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# Geospatial supply–demand modeling of biomass residues for co-firing in European coal power plants

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## Abstract

Biomass co-firing with coal is a near-term option to displace fossil fuels and can facilitate the development of biomass conversion and the build-out of biomass supply infrastructure. A GIS-based modeling framework (EU-28, Norway, and Switzerland) is used to quantify and localize biomass demand for co-firing in coal power plants and agricultural and forest residue supply potentials; supply and demand are then matched based on minimizing the total biomass transport costs (field to gate). Key datasets (e.g., land cover, land use, and wood production) are available at 1,000 m or higher resolution, while some data (e.g., simulated yields) and assumptions (e.g., crop harvest index) have lower resolution and were resampled to allow modeling at 1,000 m resolution. Biomass demand for co-firing is estimated at 184 PJ in 2020, corresponding to an emission reduction of 18 Mt CO<sub>2</sub>. In all countries except Italy and Spain, the sum of the forest and agricultural residues available at less than 300 km from a co-firing plant exceeds the assessed biomass demand. The total cost of transporting residues to these plants is reduced if agricultural residues can be used, as transport distances are shorter. The total volume of forest residues less than 300 km from a co-firing plant corresponds to about half of the assessed biomass demand. Almost 70% of the total biomass demand for co-firing is found in Germany and Poland. The volumes of domestic forest residues in Germany (Poland) available within the cost range 2–5 (1.5–3.5) €/GJ biomass correspond to about 30% (70%) of the biomass demand. The volumes of domestic forest and agricultural residues in Germany (Poland) within the cost range 2–4 (below 2) €/GJ biomass exceed the biomass demand for co-firing. Half of the biomass demand is located within 50 km from ports, indicating that long-distance biomass transport by sea is in many instances an option.

## KEYWORDS

agriculture, bioenergy, CO<sub>2</sub> emissions, co-firing, European Union, forestry, geographic information system, residues

## 1 | INTRODUCTION

The European Union (EU) aims to reduce greenhouse gas (GHG) emissions by reducing fossil fuel use. Bioenergy is

currently the largest renewable energy source used in the EU, and the biomass demand for energy is expected to increase further. Supply-side strategies aim for cost-

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effective and reliable supply systems associated with acceptable social and environmental impacts (Scarlat, Dallemand, Monforti-Ferrario, & Nita, 2015).

Currently, the EU has an installed coal power capacity of 164 GW (2016), which generates 24.5% of the total electricity mix (Eurostat, 2017b). Co-firing biomass in existing coal-fired power plants offers the possibility of significantly increasing the share of biomass through a relatively small boiler-upgrade investment, while maintaining a high conversion efficiency compared to biomass-only plants, in which steam properties are limited due to the risk of alkali-related high-temperature corrosion. Typical co-firing shares—in the order of 10%—reduces the risk of alkali-related high-temperature corrosion. Additionally, risks associated with uncertain biomass supply (shortages or price fluctuations) can be managed by varying the share of co-fired biomass (Berndes, Hansson, Egeskog, & Johnsson, 2010; IEA-ETSAP, 2013). Thus, co-firing biomass in coal plants can provide a near-term biomass market that stimulates the build-out of the biomass supply infrastructure that can facilitate the implementation of other bioenergy options once those technologies are commercially available.

Successful co-firing of forest residues with coal has been demonstrated in the EU (Al-Mansour & Zuwala, 2010), while agricultural residues can be more challenging due to the higher alkali content (e.g., slagging, fouling, and corrosion; Hansson, Berndes, Johnsson, & Kjærstad, 2009). However, Denmark has positive experiences of co-firing straw and coal (Skøtt, 2011; Veijonen, Vainikka, Järvinen, & Alakangas, 2003). Dissemination of the Danish experience may stimulate the increased use of agricultural residues in co-firing, if the costs of fuel reception, storage, and handling facilities for co-firing biomass in baled form can be reduced (IEA Bioenergy, 2016).

Previous studies of the biomass co-firing potential in the EU include Hansson et al. (2009), which assessed biomass co-firing with coal in existing coal-fired power plants in the EU-27, and Bertrand, Dequiedt, and Le Cadre (2014), which matched the demand for biomass-based electricity with the potential biomass supply in Europe. While Hansson et al. (2009) only focused on mapping biomass demand, Bertrand et al. (2014) compared the demand with the supply based on previously published biomass supply estimates at the country level. Higher resolution assessment of biomass demand and supply patterns in Europe can provide a more comprehensive understanding of how the biomass demand for co-firing and other applications can be met.

