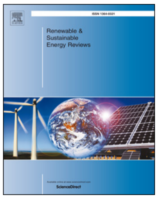
Renewable and Sustainable Energy Reviews 100 (2019) 127–142

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A spatial approach to bioeconomy: Quantifying the residual biomass potential in the EU-27

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ARTICLE INFO

Keywords:
GIS
Crop residues
Circular economy
Manure
Food waste
Straw
Residual grass

ABSTRACT

Bioeconomy is seen as a key strategic innovation pillar in the European Union, and this involves, among other things, mobilizing biomass resources. This study presents a geo-localized methodology in order to quantify the overall (theoretical) residual biomass potential for each NUTS-3 region of the EU-27 + Switzerland (NUTS-3 is the smallest regional division in Eurostat's Nomenclature of Territorial Units for Statistics). Estimates were made for biomass residues stemming from 4 main activities: i) agriculture (straw, manure, residues from pruning permanent plantations); ii) forestry (forestry residues); iii) urban greenery management (residues from managing urban green areas and roadside vegetation); and iv) food waste (agri-industrial food process waste and municipal biodegradable waste). A review of earlier assessments using a variety of spatial coverages is also presented. Our results reveal the importance of residual biomass as a key feedstock for the European bioeconomy: we found that 8500 PJ y^{-1} are available for these streams (theoretical potential), which corresponds to the whole annual (2015) primary energy consumption of Italy and Belgium combined. Straw (3800 PJ y^{-1}) and forestry residues (3200 PJ y^{-1}) were shown as the top-two contributors. Our geo-localized approach uncovered outliers in terms of regional trends, revealing very specific opportunities for these regions. This includes the NUTS-3 region of Paris (France) where the highest biomass density was found with ca. 25 TJ km^{-2} (essentially food waste), and the NUTS-3 of Jaen (Spain), the main region of olive oil in the world, with great opportunities stemming from the olive oil industry.

1. Introduction

The next 20 years are expected to be rich in environmental and social changes that will bring businesses and societies worldwide both risks and opportunities in the search for sustainable growth [1–3]. One key strategy of the European Union (EU) in facing this necessity of decoupling human progress from resource use and environmental decline is the development of an innovative bioeconomy [4,5]. This is reflected in the 2012 EU Bioeconomy Strategy [4], but also legislation, strategies, and policy and communication papers adopted by the EU in recent years (e.g. Renewable Energy Directive, EU Forestry Strategy, Common Agricultural Policy towards 2020, Blue Growth Strategy, Energy Roadmap 2050, Action Plan for the Circular Economy, Low Carbon Economy Package, etc.).

Bioeconomy, defined in the EU Bioeconomy Strategy as the sustainable production of primary biomass and the conversion of organic resources (primary or waste) into food, feed, bio-based products and bioenergy, is in fact a cornerstone linking a variety of economic activity sectors (e.g. agriculture, forestry, energy, waste management, chemical industry) and sustainable growth goals. In this context, biomass residues from primary, secondary as well as tertiary sectors of economic activity are expected to play a major role in supplying the feedstock needed for sustainable bioeconomy pathways [6,7]. In fact, the use of residual biomasses as a key bioeconomy feedstock (e.g. straw, grass residues, food waste, etc.) is typically reported as triggering much lower overall environmental impacts than their land-dependant counterparts (e.g. [8,9]), besides being at the intersection with circular economy by offering opportunities for cascading uses. In the EU, residual biomass is

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Abbreviations: AIW, Agri-Industrial Food Process waste; BioMW, Biodegradable Municipal Waste; CLC, Corine Land Cover; EU, European Union; Eurostat, Statistical Office of the European Union; GIS, Geographical Information System; LHV, Lower Heating Value; NPP, Net Primary Production; NUTS, Nomenclature of Territorial Units for Statistics; RPR, residues-to-product-ratio; WDC-RSAT, World Data Centre for Remote Sensing of the Atmosphere; ww, wet weight

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https://doi.org/10.1016/j.rser.2018.10.017
Received 30 September 2017; Received in revised form 12 October 2018; Accepted 14 October 2018

Table 1
Chronological list of studies quantifying the potential of residual biomass in the EU. Figures in the last column reflect the theoretical potentials, unless otherwise stated[a].

Authors[b]	Residual biomass type[a]	Pot.[c]	Ref. year	Resol.[d] for results	Spatial coverage[e]	Res. potential (PJ y^{-1})[h]
Fischer [16]	Crop & forestry residues, surplus grassland[i]	ST	1990[f]	11 World regions	Region WEU and EEU	13,300
EEA [17]	Municipal biowaste	TH	1995[f]	country	EU-15[k] + NO	580
Nikolaou [18]	Crop & forestry residues, livestock waste & municipal biowaste	TH-TE	2000	country	EU-27	2960
Siemons [19]	Crop (incl. pruning) & forestry residues, livestock waste & municipal biowaste	EC	2000[f]	country	EU-27	800
de Noord [20]	Crop & forestry residues, livestock waste, agri-industrial & municipal biowaste	ST/TE	1997–2001[f]	country	EU-15 + NO, CH	7570
Edwards [21]	Crop residues (straw from wheat and barley)	ST	2001–2003	NUTS-2	EU-27	820
Thran [22]	Crop (incl. pruning) and forestry residues, livestock waste, agri-industrial and municipal biowaste, surplus grassland[m]	TE	2000[f]	country	EU-27 + TR	3220[n]
Ericsson [23]	Crop & forestry residues	TE	2000[f]	country	EU-27 (without MT & CY)[o]	1210
EEA [24]	Forestry residues (fellings only here)	ST	2005[f]	NUTS-2	EU-25 (without EL, MT, LU, CY)	600
Esteban [25]	Crop (incl. pruning) and forestry residues	TH,TE	1996–2003	NUTS-2	AT, DE, DK, ES, FI, FR, GR, IT, NO, PL, PT, SE	6527
Kunikowski [26] (*“RENEW” study*)	Crop & forestry residues	TE	2000–2004[f]	country	EU-27 + CH (without MT & CY)	2200[j]
Asikainen [27]	Forestry residues (incl. stumps)	TH,TE	2007	country	EU-27 (without GR, MT & CY)	2830
Bottcher [28] (*“BEE” study*)	Crop and forestry residues, livestock waste & municipal biowaste	TH,TE	2005–2010[f]	country	EU-27	4000[p]
Panoutsou [29]	Crop and forestry residues, livestock waste, agri-industrial and municipal biowaste	TE/EC	2000[f]	country	EU-27	5640
Fischer [30]	Crop residues	ST	2000–2002[f]	country	EU-27	2000
Mantau [31]	Forestry residues (incl. bark)	TH,TE	2010[f]	country	EU-27	1230
Scarlat [32]	Crop residues (straw)	ST	1998–2007	country	EU-27	1530
Elbersen [10] (“*BiomassFutures*” *study*)	Crop & forestry residues, livestock waste, abandoned agricultural grasslands, roadside vegetation, agri-industrial & municipal biowaste.	ST	2004 and 2010[f]	NUTS-2	EU-27	6000[l]
Monforti [33]	Crop residues (straw)	ST	2000–2009	NUTS-2	EU-27	1500
Haase [7]	Crop residues (straw and root crops)	ST	2010	NUTS-1	FR, NL, DE, BE, UK (one selected NUTS-1 region per country)	140
Ronzon [34]	Crop residues (from > 130 crops)	ST	2013[g]	country	EU-28	7100

[a] Studies that are only predictive are not included. Some of these studies also include non-residual biomass.

[b] Here denoted with the first author and the date. EEA: European Environment Agency.

[c] Potential type, as defined by the authors of the study, or own judgement when judged relevant or if not defined. TH: theoretical; TE: Technical; EC: Economic; ST: Sustainable.

[d] Resol.: Resolution at which the potential figures are presented. Definitions for the various “NUTS” level can be found in [14].

[e] Definitions of countries acronyms for EU-12, EU-15, EU-16, EU-25, EU-27 and EU-28 are as in [13], and the ISO 3166 country codes are used for individual countries. WEU: Western Europe; EEU: Eastern and Central Europe.

[f] Also includes an estimation of future potentials (which is not presented herein).

[g] The authors report that the assessment was performed for the period 1961–2013, but only the 2013 results are presented. A lower heating value (LHV) of 18 GJ t^{-1} dry matter was used for conversion.

[h] Potential for European Member States only (or Member states sub-regions) and residues only (streams mentioned in the second column and regions of the 6th column), to the extent possible. Figures are given with a maximum of 3 significant digits and strive to reflect the theoretical potential when studies presented it. To get a result in PJ y^{-1}, the LHVs reported in the studies themselves were used. When not reported, the LHVs considered throughout the present study were considered, unless otherwise specified.

[i] Livestock and municipal waste are also included, but these cannot be re-calculated for the selected European regions, so excluded herein.

[j] “Wood balance” and wood industry by-products excluded.

[k] For Belgium, the results are only presented for the region Flanders and for the United Kingdom, only for England and Wales. No data are presented for Luxembourg, Portugal and Sweden.

[l] Excludes the secondary and tertiary residues estimates made for the forestry and agri-food sector, the paper and cardboard streams, as well as what the authors refer to as “common sludge”.

[m] Assumption for surplus grassland: yield of 2 t dm ha^{-1} and LHV of 14.8 MJ kg^{-1} dm (based on the assumptions used for roadside grass in this study).

[n] The original study presents a higher total, essentially because of the forest residues (here only logging residues are reported, for consistency). When a range was supplied, the higher value was used to better reflect the theoretical potential.

[o] The study also assess the potential for Ukraine and Belarus, but these values could be disaggregated and hence are not presented herein.

[p] Theoretical potential for all streams but straw, where only technical potential is available. This value excludes what the authors refer to as “secondary crop residues”.

often referred to as an untapped potential, and seen as a feedstock allowing to enlarge the biomass base [7,10]. Therefore, this study focuses on residual biomass only.

One of the key initial steps in the bioeconomy planning process is to estimate the available biomass resources [11], herein residual biomass. Though the residual biomass potential in the EU has been the object of several studies in the past (Table 1) no comprehensive study exists where a broad range of residual organic substrates have been simultaneously quantified and geo-localized for all EU Member States (MS). Further, the existing studies are often difficult to compare, as they apply restrictions (e.g. technical, economic, sustainable) to overall potentials and these are not harmonized from one study to another nor always transparently documented [6,12].

The goal of the present study is two-fold: quantifying the maximum potential for a variety of key residual biomass streams in the EU-27 [13] (plus Switzerland) and geo-localize it at the NUTS-3 region level (the smallest regional division in Eurostat's latest Nomenclature of Territorial Units for Statistics, NUTS 2013; [14]). This is among the first studies, to the authors' knowledge, which comprehensively geo-localizes a broad variety of residual biomass streams for the whole of EU, at such a regional scale. The following residual streams were addressed: straw, manure, forestry residues, residues from pruning permanent plantations, residues from managing green urban areas and roadside vegetation, as well as biodegradable municipal waste (biowaste) and agri-industrial wastes.

The paper is structured as follows: Section 2 presents an overview of existing studies quantifying the residual biomass potential in the EU-27 (plus Switzerland). Section 3 details the geo-localized methodology used to quantify the potential of each of the above-mentioned residual streams. The resulting findings are presented as maps in Section 4, and insights from these are discussed in Section 5. Based on these, we conclude in Section 6 that models for geo-localized assessment of biomass potentials are crucial for building and monitoring bioeconomy strategies, and that the model presented in this study is a fully customizable platform to build upon for such assessments.

2. Overview of existing studies quantifying EU residues potential

A variety of studies were made attempting to quantify the potential of residual biomass and non-residual biomass in the EU (among others; energy crops and stemwood are also often addressed in these studies). These are summarized in Table 1. Although a few of these studies stem from local/national initiatives, most were financed by the European Commission, including large European projects such as the BEE, Renew and BiomassFutures projects (Table 1).

These studies report both the so-called theoretical potential, i.e. the maximum amount of a certain residual stream available within fundamental biophysical limits, and a "reduced" available potential after a number of restrictions are applied to it (referred to as technical, economic and sometimes sustainable potential, depending on the constraints applied). As explained in [15,16], common sense suggests that theoretical > technical > economical > sustainable. Besides the different "type" of potentials, existing studies also involve a variety of differences in the exact resources they consider within each residue stream, as well as different time span, geographical scope and assessment methodologies to quantify the primary residual resource (i.e. even before applying any availability constraints). As a result, they are hardly comparable overall, although individual stream comparisons are possible, as exemplified in Figs. 1–3 at the country level. Still, the significant variability of the available estimates is reflected in Figs. 1–3. These are further discussed in Section 5 and compared to the estimates derived in the present study.

It should also be noted that Table 1 presents only studies that have documented biomass potentials based on "real" (or past) data; purely predictive studies are not included in Table 1, given the scope of the present study on quantifying the "current" residual biomass potentials. Similarly, only results from residual biomasses were extracted from the studies presented in Table 1, i.e. some of these studies did quantify the energy crop potentials (including stemwood) but these are not presented herein.

