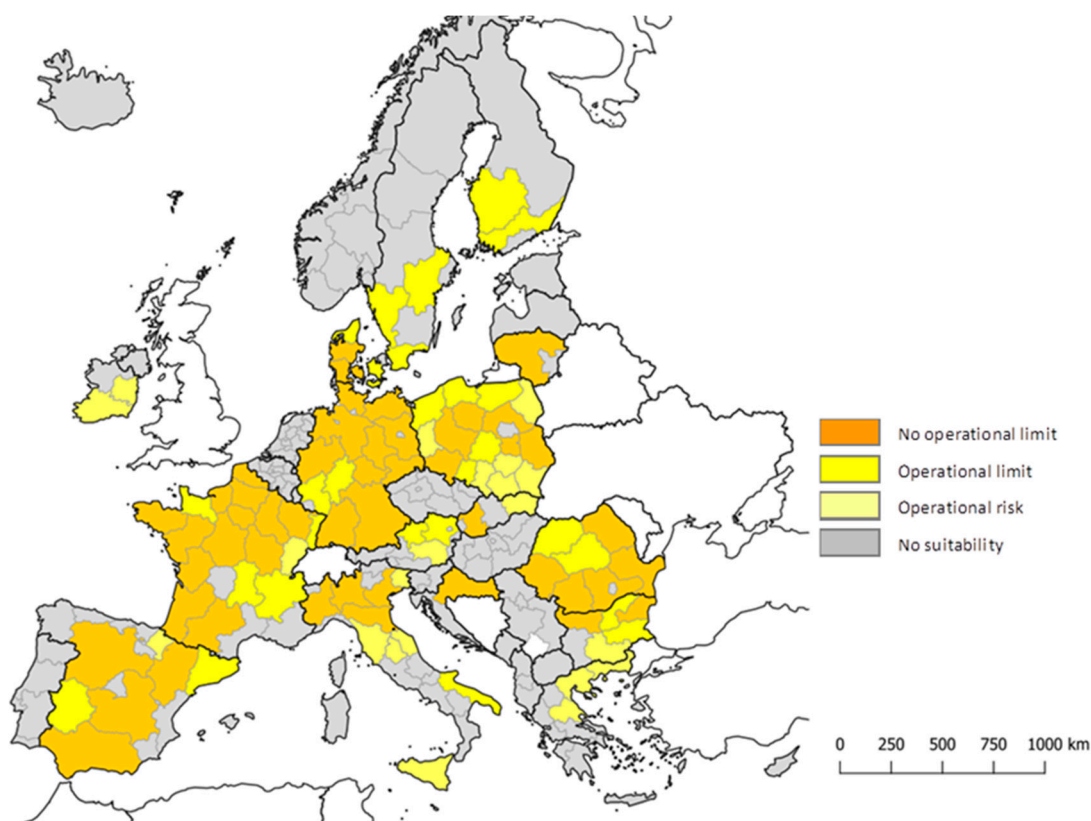


Figure 9. Regional suitability for cereal straw. Suitability class allocation of the EU regions.

3.5. MCA of the Cereal Straw Supply Chain

The scenarios provided by MCA which depict the different options and all their different implications in terms of technical feasibility, cost/effectiveness analysis and environmental pressures are chosen, hypothesizing their implementation in a specific geographical area, i.e., Hanseatic, Scandinavian, Mediterranean and Central European.

For cereal straw supply chain assessment, thirteen measurable indicators have been identified. For each of them, three different levels of performance are defined and scored (Table 1). For each indicator, a weight has been set (1, 0.6 and 0.3) in order to highlight the indicators considered fundamental for reaching the proposed objectives in terms of environmental sustainability, economic performances and logistical optimization.

MCA methodology is selected for the analysis of cereal straw supply chains, to point out the most promising regional clusters for feedstock provision in the EU. In Central Europe, the cereal straw is the most interesting chain, reaching a score of 15.7, due to a combination of high availability (i.e., the possibility to feed large plants) and low moisture content of the biomass (i.e., low complexity of storage). In the Scandinavian region, the cereal straw supply chain is less profitable with a score of 13.4, followed by the Hanseatic and the Mediterranean regions with 12.5 and 12.0, respectively. The implementation of the MCA allows application of preference modeling to the most promising supply chain for each EU district, by a scoring and weighting process (Table 8). In particular, the cereal straw is also very promising in Scandinavia even if the competition uses are more critical, in Mediterranean countries where the storage complexity rises and in the Hanseatic area where the supply chain is standardized and the storage management easier. Anyway, these three districts have a reduced number of the most promising regions if compared with the Central EU. Therefore, in this framework, for the Mediterranean and North Sea regions, the CONVERGE project implemented the MCA for multi-feedstock supply chains, useful for reaching the quantities of biomass suitable for a large plant's continuous operation. Anyway, a low level of logistic and economic optimization is required because of the complexity of different and integrated storage, transport and pre-treatment solutions.