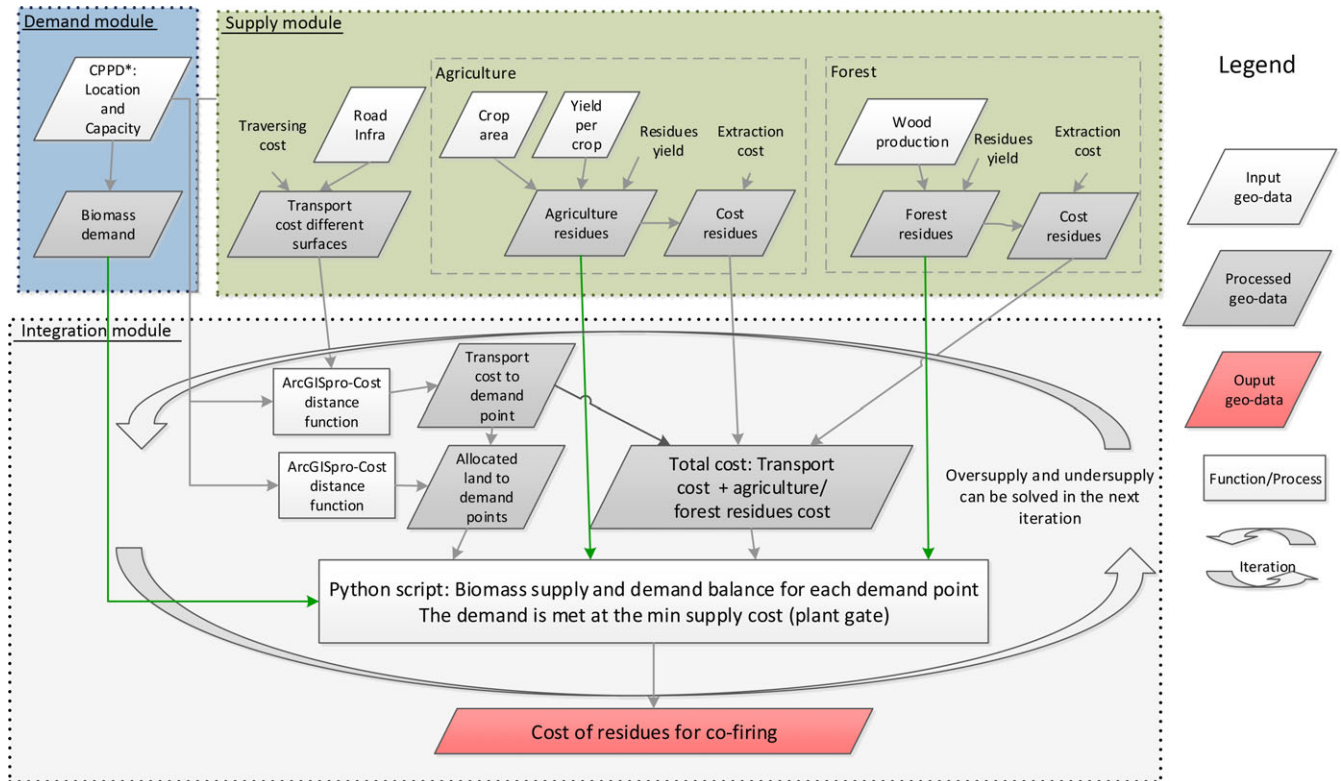
Studies have used geographic information system (GIS) approaches to estimate bioenergy supply potentials in Europe for rapeseed biodiesel systems (van Duren, Voinov, Arodudu, & Firrisa, 2015), crop residues (Haase, Rösch, & Ketzer, 2016; Monforti, Bódis, Scarlat, & Dallemand, 2013; Monforti et al., 2015), forest residues (Díaz-Yáñez,