3. Geo-Localisation and quantification of residual biomass potentials across the EU

3.1. Overview

Estimates were made for biomass residues stemming from 4 main activities: i) agriculture (straw, manure, residues from pruning permanent plantations); ii) forestry (forestry residues); iii) urban greenery management (residues from managing urban green areas and roadside vegetation); iv) food waste (agri-industrial food process waste and municipal biodegradable waste).

Through distinctions are often established between theoretical and other types of potential (e.g. technical, economic, sustainable), as detailed in Section 2, this study focuses on the theoretical residual potential only. The rationale for this is that it was judged more relevant, for such a broad geo-localized study scope, to compile and compare theoretical potentials only. In fact, as there are no agreed standards nor definitions on the "actually available" potentials [12], theoretical potentials remain the only common useful basis for comparison. The potentials presented herein should thus be interpreted as the maximum residual biomass available, and the regional stakeholders may judge of the share available after considering the local constraints.

The study covers the EU-27 ([13]; i.e. not including Croatia but including the United Kingdom) as well as Switzerland, and reports the residual biomass potentials for each NUTS-3 region (the NUTS nomenclature subdivides the economic territory of the European Union into 98 NUTS-1 regions, 276 NUTS-2 regions and 1342 NUTS-3 regions; [14]). The time span considered is 2010, based on the data availability.

3.2. Agricultural residues

3.2.1. Livestock manure

Livestock residues (or manure) refers to the excreta (urine and faeces, with or without added material such as water or bedding material) generated from housed livestock. In the EU, its most common use is as an organic fertilizer source, and as a feedstock for biogas production (ca. 3% of the manure produced in the EU was digested in 2016; [35]). In this study, three main animal production facilities were considered, namely poultry, cattle and pig farms, these representing over 89% of the livestock in the EU [36].

The theoretical potential per NUTS-3 regions was estimated based on the model developed by Vis and Dees [37], as illustrated in Eqs. (1) and (2). This potential includes the amount of manure produced in stables only, i.e. it excludes the manure excreted as animals are kept outdoor (e.g. organic farms, grazing days, etc.), as this cannot be easily collected. The theoretical potential also accounts for unavoidable in-house losses (on the channels, etc.).

$$TM_i = \sum_{j=1}^{j=3} M_{ij} \tag{1}$$

$$\boldsymbol{M_j = \sum_{j=1}^{j=3} (H_j \times LU_j \times MpH_j \times AHD_j \times \mathrm{Av})} \tag{2}$$

Where:

$\mathrm{TM_i}$: Total manure potential for a given NUTS-3 region (tonnes $\mathrm{y^{-1}}$; wet weight ww)

$\mathrm{M_j}$: Theoretical manure production for livestock type j (tonnes $\mathrm{y^{-1}}$; ww)

$\mathrm{H_j}$: Number of heads for livestock type *j* (retrieved from Eurostat for

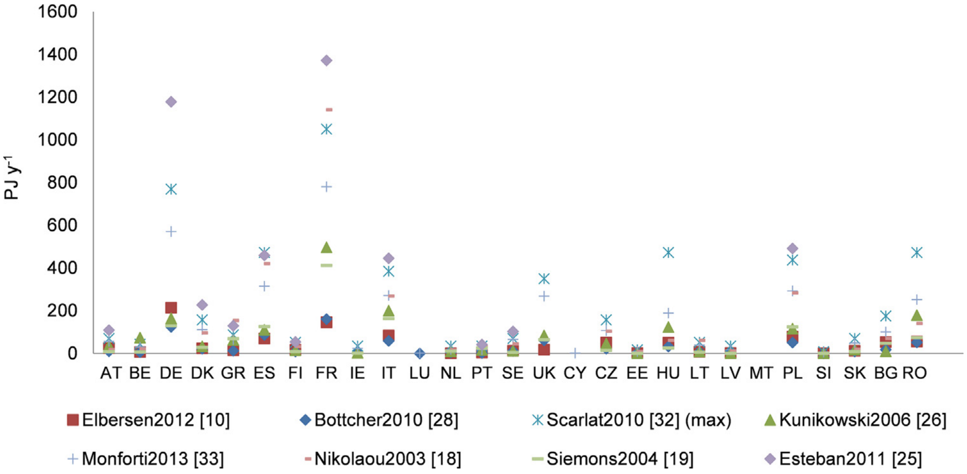

Fig. 1. Straw theoretical potential in the EU, according to the studies and nomenclature presented in Table 1. The values reported in [18] also include pruning residues.

each NUTS-3 region)

LU_j: Number of livestock units per head for livestock type *j* (established per definition in the Eurostat glossary; [38])

MpH_j: Manure excreted per livestock unit (t d^{-1}; ww) (retrieved from [28])

AHD_j: Number of days in animal houses per year (retrieved from [28])

Av: Availability factor representing the proportion of manure that can be collected from the stables after unavoidable losses during in-house storage (%). Assumption in this study: Av = 75%.

i: NUTS-3 area

j: Type of livestock.

In order to convert the resulting manure potential from a mass to an energy basis, the following (average) net calorific values (i.e. lower heating values; wet basis) for manure were used: cattle manure 0.9 GJ t^{-1}; pig manure 1.2 GJ t^{-1}; poultry manure 4.3 GJ t^{-1} (derived from [39], considering 80%, 77% and 56% moisture, respectively).

3.2.2. *Straw*

Straw is typically understood as the material left over in the field after the harvest of a (main) cereal or oilseed crop, consisting essentially of the crop stem, but including minor amount of leaves and chaff. Here, this definition is extended to also include the residue left after harvesting rice and maize. Being one of the most widely generated residual biomass in Europe, straw has generated growing interest as a key feedstock for a variety of bioeconomy applications (e.g feedstock for combined heat and power, second generation bio-ethanol, bio-based products). However, a significant portion of the straw is already used on-farm as e.g. bedding or source of long fibre ingredient for ruminants, in particular for cattle farms. Other (smaller in volume) existing agricultural uses of straw include the horticultural sector (e.g. as a valuable substrate for mushroom production for which there is no substitute, frost protection, strawberry production; [40]). When not harvested, straw is typically incorporated to the soil, unless the cost of the machinery or contract prevents it, as e.g. for some small traditional farms [40]. As explained in Spottle et al. [40], it is the net value of harvested straw (for use on-farm or sold, after deducting the harvesting costs) versus the additional cost of applying fertilizers to compensate for the loss of nutrients that will typically determine whether a given farmer will harvest it or not.

In this study, the total straw resources (theoretical potential) were first estimated at the NUTS-2 level. To this end, estimates were made on the basis of Eurostat yield data (data at NUTS-2 level; for 2005–2011) for all crops available in that database, namely: wheat, maize, barley, rapeseed, rye, oat, rice, sunflower and mixed cereals [41]. The total amount of generated straw was, for each selected straw-producing crops, derived through using the residues-to-product-ratio (RPR) (also

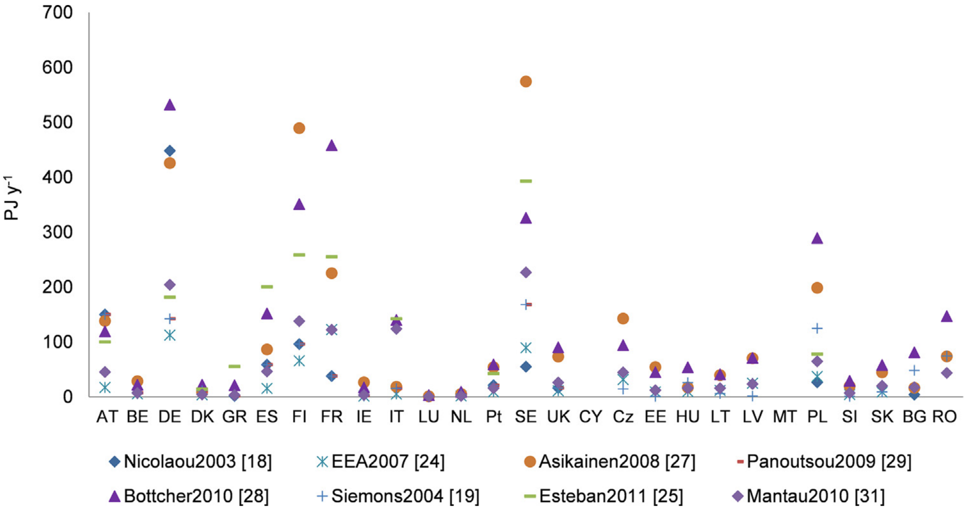

Fig. 2. Forestry residues theoretical potential in the EU, according to the studies and nomenclature presented in Table 1.

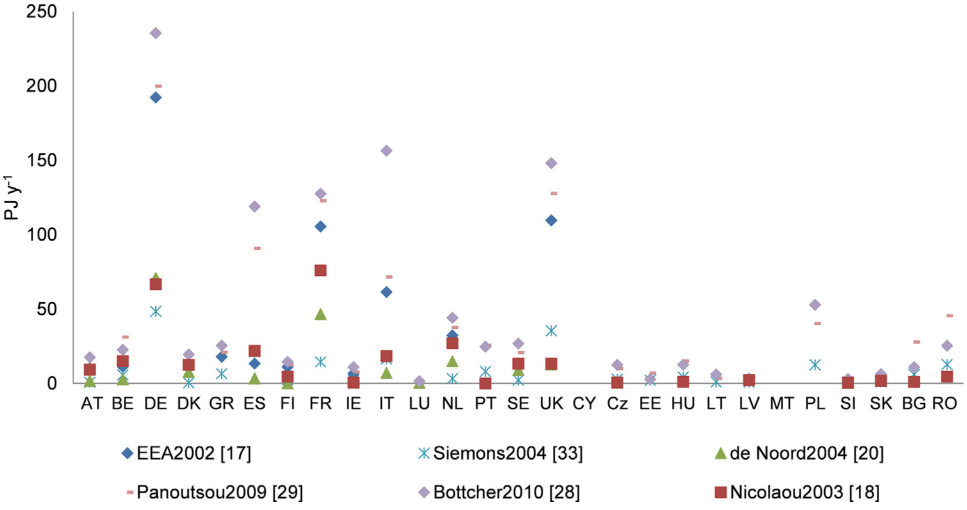

Fig. 3. Biodegradable municipal waste theoretical potential in the EU, according to the studies and nomenclature presented in Table 1.

Table 2
Algorithms used to determine the residues-to-product ratio (RPR) in each NUTS-2 region.

Crop	Algorithm to calculate the RPR	Comment
Wheat and barley[a]	0.769 − 0.129 * ATAN((Yield − 6.7)/1.5)	Smoothed discontinuous relation derived from an empirical range of harvest indices and grain yield data at NUTS-2 level. No R^2.
Maize[b]	− 0.181 * LN(Yield) + 1.337	Regression derived from a meta-analysis. R^2 = 0.1732
Rice[b]	− 1.226 * LN(Yield) + 3.845	As for maize. R^2 = 0.5727
Rapeseed[b]	− 0.452 * LN(Yield) + 2.0475	As for maize. R^2 = 0.1669
Sunflower[b]	− 1.1097 * LN(Yield) + 3.2189	As for maize. R^2 = 0.2551
Other cereals: oat & mixed cereals	0.9	Expert judgement, based on the results of [45]

[a] Algorithm taken from [21].
[b] Algorithm taken from [32].

referred to as harvest indices). This approach has been used in a variety of studies (e.g. [7,34,42–44]). The RPR were derived through available one-parameter algorithms (Table 2) with crop yield as parameter, themselves based on empirical data from a variety of studies. A summary of available RPR algorithms is provided in [34].

These potentials were afterwards scaled down from NUTS-2 (region) to NUTS-3 (sub-regions; the unit used in this study). Scaling factors were derived considering the proportion of arable land represented by each NUTS-3 as compared to the total arable land in the NUTS-2 region. To convert the straw potential into an energy unit, an average lower heating value (LHV) of 13.1 GJ t^{-1} was considered, (as received; considering 15% moisture) based on [39].

3.2.3. *Pruning residues from permanent plantations (olives, vineyards and fruit trees)*

The residues resulting from the pruning of permanent plantations (e.g. branches and leaves) were quantified. To this end, the locations of potential pruning areas were first identified using the CORINE Land Cover 2006 (CLC2006; Version 16) raster dataset of the European Environment Agency [46]. Class number 15 (vineyards), 16 (fruit trees and berry plantations), and 17 (olive groves) were used. For each NUTS-3 region, an average annual Net Primary Production (NPP) value (NPP for above- and below-ground combined) was assigned to each of these CLC classes. To this end, the NPP maps from the World Data Centre for Remote Sensing of the Atmosphere (WDC-RSAT) were used, which were built on the basis of the BETHY / DLR model (Biosphere Energy Transfer Hydrology) [47,48]. Geo-processing was conducted with a resolution of 100 m × 100 m (pixel size), and raster map were tabulated for all NUTS-3 regions. For the selected above-mentioned plantation areas, the amount of pruning residues was estimated as 50% of the total net primary production of the area. To convert this to biomass, it was considered that, for all NUTS-3, the partition between above- and below-ground NPP is roughly 50–50%, a rough estimate for representative species (namely olives, vineyards and fruit trees) with very different preferential carbon allocation behaviour [49]. It was further assumed that the carbon fraction of biomass dry matter consists of 50% carbon, based on the ranges presented in [50] for temperate and boreal biomes. Estimates were translated to energy units considering an average LHV of 9.9 GJ t^{-1} (ww; considering 40% moisture) based on [51].