Table 8. MCA scoring of the cereal straw supply chain in the investigated districts.

Region Indicator	Scandinavian	Central European	Mediterranean	Hanseatic
2nd level availability	3	3	3	2
Number of most promising regions	1	3	2	1
Transport complexity	2	2	2	2
Production seasonality	1	1	1	1
Storage complexity	2	3	2	3
Biomass competition in the geographical region	2	3	3	1
Supply chain complexity	2	2	2	2
Standardization of the supply chain	3	3	3	3
Nominal capacity of the plant	3	3	3	2
Average total transport distance	2	1	2	2
Pre-treatment necessity	2	2	2	2
Traceability complexity and certification costs	2	2	2	2
GHG emissions due to supply chain complexity	1	1	1	2
Total score	26	29	28	25
Weighted total score	13.4	15.7	15.0	12.5

4. Conclusions

The EU Member States set the ambitious target to improve the share of renewable energy within the final consumption of energy in the road and rail transportation sector by at least 14% by 2030. The residual biomasses represent a versatile key renewable energy source from which advanced liquid biofuels, sensu RED II Annex IX, Part A, can be generated. However, within the next 10 years, feedstock access could become very likely increasingly challenging, and the biomass potential is expected to become a relevant constraint for the continuous operation of the biorefineries. Therefore, it is very important to build up a constant, reliable and cost-efficient supply system of biomass in addition to the distribution system of biofuel on the basis of actual scenarios, sustainability criteria and bioeconomy cluster approach at the regional level.

Moreover, since the consumption of wood feedstock for energy production is continuously increasing, non-forestry ligno-cellulosic material should be proposed and used to satisfy the demand for biomass, especially in certain EU geographical districts, prevent the overexploitation of forestry resources and enhance forest conservation. This paper presented an innovative methodology to identify the potential of residual biomasses for biofuel production at the regional level, applying the methodology to a cereal straw case study and CONVERGE conversion plant.

The developed methodology applies four different levels of analysis to account for (i) supply limits, (ii) requested thermal input for the conversion plant, (iii) availability at the regional level (i.e., NUTS2 at European level) and (iv) a multi-criteria analysis. The four levels of analysis allowed the identification of the cereal straw supply chains in the four EU districts (Scandinavian, Hanseatic, Central European and Mediterranean). The most promising hotspots where biomass availability, logistics and feedstock requirements meet have been subsequently grouped in 18 biomass supply regional clusters (BSRCs).

Through the application of preference modeling of the supply chain for each EU district, by a scoring and weighting process of the MCA, the most promising scenarios for each EU district under investigation were defined. From the model application, it was found that Central Europe and Mediterranean districts are those with the highest cereal straw bioeconomic potentials. In practice, they allow mono-feedstock supply chains and relatively high capacity of the CONVERGE technology of 200 MW_{th} and beyond:

- (i) Central Europe has an overall bioeconomic potential of 16.249 kt (232.359 TJ) distributed over 36 regions and organized in 12 BSRCs. Cereal straw is indeed the most representative biomass supply chain of the district including 36 regions that together provide 96% of the whole bioeconomic potential of the district: 70% is held by France and Germany and the remaining 30% by Romania, Slovakia, Bulgaria and Poland. The biggest cluster is located in France (see Central Europe in Tables 6 and A3 in Appendix A) and includes the regions of Centre—Val de Loire, Poitou-Charentes, Pays de la Loire, Bretagne, Bourgogne (in total 2.978 kt; 42.590 TJ);
- (ii) the Mediterranean district has an overall bioeconomic potential of 3541 kt (50.630 TJ) distributed over nine regions and organized in four BSRCs.