Mola-Yudego, Anttila, Röser, & Asikainen, 2013), and woody biomass (Verkerk, Anttila, Eggers, Lindner, & Asikainen, 2011). Esteban and Carrasco (2011) assessed agricultural and forest resources and the associated collection costs at the NUTS2 level (Nomenclature of Territorial Units for Statistics level 2). Other GIS-based studies have analyzed biomass supply in relation to biomass demand. Hoefnagels, Searcy, et al. (2014) optimized biomass transport costs to estimate the domestic and international solid biofuel supply volume and cost at demand points in the EU at the NUTS2 level. Di Fulvio, Forsell, Lindroos, Korosuo, and Gusti (2016) assessed woody biomass supply under environmental and economic constraints, to estimate industry gate cost–supply curves, including harvest and transportation costs. Examples at the regional level include Nivala, Anttila, Laitila, Salminen, and Flyktman (2016), which balanced supply and demand for wood chips in Finland by quantifying the biomass available under ecological and technical constraints and within a certain distance from the plant. In Denmark, Nord-Larsen and Talbot (2004) estimated economically available forest resources by considering the location of conversion plants and using marginal cost–supply curves.

We present and demonstrate a GIS-based (1,000 m resolution) modeling framework for assessing and matching biomass demand and supply patterns in the EU. To the best of our knowledge, the framework allows more comprehensive assessments of biomass demand and supply than earlier studies with similar geographic scope (EU-28, Norway, and Switzerland). The general motivation behind the methodology framework is an ambition to derive geographically explicit information about the possible build-out of residue biomass supply chains to meet localized biomass demand. In this paper, the framework is used for spatial modeling and matching of biomass demand for co-firing in existing coal-fired power plants with supply in the form of forest and agricultural residues. The focus is on demand–supply patterns over relatively short distances. Future studies will consider additional sources of biomass demand and will also include biomass from dedicated plantations as a complement to residues. One ambition is to use the framework to assess pressures driving land-use change and possible environmental consequences of mobilizing biomass supplies for energy, by considering both demand and supply in a geographically explicit way.

## 2 | MATERIALS AND METHODS

The data processing and analyses were conducted in a geographically explicit modeling and assessment framework, developed in ESRI ArcGIS Pro using Python scripting, as detailed below. The framework combines (Figure 1) (a) a biomass demand module, which in this study covers the



**FIGURE 1** Modeling framework developed and applied in this work. CPPD: Chalmers Power Plant Database for Europe (Kjärstad & Johnsson, 2007)

demand for biomass for co-firing in existing coal-fired power plants; (b) a biomass supply module, which in this study covers forest and agricultural residues; and (c) an integration module where the biomass supply is modeled to match the biomass demand in the individual power plants, taking into account the costs of harvesting, treating, and transporting biomass to the power plant gate. The cost data support the supply–demand matching (i.e., the linking of biomass supply points with “lowest cost” biomass demand points) and the derivation of national-level estimates of forest and agricultural residue availability for co-firing within different cost intervals. As the focus is on residue availability in the relative vicinity of power plants suitable for co-firing, a maximum distance between points of biomass supply and demand is used in the modeling, here set to 300 km. Analyses were performed for the member states in the EU-28, Norway, and Switzerland (henceforth referred to as “Europe”).

All spatial data were reprojected to a conic projection and equal area, that is, the Europe Albers Equal Area Conic, using bilinear interpolation when necessary.

## 2.1 | Demand module

The biomass demand module quantifies the annual biomass demand for each coal-fired power plant that is suitable for

biomass co-firing. We assume that retrofitting a coal plant for biomass co-firing is economically feasible if the plant was constructed after 1990. This is in line with Hansson et al. (2009) who adopted 30 years as maximum plant age when assessing options for coal plant retrofitting for biomass co-firing in the EU. Older boilers in general have lower efficiency and are of less interest for upgrading to support co-firing due to the few remaining years of operation. Plant data are taken from the Chalmers Power Plant Database for Europe (CPPD; Kjärstad & Johnsson, 2007; updated on an ongoing basis), which includes geographic coordinates, net power capacity, construction date, fuel type, and boiler type (see Figure 2). The plant biomass demand is estimated for 2020, 2030, and 2040 (the latest decommissioning date in the CPPD) based on the following:

- Installed capacity;
- Load factors, based on the national electricity generation by fuel (Eurostat, 2016c) and the national installed capacity as per the CPPD (see Supporting Information Table S1);
- Co-firing fraction, which depends on the boiler type and is set to 15% for circulating fluidized bed (CFB) boilers and 10% for grate-fired boilers (GRATE) and pulverized coal boilers, that is, pulverized coal (PC), supercritical pulverized coal (SCPC), supercritical pulverized fuel