3.3. *Potential of forestry residues*

Whether for industrial or recreational purposes, one key activity resulting from managing forests is the harvest of the wood (stemwood, pulpwood, timber, etc.). This, in turn, implies unavoidable losses, such as tops, branches, bark, or defective stems. These are here referred to as logging residues. The remaining stump is also considered as a residue from forestry activity that can be (and is) used in bioeconomy conversion pathways. Other residual streams from primary forestry activity could include the trees removed during thinning operations (when performed), as well as the trees severely damaged due to injurious agents (e.g. storms, insects, diseases, etc.). Yet, these are influenced by variety of site-specific parameters for which no reliable data were available, therefore they were not considered in this assessment. In this study, forestry residues thus include only logging residues and stumps.

To quantify the theoretical potential for forestry residues, the country-level data (in m^3 y^{-1}) calculated in [37] were used. These figures were derived considering industrial roundwood and stemwood removals (retrieved at the country level from Eurostat data) as well as tree-dependant crown biomass expansion factor (retrieved from a variety of literature and IPCC's Guidance on land use [52]). To convert these values to dry mass units, country- and species-specific wood density values were considered, based on the data of [53].

In order to scale these country-level residue estimates to NUTS-3 level estimates, a scaling methodology similar to the one used in the case of straw was applied. Here, it considers that within a given country, the NUTS-3 regions with the highest NPP will also be those with the highest forestry residues, and vice-versa. For each NUTS-3 regions of a given country, the annual average NPP values for three specific CLC2006 classes, namely deciduous, coniferous and mixed classes were extracted from the WDC-RSAT database. From this, average "forestry NPPs" were calculated at the NUTS-3 and country level. The overall amount of produced forestry residues within a given country were then allocated between each NUTS-3 according to their overall NPP share in the country.

To convert the figures from biomass (wet weight) to energy units, a LHV of 10 MJ per kg (ww; 35% moisture assumed for forestry residues) was considered [39]. This is equivalent to 15.5 MJ per tonne of dry matter.

3.4. *Urban greenery management*

3.4.1. *Urban green areas*

Residues from urban green areas are generated from the management of artificial and non-agricultural vegetated areas. This may include biomass streams such as leaves, shrubs and grass. The potential for this stream is assessed following the exact same methodology described for the pruning residues, i.e. through cross-referencing data from CLC2006 with NPP data for specific land cover types. Here, two CLC2006 classes were selected: urban green areas (class 10) and port & leisure facilities (class 11), to which NPP values were assigned (WDC-RSAT database).

3.4.2. *Roadside vegetation*

Roadside residue is the biomass that can be obtained from cut grass, shrubs and trees grown by the roadside. Currently, there is no large scale collection of this biomass type, mostly as a result of techno-economic barriers. The first step to quantify this stream was to assess the European roads and railway networks. This was done using the vector maps available from Open Street Map (OSM). Besides railways, three main classes of road were considered relevant with regards to roadside vegetation: motor ways, primary ways and trunk ways.

Based on an analysis of aerial photographs, it was assumed that the biomass could be obtained from 10-m wide strips, except for trunk roads where 5-m strips were considered. Finally, all strips were assigned the average annual NPP value of the NUTS-3 region where they are found (WDC-RSAT database). As for the other residues, the NPP values (in t C ha^{-1} y^{-1}) were converted to t biomass ha^{-1} y^{-1} using the same assumptions as described for pruning residues.

For each NUTS-3 regions, the residual roadside potential was computed as shown in Eq. (3), considering two strips per road/railway.

$$RSV_i = 2 \times NPP_i \times C \times (0.01 \times L_1 + 0.01 \times L_2 + 0.005 \times L_3 + 0.01 \times L_w) \tag{3}$$

Where:

RSV: Roadside vegetation biomass for NUTS-3 area i (t y^{-1}; ww)
NPP: Net primary productivity, mean value (t biomass ha^{-1} y^{-1}; ww)
C: 100 (unit conversion factor; ha 0.01^{-1} km^{-2})
L_1: Length of motor ways in NUTS-3 area i (km)
L_2: Length of primary ways in NUTS-3 area i (km)
L_3: Length of trunk roads in NUTS-3 area i (km)
L_w = Length of railway in NUTS-3 area i (km)
i: NUTS-3 area.

In order to convert the modelled mass into energy, an average LHV of 14.8 GJ t^{-1} biomass (ww; 15% moisture) was considered, based on the ECN Phyllis database [39].

3.5. *Food waste*

3.5.1. *Potential of biodegradable municipal waste (BioMW)*

Biodegradable municipal waste (often referred to as "biowaste", also herein) was estimated directly at the NUTS-3 level through using country statistics on annual municipal waste production per capita level (Eurostat; [54]), statistics on waste collection in each country [55], and population data at the NUTS-3 level [56], as shown in Eq. (4) (adapted from [37]). An average for the last five years of available data was taken whenever possible, and when not possible, the latest year of available data was used. Biodegradable municipal organic waste here considers only organic food waste and exclude other organic streams such as paper, cardboard and textile waste. For each country, the portion of organic waste in the waste collected was retrieved from [57]. To convert the modelled mass data into energy data, an average LHV of 6.7 GJ t^{-1} biomass (ww) was used.

$$BMW_i = MSW_{c(i)} \times POP_i \times p_{c(i)} \times OC_{c(i)} \tag{4}$$

Where:

$BioMW_i$: Biodegradable municipal waste biomass for NUTS-3 area i (t y^{-1}; ww)
$MSW_{c(i)}$: Municipal waste production per capita of country where the NUTS-3 area i belongs (t person^{-1} y^{-1})
POP_i: Population of NUTS-3 area i (person)
$p_{c(i)}$: percentage of the population served by municipal waste services in country where the NUTS-3 area i belongs (%)
$OC_{c(i)}$: organic content of MSW in country where the NUTS-3 area i belongs (%)
i: NUTS-3 area.

3.5.2. *Agri-industrial food process waste (AIW)*

Agri-industrial food process waste in this study is limited to the process waste of two key European industries, namely olive oil and grape processing (mainly for the production of wine). Using the CLC2006 land cover, the surfaces cultivated with vineyards and olive groves (CLC classes 16 and 17) were quantified. Through the use of statistical yield data at the NUTS-2 level [41], the production of olives and grapes was estimated per NUTS-2 region. These estimates were scaled down to the NUTS-3 level distributing the NUTS-2 production to its NUTS-3 sub-regions proportionally to the surfaces occupied by the targeted crops in each NUTS-3. Though the processing of these crops occurs mostly locally [58], the proportion of olives and grapes directly exported abroad was estimated and subtracted (Eq. (5)). From this, the amount of available agri-industrial waste per crop processed could be derived through the use of the processing factors presented by [59]. This procedure is summarized through Eq. (5). To convert the modelled mass data into energy data, an average LHV of 2.2 GJ t^{-1} grape pomace (ww; 80% moisture) was used and of 5.6 GJ t^{-1} olive pomace (ww; 65% moisture), based on [39,59].

$$AIW_i = (Y_{Gn2} \times A_{Gi} \times S_G \times L_G \times PW_G) + (Y_{On2} \times A_{Oi} \times S_O \times L_O \times PW_O) \tag{5}$$

Where:

AIW_i: Agri-industrial food process waste in NUTS-3 area i (t y^{-1}; ww)
Y: Yield (t ha^{-1} y^{-1}; ww)
A: Area cultivated with the targeted crop (ha)
S: Scaling factor for production (from NUTS-2 to NUTS-3; see text)
L: Proportion of targeted crop processes locally (%)
PW: Process waste proportion out of the amount of crop processed (%)
G: Grapes
O: Olives

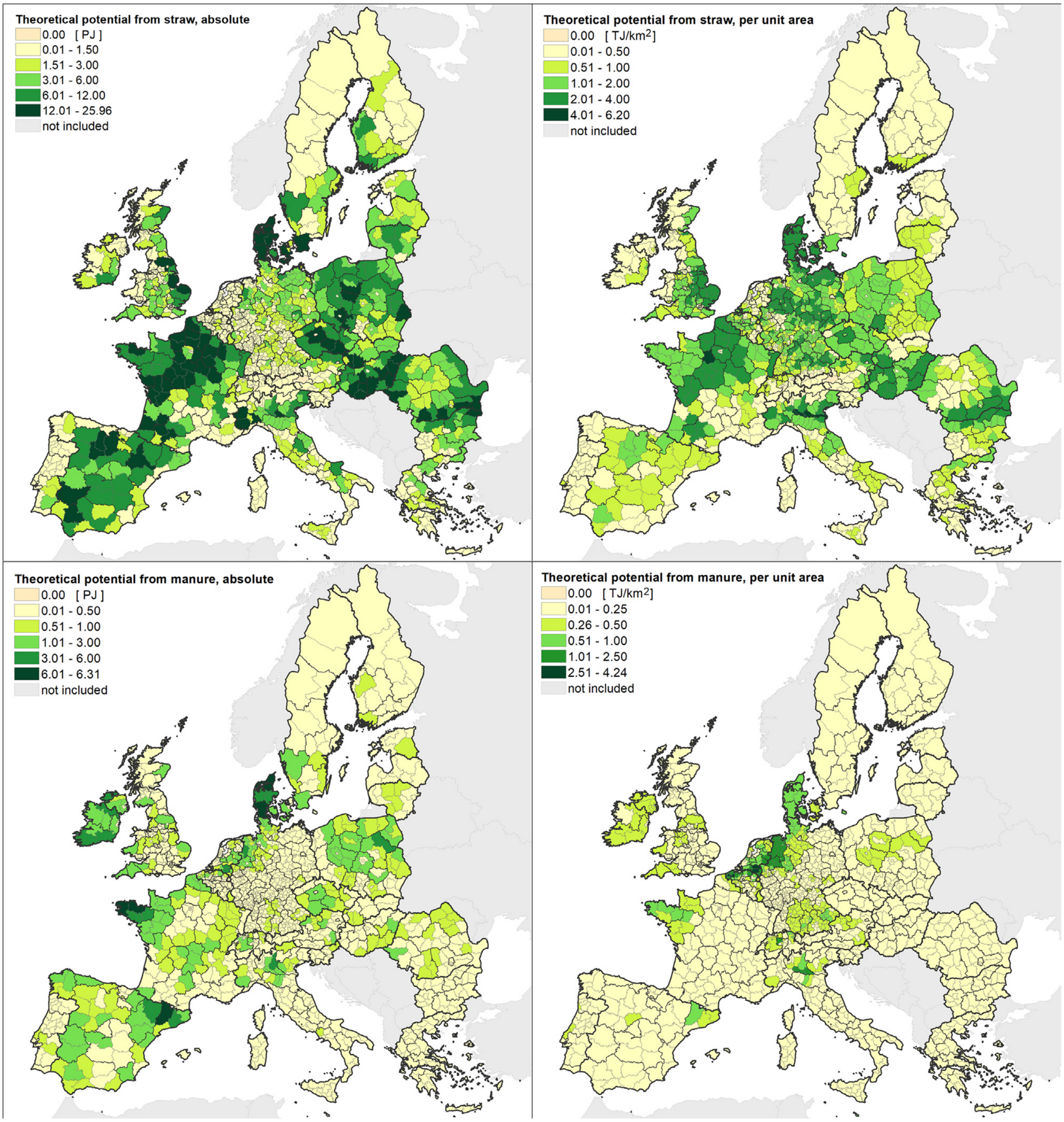

Fig. 4. Residual potential for straw (top) and manure (bottom); total (left) and per unit area (right). The two streams are reported with different scales. "Not included" represents the regions out of the assessment scope, while the category "0.00" illustrates potentials below 0.01 PJ or TJ km^{-2}.

n2: NUTS-2 area
i: NUTS-3 area.

4. Results

The results per NUTS-3 region are presented in Fig. 4 for agricultural residues (straw, manure), in Fig. 5 for urban greenery (urban green areas and roadside vegetation), in Fig. 6 for food waste (agri-industrial food waste and municipal biowaste) and in Fig. 7 for the other streams (pruning residues, forestry residues). Fig. 8 presents the aggregated residual biomass potential for each NUTS-3. For each stream, results are presented in terms of energy value, this being judged the most useful metric in order to compare the results between the streams. The overall results, however, are summarized in Table 3 both in tonnes and in energy units. Furthermore, the annual values are presented both as absolute data (in TJ for a given NUTS-3) and as density data (in TJ per km^2 of the NUTS-3). The latter allows to better visualize the concentration of the residual biomass potential and prevents the artefact of perceiving exaggerated potentials in the larger NUTS-3 regions.