The provided approach for supply chain definition allows implementation of business cases considering the different regions' suitability. This last item is particularly important because biofuel cost can be reduced by supply chain optimization, helping to improve competitiveness with conventional fossil fuels. Many different conversion processes and biomass streams can be evaluated by the presented methodology, as well as in regions where the suitability class "No operational limit" is less represented and a dominant type of biomass supply chain is missing.

These aspects are relevant assuming the strong competition for the residual biomasses from today up to 2030; the industrial plants have to not be feedstock-specific to reduce the issues related with competing for a specific local biomass as feedstock.

For the Mediterranean and Hanseatic regions, the methodology implemented for multi-feedstock supply chains highlights that multi-feedstock solutions are useful for reaching the biomass quantities required by the conversion plant. In addition, the resulting biomass mix overcomes the complexity in terms of storage, transport and pre-treatment necessity of a single feedstock, leveraging logistical and economic optimization strategies. Given this preliminary outcome, future works will focus on further applications and improvements of the methodology, mainly focusing on:

- (i) comparative analysis of all the biomass supply chains suitable for the advanced biofuel production;
- (ii) combination of the discussed methodology with a supply chain optimization tool for advanced biofuel production;
- (iii) multi-feedstock solutions for the Mediterranean and Hanseatic regions;
- (iv) integration with a dynamic model for calculating lifecycle GHG emissions of the ligno-cellulosic biomass supply chains for advanced biofuels for road transportation

markets, based on the calculation rules of the Revised Renewable Energy Directive (RED-II).

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

Appendix A

Table A1. Data set from Eurostat 2019, average data of the harvest campaigns from 2015 up to 2018, theoretical potential of cereal straw.

Year	2015	2016	2017	2018	Average
Geographical labels					
European Union—28 countries	316,628.57	301,748.74	309,984.25	295,171.77	305,883.33
France	71,788.59	53,579.13	67,728.63	61,840.31	63,734.17
Germany	48,917.70	45,401.00	45,593.20	37,974.80	44,471.68
Turkey	38,637.00	35,724.93	36,604.93	34,705.75	36,418.15
Poland	27,481.72	29,293.87	31,331.01	26,281.55	28,597.04
Romania	19,332.82	21,764.82	27,138.88	31,553.28	24,947.45
United Kingdom	24,591.19	21,710.58	22,733.55	20,839.83	22,468.79
Spain	20,783.82	24,955.45	17,188.44	25,358.14	22,071.46
Italy	16,405.76	18,363.10	16,554.95	16,850.67	17,043.62
Hungary	14,107.34	16,594.35	13,979.39	14,890.26	14,892.84
Bulgaria	8728.97	8945.12	9737.28	10,110.55	9380.48
Denmark	9907.84	9024.03	9882.96	6923.90	8934.68
Serbia	8436.97	10868.00	6793.30	n.a.	8699.42
Czechia	8183.51	8596.41	7456.78	6970.92	7801.91
Sweden	6168.80	5480.50	5958.40	3260.10	5216.95
Lithuania	6085.05	5120.82	5074.19	3999.50	5069.89
Austria	4826.90	5671.46	4847.27	4785.62	5032.81
Slovakia	3805.71	4847.85	3484.06	4070.76	4052.10
Greece	3588.78	3983.13	3015.72	3043.33	3407.74
Finland	3729.91	3609.38	3462.12	2768.19	3392.40
Croatia	2773.95	3472.83	2678.79	3268.48	3048.51
Latvia	3021.50	2703.20	2692.50	2057.30	2618.63
Belgium	3133.68	2228.79	2642.25	2431.04	2608.94
Ireland	2497.93	2184.32	2259.53	1784.91	2181.67
Bosnia and Herzegovina ¹	1150.87	1677.52	1176.89	1764.10	1442.35
Netherlands	1629.08	1344.30	1370.62	1315.25	1414.81
Norway	1342.11	1310.58	1205.81	n.a.	1286.17
Estonia	1535.30	934.10	1311.90	919.83	1175.28
Portugal	1252.36	1152.27	1128.59	1115.62	1162.21
Switzerland	901.75	752.06	986.72	876.48	879.25
Albania	695.50	698.40	n.a.	n.a.	696.95
Slovenia	624.05	638.06	546.99	596.66	601.44
North Macedonia	483.81	640.91	447.71	598.31	542.69
Kosovo ²	443.60	562.90	477.90	n.a.	494.80
Luxembourg	178.57	139.43	149.81	157.65	156.37
Cyprus	88.13	10.42	36.45	24.71	39.93
Montenegro	7.09	7.69	7.87	8.02	7.67
Iceland	n.a.	6.00	8.00	3.95	5.98
Malta	-	-	-	-	-
Liechtenstein	n.a.	n.a.	n.a.	n.a.	n.a.

n.a. = not available; ¹ estimated; ² under United Nations Security Council Resolution 1244/99.