**FIGURE 2** Coal-fired power plants included in the CPPD. Black dots: Plants constructed after 1990, for which retrofitting for biomass co-firing is considered economically feasible (Hansson et al., 2009) (142 boilers). Purple dots: Plants that are constructed before 1991 (i.e., assumed to not be available for retrofitting) or have already been retrofitted for co-firing (discussed further in Section 5)

(SCPF), and ultra-supercritical pulverized coal (USCPC; Al-Mansour & Zuwala, 2010; Berggren, Ljunggren, & Johnsson, 2008); and

- Electrical efficiency, as per the CPPD, when available; otherwise, efficiency is calculated based on Hansson et al. (2009) and the boiler age. The efficiency of the power plants under the co-firing scheme assumes efficiency losses depending on the co-firing fraction (Bertrand et al., 2014; Hansson et al., 2009) (see Supporting Information for more information).

For each plant, the CO<sub>2</sub> emissions with and without co-firing are estimated, yielding the potential CO<sub>2</sub> savings from co-firing. Emission factors for hard coal and lignite are assumed to be 0.0959 tCO<sub>2</sub>/GJ and 0.101 tCO<sub>2</sub>/GJ, respectively, in accordance with IPCC (2006) (see Supporting Information). We assume that the biomass is sourced from agricultural and forest residues and is carbon neutral (see Section 5).

### 2.1.1 | Demand scenarios

We construct two demand scenarios. They have the same total demand for biomass but differ concerning the types of biomass certain boiler types can use.

- Scenario 1: GRATE boilers use both agricultural and forest residues, while all other boiler types only use forest residues. This assumption is based on (a) forest residues having a lower alkali index and therefore being less likely to cause technical problems and (b) the successful co-firing of GRATE boilers in Europe, at 10% straw (Al-Mansour & Zuwala, 2010).
- Scenario 2: All boilers can use both agricultural and forest residues, based on operations in Denmark, for example, the Studstrup plant (PC, now decommissioned), which was co-fired with up to 20% straw (Skøtt, 2011; Veijonen et al., 2003).

The second scenario reflects the full co-firing potential if the current technical challenges of using agricultural residues can be resolved. We assume a low co-firing fraction, that is, 10% or 15% depending on the boiler type, because lower fractions are more likely to be implemented than higher due to lower investment costs and fewer technical challenges (IEA-ETSAP, 2013).

## 2.2 | Supply module

The biomass supply module provides estimates, at 1,000 m resolution, of the amounts of agriculture and forestry residues that are available for co-firing after restrictions on residue harvest rates and competing uses have been considered (designated “residue supply potential”). The roadside supply costs are also estimated.

### 2.2.1 | Agricultural residues

Agricultural residues are set to include harvest residues for the major cereals (wheat, rye, barley, and maize, referred to as straw), root crops (sugar beets), and oil plants (rapeseed and sunflower). Other organic waste and residues such as dung and food industry waste are not considered. Agricultural land use corresponds to five classes in CORINE Land Cover 2012 (CLC, 2012) (“12: Non-irrigated arable land,” “13: Permanently irrigated land,” “19: Annual crops associated with permanent crops,” “20: Complex cultivation patterns,” and “21: Land principally occupied by agriculture with significant areas of natural vegetation”). CORINE Land Cover, available at 100 m, is resampled to 1,000 m using Nearest Neighbor. The Raster calculator tool in ArcGIS Pro is used to calculate the total crop production (CP) (equation 1) and the total residue volume for each crop (equation 3):

$$\text{Crop production (CP)} \left[ \frac{\text{t}_{\text{crops}}}{\text{year}} \right] = A[\text{ha}] \times FCa \times Cy \left[ \frac{\text{t}_{\text{crops}}}{\text{ha}} \right] \quad (1)$$

- *A*: Area for each crop, adopted from the CAPRI crop database of the European Food Safety Authority (available at 1,000 m; EFSA; Gardi, Panagos, Hiederer, Montanarella, & Micale, 2011; Hiederer, 2012; Panagos, Van Liedekerke, Jones, & Montanarella, 2012).
- *FCa*: Agriculture correction factor excluding areas not designated as agriculture land use in CORINE (i.e., the five CORINE classes above), 1 for cells corresponding to the above-mentioned agricultural land classes and 0 for other land classes.
- *Cy*: Crop yields are obtained based on the statistical data at the NUTS2 level and modeling of yield variations at a resolution of 1,000 m to produce spatially disaggregated residue generation rates (equation 2), using the Raster calculator tool in ArcGIS Pro:

$$Cy \left[ \frac{t_{crops}}{ha} \right] = \frac{t_{Cy}}{at_{Cy} (NUTS2)} \times ahis_{Cy}(NUTS2) \quad (2)$$