Fig. 4 illustrates that the straw potential varies between 0 (urban regions) to 26 PJ y^{-1} in the various NUTS-3 regions of the EU, with a total of 3800 PJ y^{-1} (Table 3). About 6% of the 1304 NUTS-3 are in the "high end" category of 12–26 PJ y^{-1}, 9% in the category 6–12 PJ y^{-1}, 14% in the category 3–6 PJ y^{-1}, 17% in the category 1.5–3 PJ y^{-1}, 49% in the category 0.01–1.5 PJ y^{-1} and 5% in the category $<$ 0.01 PJ y^{-1}.

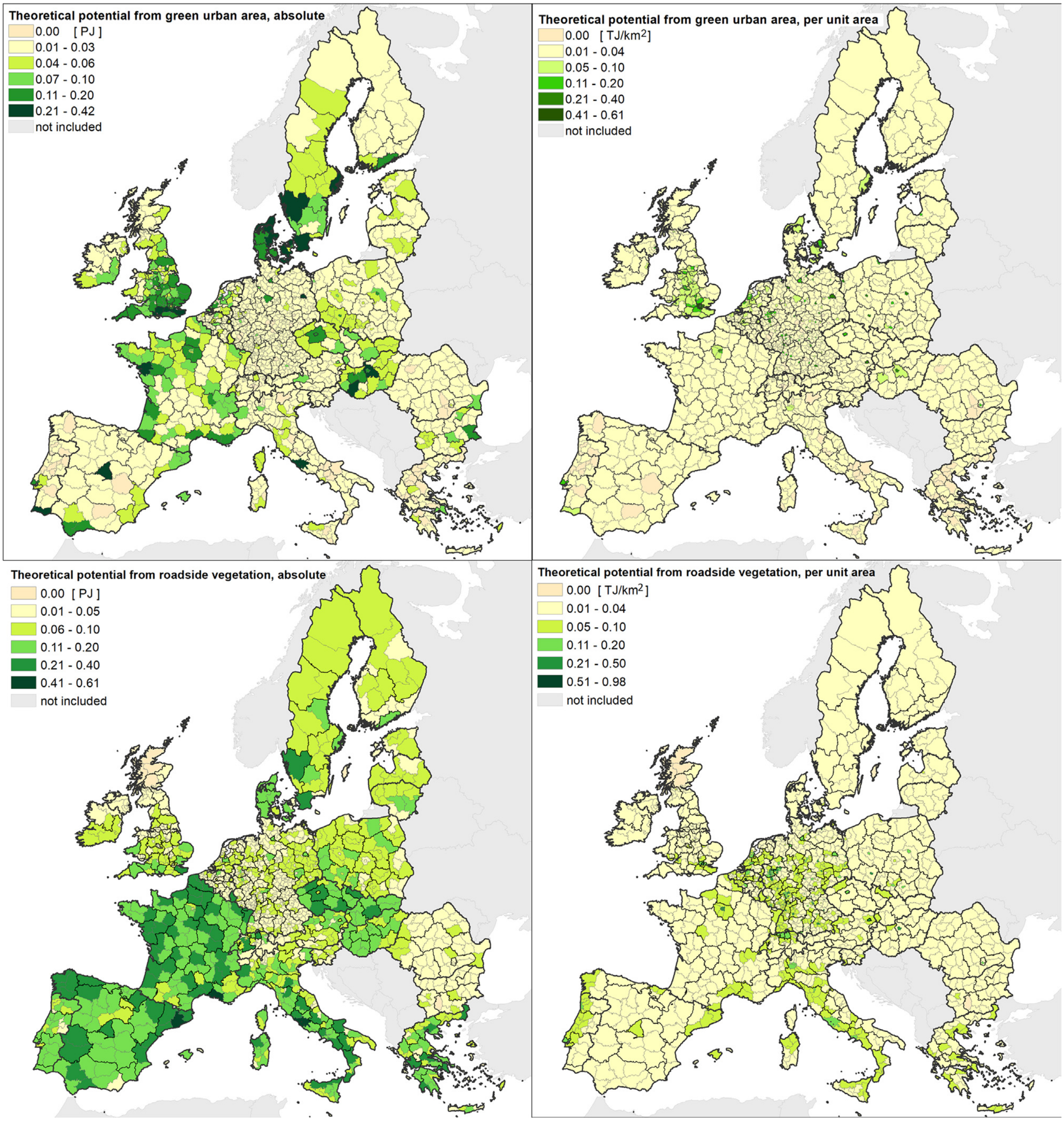

Fig. 5. Residual potential for urban green areas (top) and roadside vegetation (bottom); total (left) and per unit area (right). The two streams are reported with different scales. “Not included” represents the regions out of the assessment scope, while the category “0.00” illustrates potentials below 0.01 PJ or TJ km^{-2}.

The NUTS-3 regions with a straw potential above 20 PJ y^{-1} are located in: Czech Republic (1), Denmark (2), and France (7), and reflect regions with high agricultural intensity (in parenthesis is the number of corresponding NUTS-3 regions for the country – e.g. in the present case those with a straw potential above 20 PJ y^{-1}; this nomenclature is used from this point onwards). The regions with the highest straw concentration, however, are all found in Northern Italy (Lodi, Cremona and Mantova, with ca. 6 TJ km^{-2}). Overall, Fig. 4 indicates a certain geographical proximity between the locations where the concentration of the resource is the greatest.

As shown in Table 3 and illustrated in Fig. 4, the overall potential for manure is about 15% the one of straw, with a total of 560 PJ y^{-1}. This reflects, among others, the low energy value of manure in comparison to straw. Less than 0.5% of the 1304 NUTS-3 are in the “high end” category of > 6 PJ y^{-1}, 1% in the category 3–6 PJ y^{-1}, 9% in the category 1–3 PJ y^{-1}, 14% in the category 0.5–1 PJ y^{-1}, 67% in the category 0.01–0.5 PJ y^{-1} and 9% in the category < 0.01 PJ y^{-1}. Regions with a manure potential above 4.0 PJ y^{-1} are located in Denmark (4), Spain (1), France (3), Ireland (1), and The Netherlands (1). Regions with the highest manure concentration include Belgium (12), Switzerland (1), Germany (17), Italy (3) and The Netherlands (8), all with more than 1.0 TJ km^{-2}. These also coincide with regions where manure management is an issue. Our results show that the two most concentrated regions for manure are found in Belgium, with a potential above 3.1 TJ km^{-2} (Roeselare and Tielt, both in the West Flanders province).

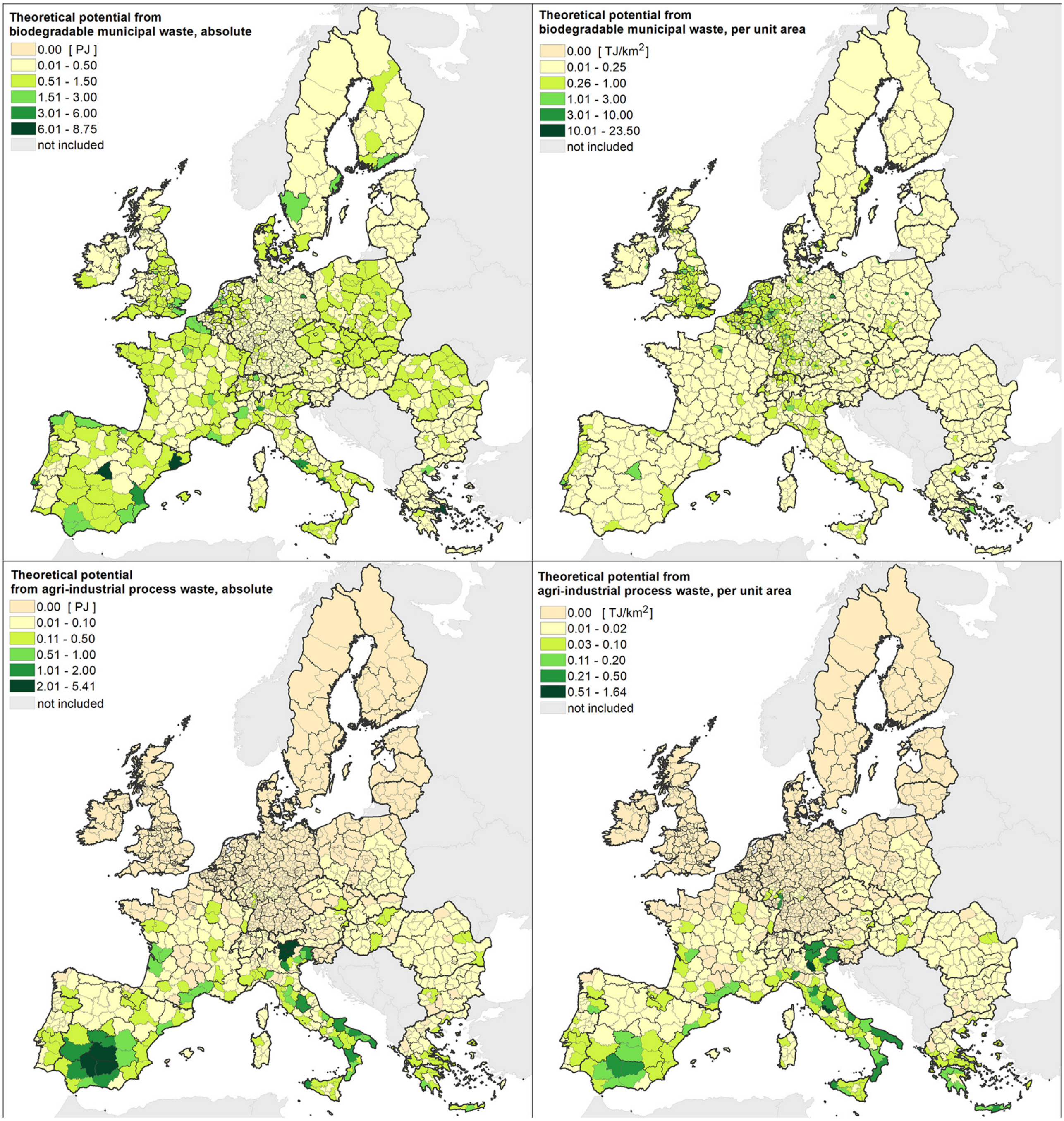

Fig. 6. Residual potential for biodegradable municipal waste (top) and agri-industrial waste (bottom); total (left) and per unit area (right). The two streams are reported with different scales. “Not included” represents the regions out of the assessment scope, while the category “0.00” illustrates potentials below 0.01 PJ or TJ km^{-2}.

In comparison with straw and manure, the potential from urban green areas (maximum of 0.41 PJ y^{-1}) and roadside vegetation (maximum of 0.60 PJ y^{-1}) is modest (Fig. 5). In total, our results show 35 PJ y^{-1} for the former and 95 PJ y^{-1} for the latter (Table 3). More than 80% of the NUTS-3 present, for urban green areas, a potential below 0.03 PJ y^{-1}, and only 1% of the NUTS-3 regions present a potential in the high-end category (> 0.20 PJ y^{-1}). The regions with the highest potential are found in Denmark (2), Hungary (1), Portugal (1), Sweden (1) and the United Kingdom (2), all with a potential above 0.30 PJ y^{-1}. The regions with the greatest concentration of urban green residues (greater than 0.3 TJ km^{-2}) are found in Germany (2), Denmark (1), France (2), Poland (1), and the United Kingdom (5).

About half the NUTS-3 regions present a potential in roadside vegetation in the category 0.01–0.06 PJ y^{-1}, and only 3 regions present an estimated potential in the high-end category (> 0.40 PJ y^{-1}). These are located in Spain, France, and Italy. The greatest concentrations, on the other hand, are found in NUTS-3 from Switzerland (1) and Germany (2), with concentrations above 0.50 TJ km^{-2}.

The overall estimated potential for biodegradable municipal waste (Fig. 6) is in the same order of magnitude as the overall potential for manure, with a total of 600 PJ y^{-1}, but it finds a much higher maximal concentration than found for manure (up to 23 TJ km^{-2} in the Paris region). The NUTS-3 areas with the greatest potential are essentially found in the most populated areas, as could be expected. However, 97% of the NUTS-3 regions present a potential below 1.5 PJ y^{-1}.