Table A2. List of the EU regions that belong to the suitability class “No operational limit”.

Progr.	Country	NUTs2 Region	Precautionary Scenario (kt/y)	Progr.	Country	NUTs2 Region	Precautionary Scenario (kt/y)
1	DE	Bayern	940.14	25	PL	Lubelskie	372.55
2	FR	Centre-Val de Loire	932.09	26	HR	Kontinentalna Hrvatska	356.17
3	ES	Castilla y León	854.06	27	FR	Nord-Pas-de-Calais	352.22
4	DE	Niedersachsen	771.92	28	RO	Nord-Est	351.83
5	RO	Sud-Muntenia	699.29	29	DK	Midtjylland	330.05
6	FR	Picardie	631.36	30	IT	Lombardia	318.36
7	RO	Sud-Est	612.53	31	FR	Haute-Normandie	318.21
8	FR	Champagne-Ardenne	605.39	32	SK	Západné Slovensko	317.08
9	FR	Poitou-Charentes	576.25	33	DE	Sachsen	314.68
10	DE	Nordrhein-Westfalen	557.79	34	DE	Brandenburg	312.22
11	LT	Vidurio ir vakaru Lietuvos regionas	555.77	35	DK	Syddanmark	308.83
12	FR	Pays de la Loire	551.22	36	FR	Lorraine	308.37
13	FR	Bretagne	492.67	37	PL	Mazowiecki regionalny	307.77
14	PL	Wielkopolskie	489.13	38	IT	Veneto	303.64
15	FR	Midi-Pyrénées	454.16	39	FR	Île de France	301.28
16	DE	Mecklenburg-Vorpommern	444.73	40	PL	Kujawsko-Pomorskie	298.08
17	ES	Castilla-la Mancha	441.64	41	DE	Thüringen	297.22
18	DE	Sachsen-Anhalt	428.22	42	IT	Piemonte	297.13
19	FR	Bourgogne	426.11	43	BG	Severoiztochen	295.90
20	RO	Sud-Vest Oltenia	419.55	44	PL	Dolnoslaskie	288.47
21	FR	Aquitaine	417.81	45	BG	Severozapaden	287.33
22	DE	Baden-Württemberg	406.34	46	IT	Emilia-Romagna	286.49
23	ES	Aragón	404.62	47	DE	Schleswig-Holstein	284.31
24	RO	Vest	384.61	48	ES	Andalucía	278.44

Table A3. Regional biomass supply cluster for cereal straw.

District	Country	Regions	Cluster Progress ID
Scandinavia	Denmark	Midtjylland Syddanmark	1
Hanseatic countries	Lithuania	Vidurio ir vakaru Lietuvos regionas	2
Central EU	France	Centre—Val de Loire Poitou-Charentes Pays de la Loire Bretagne Bourgogne	3
		Picardie Champagne-Ardenne Nord-Pas-de-Calais Haute-Normandie Lorraine Île de France	4
		Aquitaine Midi-Pyrénées	5
	Germany (NUTS1)	Bayern Baden-Württemberg	6
		Niedersachsen Nordrhein-Westfalen	7
		Mecklenburg-Vorpommern Sachsen-Anhalt Sachsen Brandenburg Schleswig-Holstein Thüringen	8
		Poland	Wielkopolskie Dolnoslaskie Kujawsko-Pomorskie Lubelskie Mazowiecki regionalny
	Romania	Sud—Muntenia Sud-Est Sud-Vest Oltenia Nord-Est Vest	10 11
	Slovakia	Západné Slovensko	12
	Bulgaria	Severozapaden	13
		Severoiztochen	14
Mediterranean EU	Spain	Castilla y León Aragón	15
		Castilla-la Mancha Andalucía	16
	Croatia	Kontinentalna Hrvatska	17
	Italy	Piemonte Lombardia Veneto Emilia-Romagna	18

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