- *t<sub>Cy</sub>*: modeled crop yield in each cell (source: GAEZ model (IIASA/FAO, 2012), with input parameters: water supply: rain-fed; input level: high; time period: baseline period 1961–1990; climate model: no; CO<sub>2</sub> fertilization: no). The data are available at a resolution of 5 arc min and are resampled to 1,000 m using bilinear convolution.
- *at<sub>Cy</sub>*: average modeled crop yield calculated at NUTS2 and derived from *t<sub>Cy</sub>*. Obtained using the Zonal Statistics tool in ArcGIS Pro where the average of *t<sub>Cy</sub>* is calculated for each NUTS2 region.
- *ahis<sub>Cy</sub>*: historical crop yield (the 2011–2016 average) at the NUTS2 level (Eurostat, 2016a). The table with data on historical crop yields was joined with the attribute table for the NUTS2 polygons (Eurostat, 2013a; using “Add join” with “NUTS ID” as the join field). Thereafter, the “Feature to Raster” tool was used to create a raster map with the historical yield for each crop.

$$\text{Crop residues} \left[ \frac{GJ}{year} \right] = CP \left[ \frac{t_{crops}}{ha} \right] \times CF \times RPC \left[ \frac{t_{residues}}{t_{crops}} \right] \times LHV \left[ \frac{GJ}{t_{residues}} \right] \quad (3)$$

- *CF*: Correction factor assuring that the modeled crop production corresponds to historical production at the NUTS2 level, calculated using the Raster calculator tool in ArcGIS Pro:

$$CF = \frac{ahis_{Pr}(NUTS2)}{at_{Pr} (NUTS2)} \quad (4)$$

- *ahis<sub>Pr</sub>*: historical production (the 2011–2016 average) for each crop at the NUTS2 level (Eurostat, 2016a). Tabulated data are converted to a geo-explicit raster as explained above.
- *at<sub>Pr</sub>*: total crop production at the NUTS2-level derived CP. It is obtained using the Zonal Statistics tool in ArcGIS Pro, where the average production is calculated within a NUTS2 raster.
- *RPC*: residue-to-product ratio (see Supporting Information Table S2).
- *LHV*: lower heating value (see Supporting Information Table S2).

The agricultural residue supply potentials are estimated using regionally varying harvest rates and deducting the amount estimated required for other purposes. Possible residue harvest rates depend on location-specific factors, including soil and climate conditions and agronomic practices (e.g., tillage and crop rotations). No datasets with location-specific information supported by field experiments exist (Kluts, Wicke, Leemans, & Faaij, 2017; Spöttle et al., 2013), and estimates of possible harvest rates can differ for the same crop and location. European-wide averages for so-called sustainable harvest rates are commonly in the 40–60% range for major cereals and oil seed crops (Daioglou, Stehfest, Wicke, Faaij, & Vuuren, 2016; De Wit & Faaij, 2010; Elbersen et al., 2012; Monforti et al., 2013; Pudelko, Borzecka-Walker, & Faber, 2013; Scarlat, Martinov, & Dallemand, 2010), while site-specific estimates vary within a broader range (Monforti et al., 2015; Spöttle et al., 2013).

In this study, the residue supply potentials are calculated based on the information about the topsoil carbon content available in the CAPRI database at 1,000 m. Based on Haase et al. (2016), it is assumed that the net residue harvest is 20%/60% of the crop residues if the topsoil carbon content is below/above 2%. These net estimates reflect both the need to leave some residues in the field and the losses from harvesting, handling, and storage, which reduce the amount of residues that in the end become available for co-firing or other uses.

Agricultural residues can be used for a variety of purposes, such as animal bedding, mushroom production, and incineration in heating plants, but only the straw demand for animal bedding is considered a significant competing demand in the modeling, based on Haase et al. (2016) and Einarsson and Persson (2017). For example, Einarsson and Persson (2017) and Scarlat et al. (2010) report that less than one percent of the agricultural residue volume is used for either mushroom production or incineration.