With an overall potential of 80 PJ y^{-1}, agri-industrial biowaste (in

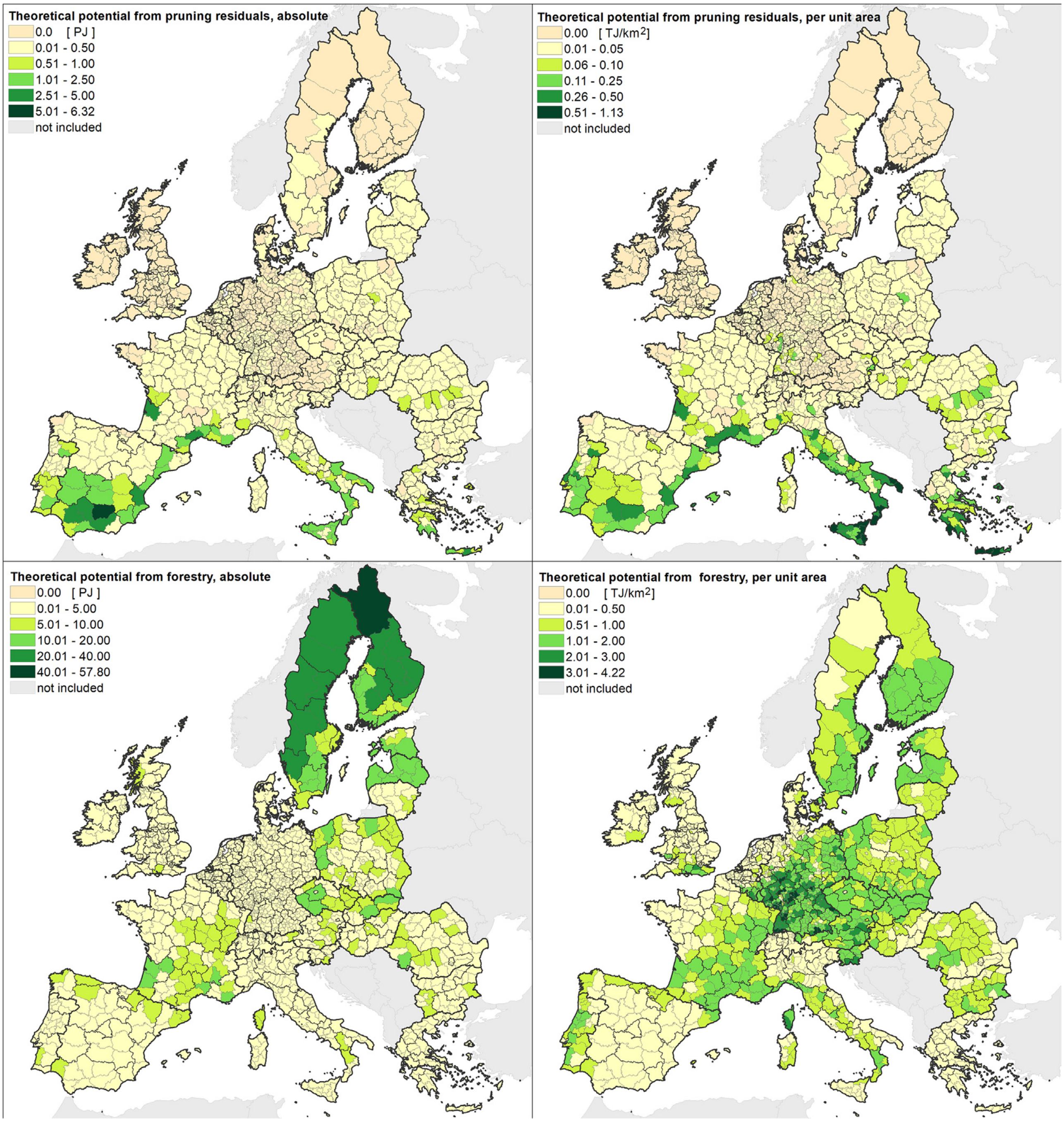

Fig. 7. Residual potential for pruning residues (top) and forestry residues (bottom); total (left) and per unit area (right). The two streams are reported with different scales. “Not included” represents the regions out of the assessment scope, while the category “0.00” illustrates potentials below 0.01 PJ or TJ km^{-2}.

this study stemming from the processing of grapes and olives only) is in the same order of magnitude as roadside vegetation. The greatest amount are found in the NUTS-3 from Spain (3) and Italy (2). Only 3 regions present a concentration above 0.5 TJ km^{-2}, all located in Italy (reflecting areas with both high wine and olive processing). Because of the specific streams considered for AIW, 75% of the 1304 NUTS-3 regions present a potential in the low-end category (< 0.01 PJ y^{-1}).

If the overall potential of pruning residues roughly corresponds to the one of roadside vegetation and urban green areas combined (i.e. total of 150 PJ y^{-1}; Table 3), the overall potential for forestry residues is comparable to the one of straw, with 3200 PJ y^{-1} (Table 3). About 83% of the NUTS-3 regions present a potential for forestry residues in the category 0.01–5 PJ y^{-1} (Fig. 7). Only 16 NUTS-3 regions present a potential above 20 PJ y^{-1} (the top two high-end categories); these are all located in the Nordic countries (8 in Sweden and 8 in Finland). The highest concentrations (above 3 TJ km^{-2}), however, are all found in Germany (21 NUTS-3 regions).

Pruning residues, on the other hand, are mostly found in the Southern regions. Only 8 NUTS-3 regions present a potential above 2.5 PJ y^{-1} (the top two high-end categories), these are found in Greece (1), Spain (5), and South of France (2). On the other hand, over 65% of the 1304 NUTS-3 regions present a potential in the low-end category (< 0.01 PJ y^{-1}). The greatest concentrations (above 0.5 TJ km^{-2}) are found in Greece (6) and Italy (8).

Fig. 8 presents the aggregated potential from all residual streams, which amounts to 8500 PJ y^{-1}. The NUTS-3 regions with the greatest

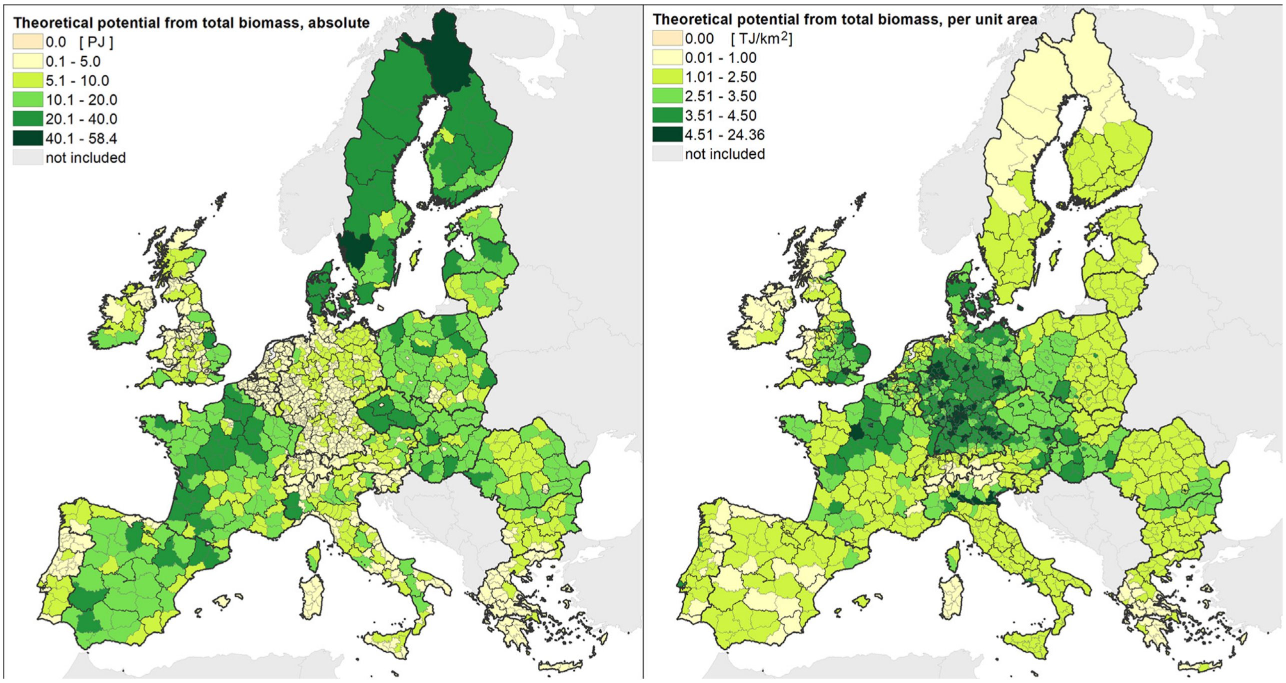

Fig. 8. Residual potential, all streams; total (left) and per unit area (right). “Not included” represents the regions out of the assessment scope, while the category “0.00” illustrates potentials below 0.1 PJ or 0.01 TJ km^{-2}.

Table 3

Summary of total residual biomass potential inventoried for EU-27 and Switzerland[a].

	Total	Straw	Pruning residues	Manure	Forestry residues	Urban green areas	Roadside vegetation	BioMW[b]	AIW[c]
Mtonnes	1400	290	15	690	320	2.4	6.3	90	14
PJ	8500	3800	150	560	3200	35	95	600	80
t km^{-2}	330	67	3.5	160	74	0.54	1.5	21	3.3
TJ km^{-2}[d]	2.0	0.87	0.035	0.13	0.74	0.008	0.022	0.14	0.018
Highest NUTS-3 density (TJ km^{-2})	24 (Paris)	6.1 (Cremona)	1.1 (Irakleto)	4.2 (Tielt)	4.2 (Sudwestpfalz)	0.60 (Paris)	0.98 (Basel-Stadt)	23 (Paris)	1.6 (Gorizia)
Highest NUTS-3 potential (PJ)	58 (Lapland)	26 (Marne)	6.3 (Jaen)	6.3 (Cotes-d’Armor)	58 (Lapland)	0.41 (Vest- og Sydsjaelland)	0.60 (Roma)	8.7 (Madrid)	5.4 (Jaen)

[a] Results are presented with 2 significant digits (at most), not with the aim to reflect precision but to ensure tractability only. Eventual inconsistencies due to rounding.

[b] BioMW: Biodegradable municipal waste.

[c] AIW: Agri-industrial food process waste.

[d] Total resource out of total inventoried area (4.35 Mkm^2), and not the sum of the individual densities found at the NUTS-3 level, which would give a much higher result as illustrated in the next row.

amount of available residues (above 20 PJ y^{-1}; top two high-end categories in Fig. 8) are found in 13 countries, namely: Czech Republic (5 regions; straw and forestry residues combined make ca. 90% of the potential), Denmark (5 regions; straw makes 60–70% of the total potential in these regions), Spain (6 regions; straw makes 45–70% of the potential in these regions except for one specific region with high biodegradable municipal waste), Finland (11 regions; forestry residues making 65–99% of the potential in these regions), France (25 regions; straw makes 60–90% except in 3 regions with high forestry residues), Hungary (2 regions; straw makes ca. 70% of the potential), Italy (2 regions; 65% straw), Latvia (2 regions; more than 80% from forestry residues), Poland (5 regions; straw and forestry residues combined represents more than 80% of the potential), Romania (1 region; straw makes 75% of the potential), Sweden (11 regions, forestry residues make 65–98% of the potential, except for 1 region with a high straw potential), Slovakia (1 region, the potential is 75% from straw) and the United Kingdom (1 region, the potential is 90% from straw).

The highest biomass concentration is found in the NUTS-3 region of Paris (France) with ca. 25 TJ km^{-2}, mostly reflecting the biodegradable municipal waste potential. This highlights opportunities for the management of this resource in that region. Except for that region, total residual biomass concentrations per NUTS-3 are in average 3 TJ km^{-2}. Only a few regions present densities that are more than twice this average, namely: Austria (1 region; ca. 80% is BioMW), Belgium (2 regions, 90% BioMW in one case and 70% manure in the other case), Switzerland (1 region; ca. 80% BioMW), Germany (4 regions, 3 where BioMW is at least 60%), France (4 regions, BioMW is at least 85% for all), Italy (4 regions, 3 where straw is at least 75%), Romania (1 region, BioMW is 90%), and the United Kingdom (2 regions, both where BioMW is ca. 95%).