The straw demand for animal bedding is estimated based on the statistical data on (a) the heads of animals of

different types at the NUTS2 level (Eurostat, 2017a) and (b) the percentage of animals for which straw is used and straw use per animal unit, which are set to 25% and 1.5 kg/day for cattle, 100% and 1.5 kg/day for horses, 100% and 0.1 kg/day for sheep, and 12.5% and 0.5 kg/day for pigs (Scarlat et al., 2010; Thorenz, Wietschel, Stindt, & Tuma, 2018). The straw demand for animal bedding is calculated at the NUTS2 level for all countries except Germany, where the NUTS1 level was used due to limited data availability. The tabular demand data are turned into geo-explicit raster data as previously described for “*ahis\_Cy*” in equation 2. Demand is assumed to be uniform across the agricultural area. Demand per unit area is calculated by dividing the total demand by the total agricultural area in each NUTS2 region (areas with straw are calculated using “Zonal Statistics as Table” with NUTS2 polygons as “feature zone” and harvestable amount of straw as “Input value raster”). Straw demand per area is converted to a raster at 1,000 m using “Feature to Raster.” Finally, the amount of straw available for co-firing (the residue supply potential) is obtained by subtracting the straw demand for bedding from the estimated harvestable straw (net residue harvest) in the same area.

The amount of straw that is needed for bedding depends on the animal management systems. An increased demand for straw for energy purposes may result in shifts toward alternative animal management systems that require less/no straw, thus making more straw available for other uses. The residue supply potential may in that regard be underestimated. More importantly, assumptions applied to facilitate the calculations add significant uncertainty concerning residue supply potentials in specific locations. This includes the assumptions that straw demand is uniform across the agricultural area and that straw is not transported across NUTS2 borders (following Einarsson and Persson (2017)).

## 2.2.2 | Forest residues

Forest residues here include tops and branches from forest thinning and final felling. Stumps and forest industry by-products are not considered. Forest land use corresponds to four CORINE Land Cover 2012 classes (23: broad-leaved forest; 24: coniferous forest; 25: forest; and 29: transitional woodland/shrub). The total residue volume is derived from equation 5 using the Raster calculator tool:

$$\text{Forest residues} \left[ \frac{\text{GJ}}{\text{year}} \right] = WPa \left[ \frac{\text{m}^3}{\text{ha}} \right] \times \text{density} \left[ \frac{\text{t}}{\text{m}^3} \right] \\ \times \text{bark ratio} \times \text{residues ratio} \left[ \frac{t_{\text{residues}}}{t_{\text{wood production}}} \right] \times LHV \left[ \frac{\text{GJ}}{t_{\text{residues}}} \right] \quad (5)$$

where

- *WPa*: adjusted wood production, based on the average wood production (WP) covering all land classes (Verkerk et al., 2015) and the reallocation to the corresponding forest land classes (equation 6).

$$WPa = WP \times FCf \times \frac{Wpt(NUTS0)}{WPat(NUTS0)} \quad (6)$$

- *WP*: the annual wood production (m<sup>3</sup>/ha) in each grid cell is set to be equal to the average annual wood production in the landscape based on Verkerk et al. (2015).
- *FCf*: Forest identification factor, set to 1 for cells corresponding to the above-mentioned CORINE land classes and set to 0 for all other land classes.
- *Wpt*: total average wood production at the country level derived from WP. Obtained using the Zonal Statistics tool in ArcGIS Pro, where the average production is calculated within a NUTS0 raster.
- *WPat*: total average wood production at the country level derived from WP and harmonized with the CORINE database. The Raster calculator tool was used to only consider wood production on forestland. The average wood production was calculated using the “Zonal Statistics as Table” tool as above.
- Country-specific data on *density* and *bark ratio* for roundwood are based on UNECE (2010).
- *Residue ratio*: amount of biomass in tops and branches (from thinning and final felling) per unit of stemwood produced, based on Buck (2013) and Daioglou et al. (2016), which estimated an average residue-to-wood production ratio for boreal forest and for cool conifer/temperate forest of 0.69 and 0.53, respectively.
- *LHV*: lower heating value for woodchips is set to 8.35 GJ/Mg biomass having 50% water content (19.2 GJ/Mg dry matter). Density is set to 373 kg/m<sup>3</sup> dry density and 236 kg/m<sup>3</sup> bulk density, according to average values for the EU (UNECE, 2010).