Overall, straw and forestry residues are the most important residual biomass streams, representing 44% and 38% of the total, respectively, on a PJ basis (Table 3). At the NUTS-3 level, they are also the most important biomasses. Concentration-wise, straw and forestry residues represent more than 60% of the concentration for 19% and 18% of the NUTS-3 regions, respectively. They are thus the most concentrated streams, followed by BioMW (representing more than 60% of the concentration in 7% of the NUTS-3 inventoried). For all other streams, this

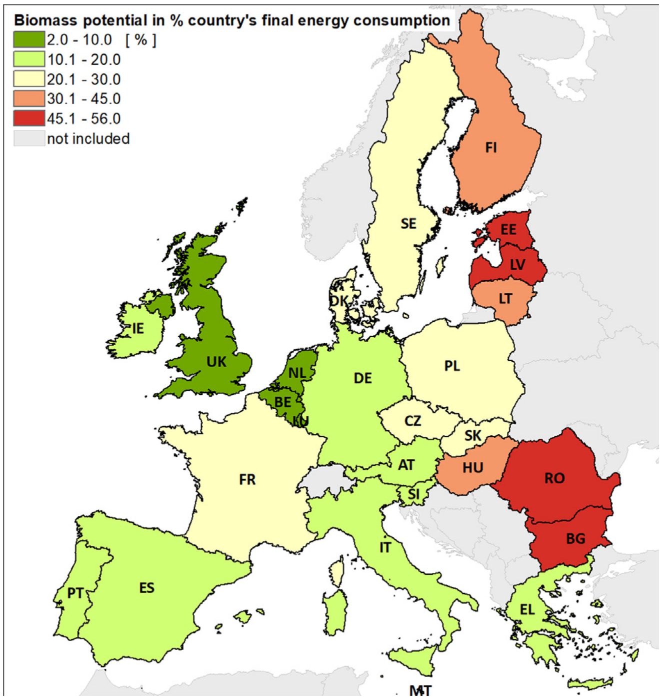

Fig. 9. Total residual potential aggregated per country, expressed as a percentage of the final energy consumption in each country for the reference year 2010. "Not included" represents the regions out of the assessment scope.

(i.e. a stream representing at least 60% of the concentration in a given NUTS-3) happens for less than 1% of the NUTS-3 inventoried. In other words, the concentration of these streams is negligible, in comparison to that of the other residues inventoried. In a bioeconomy perspective, these would likely find attractiveness mostly in combination with other streams.

In Fig. 9, the residual biomass potentials are aggregated per country, and expressed as a percentage of the final energy consumption in the country (the final energy consumption data were retrieved from Eurostat; to represent 2010, data for year 2011 were used as data are presented for January 1st; [60]). Fig. 9 considers the final energy consumption (i.e. the losses of energy transformation and distribution associated to current energy carriers are not considered) in the endeavour to fairly represent the actual energy demand of countries (i.e. independently of the current energy sources used, among others). In the perspective of local bioeconomy relying on a minimum of biomass imports, Fig. 9 shows the important potential of several countries formerly under the Soviet Union (FSU countries), among others Bulgaria (the theoretical potential represents 56% of the 2010 final energy consumption), Latvia (55%), Romania (49%), Estonia (48%) and Lithuania (45%).

5. Discussion

Our results reveal the importance of residual biomass as a key feedstock for the European bioeconomy: we found that 8500 PJ y^{-1} could be available, which corresponds to the whole annual (2015) energy consumption of Italy and Belgium combined [61] (primary consumption; i.e. including the losses during the transformation and distribution, as opposed to Fig. 9). In terms of final energy consumption, this theoretical residual biomass potential represents 18% of the 2010 final energy consumption of EU-27 countries. In other words, it is not negligible. Of course, our results should be seen as the upper end-of-the-interval (theoretical potentials); no restrictions (environmental, economic, competing uses, etc.) are applied on these potentials.

Straw (3800 PJ y^{-1}), for example, is one residue already required for animal feeding, animal bedding and mushroom production, among others. Yet, agricultural residues at the same time play a major role in preserving the long-term soil quality, in particular as they are a key input of carbon to soils. Scarlat et al. [32], for example, suggest sustainable rates of residue removal varying between 15% and 60% for cereal straw (the authors use 40%), 30–60% for sunflower straw (the authors use 50%) and 30–50% for rapeseed straw (the authors use 50%). Considering this and other competing uses, [32] estimated an average EU (sustainable) straw potential of 1530 PJ y^{-1}, ca. a third of the potential found in the present study (Table 3).

Our estimate for straw potential is close to the estimates previously published. The theoretical crop residues potential estimated by Scarlat et al. [32], for example, amounts to 3600–5500 PJ y^{-1} (with 1998–2007 as a time scope, considering a LHV of 18 GJ t^{-1} dry matter). Similarly, the theoretical potential (3700 PJ y^{-1}) calculated by Monforti et al. [33] for 2000–2009, also on the basis of the methodology and functional RPR of [32], is very close to the total crop residue potential assessed herein. Further, their geographical (density) results are quite comparable to those presented in Fig. 4 (i.e. same geographical hot spots). The theoretical potential evaluated by Nikolaou et al. [18] (3200 PJ y^{-1}; derived by aggregating individual country estimates) for 2000 is also close to our estimate. The estimate of [18], however, includes pruning residues. Esteban & Carrasco [25], on the other hand, found a theoretical straw potential ca. 1000 PJ higher than the one found herein, using data for 1996–2003.

Besides the different time spans, reasons for the differences between the studies include the broadness of included residues (oat and mixed cereals are seldom included) and the different RPR considered, although many studies post-2010 (e.g. [33,40,62]; this study) appear to use the RPR functions published by Scarlat et al. [32] as a basis. Yet, the functional RPR of [32] are logarithmic, and as illustrated in [34], these fail to represent the expected decrease in RPR as crop yield increases (since higher yields typically result in the improvement of the harvestable component rather than the residue component). Moreover, [25] used fixed RPRs, with an attempt to make distinctions between countries.

One arguable limitation of the present study is the use of average functional RPR (harvest index) figures for each crop type, rather than region-specific RPRs (although regional differences could be captured by the different yield for these crops). Nevertheless, the model applied is fully customizable in order to account for local differences, as data are available. This enhancement (i.e. regional RPRs functions) is regarded as a next step to improve the resource assessment model presented herein. Furthermore, it should be highlighted that although acknowledged as the most abundant crop residue, straw from cereal and oilseed crops is not the only type of crop residue. Residues from sugar, root, tuber, protein and fibre crops could also be considered, as well as fruits and vegetable residues. This was done in [34] at the EU-28 level, resulting in a theoretical potential slightly less than twice the one estimated herein for straw (6800 PJ y^{-1}; average for the time scope 2000–2013, considering a LHV of 18 GJ t^{-1} dry matter). This reflects the seamingly non-negligible importance of these other crop residue streams, and neglecting these would fail to reflect possible synergies at the regional level (e.g. some regions of the Netherlands with high sugarbeet density, at least prior to 2017). Nonetheless, crop residues can be highlighted as one of the most important bioeconomy feedstocks for EU-27, whether it is for fuel production (e.g. 2nd generation bioethanol), for heat and electricity (e.g. pellets for combined heat and power plants), for gas (e.g. co-digestion for bio-methane production), as a source of fibre for insulation materials, or as a building block for a variety of applications (e.g. mono-ethylene glycol for bio-plastics). Further, for assessments striving to assess the"available" potential, it should be remembered that a considerable share of the straw needed for animal bedding will reappear as"deep litter" manure (i.e. manure mixed with straw). This may not involve a large change on a cumulative energy basis (i.e. in PJ), but will involve the generation of a new product with its own biochemical properties, for which the most suitable conversion pathways may be different than for straw and manure considered individually.

Manure was shown as a key resource for some regions with high animal production density (Fig. 4), albeit not amongst the most important biomass streams, both at the regional and aggregated EU-27 level (Table 3). However, when found in high concentration, manure is often seen as a problematic waste management challenge. The main bioeconomy use of manure is typically as a source of fertilizer. Yet, there are high synergies in using it for anaerobic digestion first, since at least two products are simultaneously obtained (production of biogas/biomethane and of fertilizers in the form of a digestate). In fact, after anaerobic digestion, the digested manure is most commonly used as a fertilizer on fields (in the same way as raw manure); the macro-nutrients (nitrogen, phosphorus and potassium) are typically conserved during the digestion process [9]. Besides, the fertilizer value of nitrogen is enhanced, since the digestion process converts a great share of the organic nitrogen into inorganic nitrogen than can be used directly by the plants. Nevertheless, the European Biogas Association (EBA) indicates that only 3.3% of the overall manure generated in the EU was used for biogas production in 2016 [35]. Anaerobic digestion appears as an obvious bioeconomy pathway to favour for residual biomass in regions with the highest manure concentration (found in two countries, namely Belgium: Tielt, Ieper, Diksmuide, Roeselare; and the Netherlands: Noordoost-Noord-Brabant, Zuidoost-Noord-Brabant, Noord-Limburg), besides being amongst the most efficient mitigation technologies for manure management [63–65]. In other words, the availability of manure in these regions may drive the other residues towards anaerobic digestion as a main bioeconomy pathway. Although most of the current biogas plants operate with a mix of substrates dominated by energy crops, recent and upcoming legislative changes are expected to promote the use of manure and residues [64]. The total manure potential found in this study (560 PJ y^{-1}; Table 3) is sligthly below the potential estimated in earlier studies (e.g. 765 PJ y^{-1} in [66]). It is interesting to note that the only study relying on data from econometric models (CAPRI and GAINS, the latter for animal excretion rates only) [10], in which only areas above 170 kg N ha^{-1} are considered, presents an extreme estimate (2380 PJ y^{-1}) in comparison to the above-mentioned bio-physical studies.

Forestry residues (3200 PJ y^{-1}) were shown as the second most important residual biomass resource generated in the European regions (Table 3; Fig. 7). This is in the same magnitude as the estimate reported in [28], and slightly above the estimates from [25,27,31] (all above 1000 PJ y^{-1}). In the earlier study of [18] (reference year 2000), a theoretical potential of 960 PJ y^{-1} is reported (obtained through aggregating individual country results), while an available potential (i.e. with restrictions; reference year 2010) of 850 PJ y^{-1} is presented in [10]. Bentsen and Felby [15], in their review of published estimates for selected streams, highlighted forestry residues as the biomass stream with the highest variation, with estimates between 800 and 6000 PJ y^{-1}. The authors [15] explain that one reason for the divergence between published estimates is the exact fraction included. In our study, stumps are included, but the potential from the so-called unutilized stem wood net increment was excluded. With the EU ambition to achieve greenhouse gas reductions of 40% by 2030 (compared to 1990 levels) [5], forestry residues is seen as a key residual biomass stream in the coming years. In particular for coal-based power plant, the shift of feedstock from coal towards woody biomass involves a minimum of investment [67] and may be seen as highly attractive in the coming years [68]. Other trends in the bio- and circular economy may also trigger new demands for this stream, for example as a storable combustible feedstock for those municipal waste incineration plants which are under capacity (i.e. not enough waste is available to supply the heat & power that the incineration plants are obliged to supply due to binding contracts). In fact, as recycling and biowaste recovery are increasing (as a consequence, among others, of the targets proposed in the EU Circular Economy Package; 65% recycling of municipal waste by 2030 [5]), and as newly built (and older) municipal incineration plants have long-term obligations in terms of heat and electricity to deliver, forestry residues may be seen as a cheap and valuable feedstock to supply the missing energy.

BioMW, herein estimated to 600 PJ y^{-1}, was also quantified to 600 PJ y^{-1} by [17] (for year 1995). Higher estimates were derived by [29] with ca. 1000 PJ y^{-1}, by [28] (1100 PJ y^{-1}), and by [10] to 1200 PJ y^{-1}. As for the other streams assessed in this study, the estimate of [18] is significantly lower at 300 PJ y^{-1}. This is due to the fact that [18] only considers the share of organic waste going to incineration (and thus ignores the BioMW undergoing other fates). Although BioMW here represents only 7% of the total residual potential, the geo-localized approach applied in our study highlights the importance of this stream at the regional level, in particular in the case of populated cities where it is highly concentrated. The NUTS-3 region of Paris, among others, where the highest concentration of both BioMW and residues from the management of urban green areas is found, shows a great potential for urban bioeconomy. Some key bioeconomy pathways with this stream involve anaerobic digestion, the recovery of protein and carbohydrates for animal feed, the recovery of platform molecules (also called building blocks; e.g. lactic acid) for a variety of application (food, cosmetics, bio-plastics, etc.), or a combination of these applications. Other so-called “lower value” application could include composting. Of course, the pre-condition to fully harness the potential of this stream is the efficient recovery of the organic stream from the residual municipal waste, whether through separate or central collection schemes. Assessing this, however, was besides the scope of the present study, although it is key to building integrated bio- and circular economy strategies in urban areas.

For roadside vegetation, Elbersen et al. [10] obtained half our estimate (45 PJ y^{-1}; technical potential). No other estimates were found at the EU-27 level for this stream. Besides the fact that the estimate of [10] is a technical potential, the differences may be explained by their rougher estimation for the primary- and trunk roads outside The Netherlands, as well as their omission of grass along railways (although this is not clear).

The AIW estimate found in this study (80 PJ y^{-1}) focussed on two types of waste only, namely the pomace resulting from processing olives and grapes. This is, as expected, much below other estimates reported for this type of waste ([69], for example, reports twice as much). In fact, the biowaste of food industries also include a variety of other streams, such as beet pulp, molasses, waste malt, meal, whey, waste from other fruit and vegetables processing. Further, our analysis only focussed on pomace, but the wine industry, in the case of grapes, involves many more waste streams that could be used for bioeconomy, as detailed in [70]. Moreover, our analysis endeavoured to exclude the grapes and olives exported from the EU, however, it looked at exports at the country level and without distinguishing if it was intra- or extra-European. This is another potential source of underestimation of AIW in this study. Nevertheless, our analysis revealed regional opportunities. Jaen (Spain) is the main region of olive oil in the world [71], and was highlighted as the most dense region for both AIW and pruning residues, indicating synergies potential for that region. Finally, it must be stressed that a great share of AIW is already used for the food (e.g. pomace olive oil, grappa) and feed industry (whey, brewer grains, beet pulp), and diverting these already used AIW residues from food/feed to other bioeconomy uses typically translates into negative environmental impacts, as shown in e.g. [8].

Pruning residues (150 PJ) estimates appear low in this study compared to the potentials reported in other studies. Elbersen et al. [10], for example, report a sustainable potential of 390 PJ y^{-1} (reference year 2004), and account for similar crops as we did herein. The key difference between both studies is the methodology. While we based our assessment on the CORINE land cover for permanent plantations combined with NPP data, Elbersen et al. [10] used cropping areas from the

CAPRI database and combined it with residues yield estimates for a variety of crops. This, again, highlights the potential variation in results stemming from bio-physical versus econometric approaches.

One potentially important missing residue is the unharvested cut grass from semi-natural grasslands. With the decreasing number of grazers kept outside stable in the EU, mowing semi-natural grassland areas could not only supply an additional residual stream for bioeconomy, but also improve the biodiversity value of these areas through decreasing the supply of nutrients (the oversupply of nutrients favour the dominance of a few species) [72]. Elbersen et al. [10] forecasted 150 PJ y^{-1} from abandoned agricultural grassland to be available in 2020, which is in the same order of magnitude as our estimate for pruning residues (Table 3). Meyer [73] estimated the potential from surplus grass from rotational and permanent grasslands as well as meadows in the EU-27 (in 2015) to vary from 45 to up to 250 PJ y^{-1}. The wide range reflects the assumptions used to evaluate the surplus. Marine residues (seaweed), similarly, are subject to growing interest and their inclusion is an obvious next step towards improving the completeness of existing assessments.

The estimation methodology used for several categories of residues relied on the CORINE land cover (CLC2006; minimum mapping unit of 25 ha). As shown by different studies (e.g. [74–76]), improved land cover maps (i.e. improved accuracy of the classification) can now be made through the use of higher resolution data from the Sentinel satellites launched in 2014 (Sentinel-1A and Sentinel-2, among others; 10–60 m spatial resolution). The present estimations could thus be fine-tuned through the use of revised land cover maps based on the so-called “high resolution layers” and “very high resolution imagery” from Sentinel-1A and Sentinel-2, as these improved land cover maps become available.

Another obvious next step is the geo-localized assessment of the competing (current and future) uses. Similarly, introducing a dynamic component on top of the geo-localized one would introduce an additional level of information support, as some streams are available at certain points of the year only (e.g. crop residues), while others are available more constantly (e.g. agri-industrial waste). Equally important would be introducing the dimension of the feedstock properties (quality; water content, heavy metal or corrosive element content, etc.), since some highly specialized conversion processes require specific and stable feedstock [34]. On that basis, integrated bioeconomy strategies which fully take advantage of the available resources, options for storage and cost optimization could be built. Moreover, building state-of-the-art strategies would require the exercise to be repeated with prospective assessments and scenarios.

6. Conclusion

The main contributions of this study can be summarized as follows:

- A geo-localized assessment method was developed and allowed to estimate the theoretical residual biomass potential of 8 key residual streams at the NUTS-3 level, for EU-27, with 2010 as the temporal scope. Such geo-localized assessment revealed general trends as well as specific regional trends requiring different biomass management strategies. This cannot be captured with rougher aggregations made at the country level.
- The theoretical potential for residual biomass was estimated to 8500 PJ y^{-1}, which corresponds to the whole annual (2015) primary energy consumption of Italy and Belgium combined. Straw (3800 PJ y^{-1}) and forestry residues (3200 PJ y^{-1}) are the two most important streams. They are also the two most concentrated streams (in TJ km^{-2}) at the NUTS-3 level, followed by municipal biowaste.
- The key regional highlights are: (i) the highest biomass concentration is found in the NUTS-3 region of Paris (France) with ca. 25 TJ km^{-2}, mostly reflecting the biodegradable municipal waste potential; and (ii) Jaen (Spain) is the main region of olive oil in the world, and was highlighted as the most dense region for both agri-industrial biowaste and pruning residues.
- The regions with the greatest amount of available residues (above 20 PJ y^{-1}) are found in 13 countries, namely: Czech Republic (5 regions), Denmark (5 regions), Spain (6 regions), Finland (11 regions), France (25 regions), Hungary (2 regions), Italy (2 regions), Latvia (2 regions), Poland (5 regions), Romania (1 region), Sweden (11 regions), Slovakia (1 region) and the United Kingdom (1 region).
- In the endeavour of building sustainable bioeconomy strategies, one of the most important addition to this study is to identify, for each NUTS-3 regions and residual biomass streams, the current and future use of the residual biomass (so-called counter-factual).
- The study includes a number of limitations. A major one relates to the methodology used to estimate crop residues. First, it only includes straw from cereals and oilseed crops and completely disregards other streams belonging to this category (e.g. from fruit & vegetables, sugar, roots, tubers). Second, it uses, for each crop, residues-to-product-ratios (RPR) that are averaged at the country level, rather than considering regional RPRs. Other limitations include the limited scope considered for agri-industrial waste (limited to pomace from processing olives and grapes), as well as the reliance upon the CLC2006 land cover maps (higher resolution cover maps will, within the next years, become available through the use of the Sentinel data). Finally, potentially important streams such as the unharvested cut grass from EU semi-natural grasslands or residual seaweed were not included in the assessment.

Acknowledgements

This paper was written based on research results from the project BioBoost, Supported under the 7th Framework Programme of the European Commission under Contract 2882873. Funding for additional analysis and relations to bioeconomy was supplied through the Horizon 2020 research project “New Strategies on Bioeconomy in Poland”, funded by the European Commission under Grant agreement 669062. At the time of finalizing the paper, the lead author was funded by the Cambioscop project, supported by the French National Research Agency, Programme Investissement d’Avenir (ANR-17-MGPA-0006). All these sponsors had no involvement in the study.

Competing interests statement

The authors declare no competing interests.

References

[1] KPMG. Sustainable Insight. Expect the unexpected: building business value in a changing world; 2012. 〈https://home.kpmg.com/content/dam/kpmg/pdf/2012/08/building-business-value-part-1.pdf〉 [Accessed 13 September 2018].

[2] WEF. Global risks report 2017 - reports - World Economic Forum. 2017 [Accessed 13 September 2018]. 〈http://reports.weforum.org/global-risks-2017/〉.

[3] PWC. The World in 2050. The long view: how will the global economic order change by 2050?; 2017. 〈https://www.pwc.com/gx/en/issues/economy/the-world-in-2050.html〉, [Accessed 13 September 2018].

[4] European Commission. Innovating for sustainable growth - a bioeconomy for Europe; 2012. 〈http://dx.doi.org/10.2777/6462〉. 〈https://publications.europa.eu/en/publication-detail/-/publication/1f0d8515-8dc0-4435-ba53-9570e47dbd51〉, [Accessed 26 June 2017].

[5] Ronzon T, Lusser M, Klinkenberg M, Landa L, Sanchez Lopez J, M’Barek R, et al. Bioeconomy report 2016. JRC scientific and policy report [EUR 28468 EN]. 2017 [Accessed 26 June 2017]. 〈http://online.liebertpub.com/doi/10.1089/ind.2017.29078.tro〉.

[6] Kluts I, Wicke B, Leemans R, Faaij A. Sustainability constraints in determining European bioenergy potential: a review of existing studies and steps forward. Renew Sustain Energy Rev 2017;69:719–34. https://doi.org/10.1016/j.rser.2016.11.036.

[7] Haase M, Rösch C, Ketzer D. GIS-based assessment of sustainable crop residue potentials in European regions. Biomass Bioenergy 2016;86:156–71. https://doi.org/10.1016/j.biombioe.2016.01.020.

[8] Tonini D, Hamelin L, Astrup TF. Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes. GCB Bioenergy 2016:8. https://doi.org/10.1111/gcbb.12290.

[9] Hamelin L, Naroznova I, Wenzel H. Environmental consequences of different carbon alternatives for increased manure-based biogas. Appl Energy 2014;114:774–82. https://doi.org/10.1016/j.apenergy.2013.09.033.

[10] Elbersen B, Startisky I, Hengeveld G, Schelhaas M-J, Naeff H, Bottcher H. Atlas of EU biomass potentials; 2012. ⟨http://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/biomass_futures_atlas_of_technical_and_economic_biomass_potential_en.pdf⟩, [Accessed 13 September 2018].

[11] OECD/IEA F. How2Guide for Bioenergy. Roadmap Development and Implementation; 2017. ⟨http://dx.doi.org/ISBN978-92-5-109586-7⟩. ⟨https://www.iea.org/publications/freepublications/publication/How2GuideforBioenergyRoadmapDevelopmentandImplementation.pdf⟩, [Accessed 13 September 2018].

[12] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials—methodological lessons from review of state of the art bioenergy potential assessments. Renew Sustain Energy Rev 2012;16:6598–630. https://doi.org/10.1016/j.rser.2012.09.002.

[13] Eurostat. glossary: EU enlargements – statistics explained; 2014. ⟨https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:EU_enlargements⟩, [Accessed 13 September 2018].

[14] Eurostat. Regions in the European Union: nomenclature of territorial units for statistics NUTS 2013/EU-28. Luxemburg; 2015. ⟨http://dx.doi.org/10.2785/15544⟩. ⟨http://ec.europa.eu/eurostat/documents/3859598/6948381/KS-GQ-14-006-EN-N.pdf/b9ba3339-b121-4775-9991-d88e807628e3⟩, [Accessed 13 September 2018].

[15] Bentsen NS, Felby C. Biomass for energy in the European Union – a review of bioenergy resource assessments. Biotechnol Biofuels 2012;5:25. https://doi.org/10.1186/1754-6834-5-25.

[16] Fischer G, Schrattenholzer L. Global bioenergy potentials through 2050. Biomass Bioenergy 2001;20:151–9. https://doi.org/10.1016/S0961-9534(00)00074-X.

[17] European Environment Agency. Biodegradable municipal waste management in Europe. Copenhagen and Aarhus, Denmark; 2002. ⟨https://www.eea.europa.eu/publications/topic_report_2001_15_Part1⟩, [accessed 13 September 2018].

[18] Nikolaou A, Remrova M, Jeliazkov I. Biomass availability in Europe; 2003. ⟨https://np-net.pbworks.com/f/CRES + (2003) + Biomass + availability + in + EU.pdf⟩, [accessed 13 September 2018].

[19] Siemons R, Vis M, Van den Berg D, Mc Chesney I, Whiteley M, Nikolaou N. Bioenergy's role in the EU Energy market. A view of developments until 2020. Enshcede, the Netherlands; 2004. ⟨http://www.cleanfuels.nl/Sitepdfs/Bioenergy%27sRoleintheEUEnergyMarket,AViewofDevelopmentsuntil2020.pdf⟩, [Accessed 13 September 2018].

[20] de Noord M, Beurskens L, de Vries H. Potentials and costs for renewable electricity generation. A data overview; 2004. ⟨https://www.ecn.nl/docs/library/report/2003/c03006.pdf⟩, [Accessed 13 September 2018].

[21] Edwards RAH, Šúri M, Huld TA, Dallemand JF. GIS-based assessment of cereal straw energy resource in the European Union. In: Proceedings 14th Eur. biomass conference exhib. ETA-renewable energies WIP-renewable energies; 2005. ⟨https://iet.jrc.ec.europa.eu/remea/gis-based-assessment-cereal-straw-energy-resource-european-union⟩, [Accessed 13 September 2018].

[22] Thrän D, Weber M, Scheuermann A, Fröhlich N, Zeddies J, Henze A, et al. Sustainable Strategies for Biomass Use in the European Context. Analysis in the charged debate on national guidelines and the competition between solid, liquid and gaseous biofuels; 2005. ⟨http://iinas.org/tl_files/iinas/downloads/bio/oeko/2005_EU-25_Biotrade-EN.pdf⟩, [Accessed 13 September 2018].

[23] Ericsson K, Nilsson LJ. Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass Bioenergy 2006;30:1–15. https://doi.org/10.1016/j.biombioe.2005.09.001.

[24] European Environment Agency. Environmentally compatible bio-energy potential from European forests. Copenhagen, DK; 2007. ⟨http://www2.gip-ecofor.org/doc/libre/EEA_environmentally_2007.pdf⟩, [Accessed 13 September 2018].

[25] Esteban LS, Carrasco JE. Biomass resources and costs: assessment in different EU countries. Biomass Bioenergy 2011;35:S21–30. https://doi.org/10.1016/j.biombioe.2011.03.045.