The impacts of harvesting forest residues differ depending on the harvesting volume, type of biomass, and from where in the landscape the biomass is harvested, as well as other factors (de Jong, Akselsson, Egnell, Löfgren, & Olsson, 2017). Therefore, estimates of harvestable fractions, or of actually harvested fractions, vary significantly (Abbas et al., 2011; Stupak et al., 2007; Thiffault, Béchar, Paré, & Allen, 2015; Verkerk, Lindner, Anttila, & Asikainen, 2010; Verkerk et al., 2011). Environmental considerations and regulations of forestry operations in general influence harvest rates; further, some forest residues are left on site due to technical and profitability constraints (Egnell & Björheden, 2013). Due to difficulties in producing a literature

synthesis supporting the use of geographically varying residue harvest rates in the modeling, we adopted a constant harvest rate and used it for all countries, based on de Jong, Akselsson, et al. (2017). This harvest rate (28%) specifies the share of residues in the landscape that is harvested, that is, the share of stands in the landscape subject to residue harvest and the harvest rate of residues in those stands. A 40% harvest rate, corresponding to roughly a 50% higher share of stands being subject to residue harvest, was adopted in a sensitivity analysis (see Section 14).

The forest residue supply potential is assumed equal to the estimated harvestable volumes; that is, it is assumed that there is no significant competing demand for this biomass source. In reality, forest residues are already used for heating or co-firing. Power plants that already co-fire biomass with coal have been excluded from the analysis as their biomass demand is mainly met by other resources (e.g., sawdust pellets, waste, or demolition wood; IEA Bioenergy, 2016). Some countries, such as Sweden, Finland, and Estonia, already use a significant amount of their forest residues for energy purposes [see, for example, Díaz-Yáñez et al. (2013)], and the implications of this “competing” use are discussed below.

Agricultural and forest residue harvest influences the cycling of carbon between the biosphere and atmosphere and can consequently influence biospheric carbon stocks on the land from which the biomass is removed. The size and temporal dynamics of such changes depend on many factors, and residue harvest may covary with other aspects of land management. Thus, the outcome depends on the specific conditions, such as type of climate and soil, agriculture/forest characteristics, and social and economic factors including product markets. We do not consider how the residue harvest influences the cycling of carbon between the biosphere and the atmosphere. See Berndes, Ahlgren, Börjesson, and Cowie (2013); Cintas et al. (2016, 2017) for further reading on this topic.

### 2.2.3 | Residue supply cost

The residue supply costs include the costs for harvest, in-field transport, storage, treatment, and transportation of residues to the power plant gate. For agricultural residues, the cost for harvesting and forwarding is set to 1.3 €/GJ (Esteban & Carrasco, 2011), and the cost for handling, storing, and drying is set to 0.4 €/GJ (Allen, Browne, Hunter, Boyd, & Palmer, 1998; De Wit & Faaij, 2010; Edwards, Šuri, Huld, & Dallemund, 2005). The originally data in €/Mg are converted to energy units using the LHV's in Supporting Information Table S2. Other costs associated with residue harvest, for example, fertilization to compensate for nutrient losses (Karlen, Kovar, & Birrell, 2015), are not considered. For forest residues, the cost is set to the

average for three improved collection systems in Sweden described by Eriksson and Gustavsson (2010): forwarding residues to the roadside (0.5 €/GJ); chipping and compressing (1.28 €/GJ); and other operations, that is, storage, covering pile, operation and maintenance, and overhead costs (0.4 €/GJ). This is similar to the cost structure applied in Daioglou et al. (2016).

The costs above are representative for Swedish (forest) and Spanish (agriculture) conditions. The corresponding costs in the other countries are calculated using country-specific conversion factors obtained by summing the following (weighted) economy indicators and dividing the sum by the total indicator value for Sweden or Spain, in accordance with Esteban and Carrasco (2011):

- Transport index, price-level indices (a0107) (Eurostat, 2016b) (weighted index 15%).
- Personal transport index, price-level indices (a010701) (Eurostat, 2016b) (weighted index 5%).
- Communication index, price-level indices (a0108) (Eurostat, 2016b) (weighted index 5%).
- Machinery and equipment index, price-level indices (a0501) (Eurostat, 2016b) (weighted index 25%).
- Labor cost level by industry, construction, and services—population and social condition (except public administration, defense, and compulsory social security) (Eurostat, 2015) (weighted index 50%).