[26] Kunikowski G, Wróbel A, Rutkowska-Filipczak M, Gańko E. Residue biomass potential inventory results; 2006. ⟨http://www.renew-fuel.com/download.php?dl = del_sp5_wp1_5-1-3-methodology_07-01-05_ecbrec.pdf&kat = 13%5Cnfiles/541/del_sp5_wp1_5-1-3-methodology_07-01-05_ecbrec.pdf⟩, [Accessed 13 September 2018].

[27] Asikainen A, Liiri H, Peltola S, Karjalainen T, Laitila J. Forest Energy Potential in Europe (EU27), Vol. 69. Helsinki; 2008. ⟨http://www.metla.fi/julkaisut/workingpapers/2008/mwp069.htm⟩, [Accessed 13 September 2018].

[28] Bottcher H, Dees M, Fritz SM, Goltsev V, Gunia K, Huck I, et al. Biomass Energy Europe: Illustration Case for Europe; 2010. ⟨http://www.eu-bee.eu/defaulta721.html?SivuID = 24158⟩, [Accessed 13 September 2018].

[29] Panoutsou C, Eleftheriadis J, Nikolaou A. Biomass supply in EU27 from 2010 to 2030. Energy Policy 2009;37:5675–86. https://doi.org/10.1016/j.enpol.2009.08.032.

[30] Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M, et al. Biofuel production potentials in Europe: sustainable use of cultivated land and pastures, Part II: land use scenarios. Biomass Bioenergy 2010;34:173–87. https://doi.org/10.1016/j.biombioe.2009.07.009.

[31] Mantau U, Saal U, Prins K, Steierer F, Lindner M, Verkerk H, et al. EUwood – real potential for changes in growth and use of EU forests. Final report. 2010 [Accessed 13 September 2018]. ⟨https://www.egger.com/downloads/bildarchiv/187000/1_187099_DV_Real-potential-changes-growth_EN.pdf⟩.

[32] Scarlat N, Martinov M, Dallemand J-FF. Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. Waste Manag 2010;30:1889–97. https://doi.org/10.1016/j.wasman.2010.04.016.

[33] Monforti F, Bódis K, Scarlat N, Dallemand J-F. The possible contribution of agricultural crop residues to renewable energy targets in Europe: a spatially explicit study. Renew Sustain Energy Rev 2013;19:666–77. https://doi.org/10.1016/j.rser.2012.11.060.

[34] Ronzon T, Piotrowski S. Are primary agricultural residues promising feedstock for the European bioeconomy? Ind Biotechnol 2017;13:113–27. https://doi.org/10.1089/ind.2017.29078.tro.

[35] Lukas P. Potential biomethane production in Europe. The role of renewable gases in a smart low-carbon energy system; 2016. ⟨http://www.geode-eu.org/uploads/GEODEGermany/DOCUMENTS2016/EUSEWpresentationPHL.pdf⟩, [Accessed 13 September 2018].

[36] Eurostat. Agri-environmental indicator – livestock patterns – statistics explained; 2017. ⟨http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_livestock_patterns⟩, [Accessed 26 May 2017].

[37] Vis MW, van den Berg D, et al. Anttila P, Böttcher H, Dees M, Domac J. Biomass Energy Europe, Harmonization of biomass resource assessments. Best practices and methods handbook. Biomass Energy Europe, Harmonization of biomass resource assessments I. 2010. p. 1–220 [Accessed 13 September 2018]. ⟨http://www.uvm.edu/~cdl/2012workshop/BEE%20Biomass%20Methods%20Handbook%202010.pdf⟩.

[38] Eurostat. Glossary: Livestock unit (LSU) – statistics Explained; 2013. ⟨http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Livestock_unit_(LSU)⟩, [Accessed 26 May 2017].

[39] ECN. Phyllis2 - database for biomass and waste. Energy Res Cent Netherlands; 2012. ⟨https://www.ecn.nl/phyllis2/⟩, [Accessed 26 May 2017].

[40] Spöttle M, Alberici S, Toop G, Peters D, Gamba L, Ping S, et al. Low ILUC potential of wastes and residues for biofuels. Utrecht, The Netherlands: Straw, forestry residues, UCO, corn cobs; 2013⟨https://www.ecofys.com/files/files/ecofys-2013-low-iluc-potential-of-wastes-and-residues.pdf⟩ [Accessed 13 September 2018].

[41] Eurostat. Agriculture. Data. Database; 2017. ⟨http://ec.europa.eu/eurostat/web/agriculture/data/database⟩, [Accessed 26 May 2017].

[42] Sommer SG, Hamelin L, Olesen JE, Montes F, Jia W, Chen Q, et al. Agricultural waste biomass. Supply chain manag. sustain. food networks. Chichester, UK: John Wiley & Sons, Ltd.; 2015. p. 67–106. https://doi.org/10.1002/9781118937495.ch3.

[43] Hamelin L, Jørgensen U, Petersen BM, Olesen JE, Wenzel H. Modelling the carbon and nitrogen balances of direct land use changes from energy crops in Denmark: a consequential life cycle inventory. GCB Bioenergy 2012:4. https://doi.org/10.1111/j.1757-1707.2012.01174.x.

[44] Bentsen NS, Felby C, Thorsen BJ. Agricultural residue production and potentials for energy and materials services. Prog Energy Combust Sci 2014;40:59–73. https://doi.org/10.1016/j.pecs.2013.09.003.

[45] Harasim A. Gospodarowanie słomą [straw management]. Pulawy: Wydawnictwo IUNG-PIB; 2011.

[46] European Environment Agency. Corine Land Cover 2006 raster data. Version 16 (04/2012); 2015. ⟨https://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2⟩, [Accessed 26 June 2017].

[47] Wißkirchen K, Tum M, Günther KP, Niklaus M, Eisfelder C, Knorr W. Quantifying the carbon uptake by vegetation for Europe on a 1 km^2 resolution using a remote sensing driven vegetation model. Geosci Model Dev 2013;6:1623–40. https://doi.org/10.5194/gmd-6-1623-2013.

[48] Tum M, Günther KP. Validating modelled NPP using statistical yield data. Biomass Bioenergy 2011;35:4665–74. https://doi.org/10.1016/j.biombioe.2011.09.015.

[49] Montanaro G, Tuzio AC, Xylogiannis E, Kolimenakis A, Dichio B. Carbon budget in a Mediterranean peach orchard under different management practices. Agric Ecosyst Environ 2017;238:104–13. https://doi.org/10.1016/j.agee.2016.05.031.

[50] IPCC. Chapter 4: forest land. In: 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: agriculture, forestry and other land use; 2006. ⟨https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html⟩, [Accessed 13 September 2018].

[51] Voivontas D, Assimacopoulos D, Koukios EG. Assessment of biomass potential for power production: a GIS based method. Biomass Bioenergy 2001;20:101–12. https://doi.org/10.1016/S0961-9534(00)00070-2.

[52] IPCC. Good Practice Guidance for Land Use, Land-Use Change and Forestry; 2003. ⟨https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html⟩, [Accessed 13 September 2018].

[53] UNECE/FAO. Forest product conversion factors for the UNECE region. Geneva timber and forest discussion paper 49. ECE/TIM/DP/49; 2010. ⟨https://www.unece.org/fileadmin/DAM/timber/publications/DP-49.pdf⟩, [Accessed 13 September 2018].

[54] Eurostat. Database. Dataset (env_wasmun); 2017. ⟨http://ec.europa.eu/eurostat/data/database⟩, [Accessed 27 July 2017].

[55] UN. United Nations Statistics Division - Environment Statistics. Waste. Municipal waste collection; 2011. ⟨https://unstats.un.org/unsd/environment/municipalwaste.htm⟩, [Accessed 27 July 2017].

[56] ESRI. Europe Population Density; 2017. ⟨http://www.arcgis.com/home/item.html?id = cf3c8303e85748b5bc097cdbb5d39c31⟩, [Accessed 27 July 2017].

[57] Harmelink M, Voogt M, Joosen S, de jager D, Palmers G, Shaw S, et al. Pretir. Implementation of renewable energy in the European Union until 2010; 2002. ⟨http://harmelinkconsulting.nl/files/2015-09/harmelinkconsulting-29cb09dfcb43407e2dd22f7551b12075-pretir-implementation-of-renewable-energ.pdf⟩, [Accessed 13 September 2018].

[58] Di Blasi C, Tanzi V, Lanzetta M. A study on the production of agricultural residues in Italy. Biomass Bioenergy 1997;12:321–31. https://doi.org/10.1016/S0961-9534(96)00073-6.

[59] Mahro B, Timm M. Potential of biowaste from the food industry as a biomass resource. Eng Life Sci 2007;7:457–68. https://doi.org/10.1002/elsc.200620206.

[60] Eurostat. Final energy consumption (sdg_07_11); 2018. ⟨https://ec.europa.eu/eurostat/tgm/table.do?tab = table&init = 1&language = en&pcode = sdg_07_11&plugin = 1⟩, [Accessed 12 October 2018].

[61] Eurostat. Consumption of energy – statistics explained; 2017. ⟨http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy#Further_Eurostat_information⟩, [Accessed 29 June 2017].

[62] Daioglou V, Stehfest E, Wicke B, Faaij A, van Vuuren DP. Projections of the availability and cost of residues from agriculture and forestry. GCB Bioenergy 2016;8:456–70. https://doi.org/10.1111/gcbb.12285.

[63] Hamelin L, Wesnæs M, Wenzel H, Petersen BM. Environmental consequences of future biogas technologies based on separated slurry. Environ Sci Technol 2011;45:5869–77. https://doi.org/10.1021/es200273j.

[64] Giuntoli J, Agostini A, Caserini S, Lugato E, Baxter D, Marelli L. Climate change impacts of power generation from residual biomass. Biomass Bioenergy 2016;89:146–58. https://doi.org/10.1016/j.biombioe.2016.02.024.

[65] Pellerin S, Bamière L, Angers D, Béline F, Benoit M, Butault J-P, et al. Identifying cost-competitive greenhouse gas mitigation potential of French agriculture. Environ Sci Policy 2017;77:130–9. https://doi.org/10.1016/J.ENVSCI.2017.08.003.

[66] Bottcher H. Biomass energy Europe – summary report on illustration cases. Deliverable 6.1. 2010 [Accessed 13 September 2018]. ⟨http://www.eu-bee.eu/defaulta721.html?SivuID = 24158⟩.

[67] Wenzel H, Høibye L, Duban Grandal R, Hamelin L, Bird DN, Olesen A. Carbon footprint of bioenergy pathways for the future Danish energy system; 2014. ⟨https://ens.dk/sites/ens.dk/files/Bioenergi/carbon_footprint_of_bioeneergy_pathways_for_the_future_danish_energy_system_-_final_210314_l.pdf⟩, [Accessed 13 September 2018].

[68] DONG Energy. DONG Energy to stop all use of coal by 2023; 2017. ⟨http://www.dongenergy.com/en/media/newsroom/news/articles/dong-energy-to-stop-all-use-of-coal-by-2023⟩, [Accessed 30 June 2017].

[69] Scarlat N, Dallemand J-F, Banja M. Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. Renew Sustain Energy Rev 2013;18:595–606. https://doi.org/10.1016/j.rser.2012.10.040.

[70] Zacharof M-P. Grape winery waste as feedstock for bioconversions: applying the biorefinery concept. Waste Biomass Valoriz 2017;8:1011–25. https://doi.org/10.1007/s12649-016-9674-2.

[71] Anatoliki SA. Market of olive residues for energy. Deliverable 3.2; 2008. ⟨https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/m.o.r.e._swot_analyses_on_use_of_solid_olive_oil_residues_en.pdf⟩, [Accessed 13 September 2018].

[72] Al-Mufti MM, Sydes CL, Furness SB, Grime JP, Band SR. A quantitative analysis of shoot phenology and dominance in herbaceous vegetation. J Ecol 1977;65:759. https://doi.org/10.2307/2259378.

[73] Meyer A. Sustainable biomass resources for biogas production: mapping and analysis of the potential for sustainable biomass utilization in Denmark and Europe. Aalborg, Denmark: Aalborg University; 2015 [Accessed 13 September 2018]. ⟨http://vbn.aau.dk/en/publications/sustainable-biomass-resources-for-biogas-production–mapping-and-analysis-of-the-potential-for-sustainable-biomass-utilization-in-denmark-and-europe(f21de02a-c3cb-495a-a6d3-d5ca9b45e34b).html⟩.

[74] Nguyen DB, Wagner W. European rice cropland mapping with sentinel-1 data: the Mediterranean region case study. Water 2017;9:392. https://doi.org/10.3390/w9060392.

[75] Balzter H, Cole B, Thiel C, Schmullius C, et al. Mapping CORINE land cover from sentinel-1A SAR and SRTM digital elevation model data using random forests. Remote Sens 2015;7:14876–98. https://doi.org/10.3390/rs71114876.

[76] Inglada J, Vincent A, Arias M, Tardy B, Morin D, Rodes I. Operational high resolution land cover map production at the country scale using satellite image time series. Remote Sens 2017;9:95. https://doi.org/10.3390/rs9010095.