For instance, the calculated Danish and Norwegian farm gate costs for agricultural residues are similar to those reported by Stupak (2016) (2.6 €/GJ) and by Belbo and Talbot (2014) (2.7 €/GJ). Costs may decrease over time due to learning or increase due to certain input factors becoming costlier. However, in this study, it is assumed that the costs are constant over time, which is a simplification. The motivation is that the use of dynamic costs would add a layer of complexity while not altering the outcome of the supply–demand matching (unless cost development varies by location). Costs at the power plant, such as storage and treatment to comply with different boiler requirements, are outside the scope of the modeling.

The costs of traversing different surfaces are estimated based on the following:

- Map of surfaces:
  - Transport infrastructure: spatial data on road infrastructure with paved and unpaved roads (EuroGeographics, 2016). The available polylines were converted into different rasters for paved and unpaved roads (information about the network of unpaved roads is only available for five countries, which was handled via simplifying assumptions—complemented

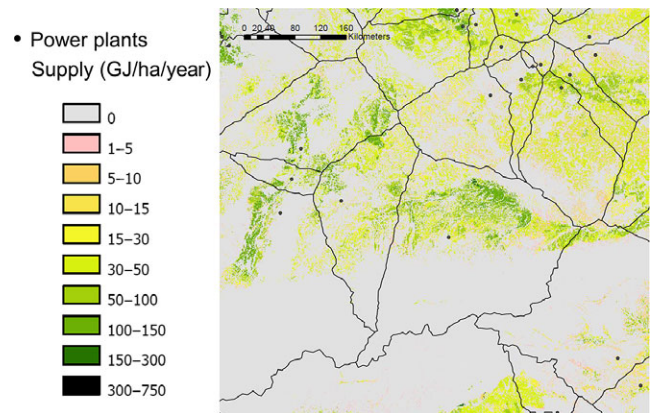
by sensitivity analysis—concerning transport costs outside the paved road network, see Supporting Information).

- Land cover: spatial information on different land surfaces. Source: CORINE 2012 (CLC, 2012) resampled to a resolution of 1,000 m. Areas designated as agricultural and forest land can be used to access biomass resources outside registered road network (see Supporting Information)”
- Transport cost as a function of traveled distance (see Supporting Information). Fixed costs include loading and unloading, set to 0.31 €/Mg DM (5 €/GJ) for each, for Swedish conditions (de Jong, Hoefnagels, et al., 2017). The variable costs are defined for different surfaces in Supporting Information Table S3 (see also Supporting Information Figure S1). The cost of road transport of baled straw and other agricultural residues is set to be 25% higher than road transport of wood chips, based on Ortiz, Curtright, Samaras, Litovitz, and Burger (2011) and Stupak (2016).

The maps of land cover and road infrastructure are first reclassified in ArcGIS Pro according to the transport cost estimates and then combined (with the Raster calculator) into one map of the cost of traversing different surfaces. Forest transport cost on paved roads in Sweden is set to 0.16 €/km Mg DM, based on de Jong, Hoefnagels, et al. (2017) (see Supporting Information for costs on other surfaces). The same cost in other countries is calculated based on the cost in Sweden and the correction factors described above. Comparisons with other studies indicate that the derived cost pattern is reasonable; the estimated transport costs for woodchips in Ireland and Finland are similar to the ones reported by Sosa, McDonnell, and Devlin (2015) (0.15 €/km Mg DM) and by Laitila, Asikainen, and Ranta (2016) (0.14 €/km Mg DM) for a trailer with similar characteristics. The estimated transport cost for agricultural residues in Denmark (1.3 €/GJ for 50 km) is slightly lower than the one reported by Stupak (2016) (1.7 €/GJ).

### 2.3 | Integrating module: Balancing supply and demand

The balancing of supply and demand is made through an iterative process where biomass demand in each of the power plants is compared with biomass supply within the area allocated to a specific power plant (see Figure 3 and the section on supply and demand balance for each plant). The comparison is made for one power plant at a time and is repeated as long as there are plants with unmet demand and unutilized supply (see script in the Supporting Information). Each iteration consists of the following steps:



**FIGURE 3** Illustrative allocation (black cell borders) of land to power plants (black dots)

1. *Cost distance analysis and land allocation to power plants:* Following England, Berndes, Persson, and Sparovek (2015), the “Cost Distance” tool in ArcGIS Pro was used to estimate, for each cell across the landscape, the lowest cost of transporting one metric ton of biomass to a power plant (which is often, but not necessarily, the closest one). This optimization analysis uses information about (a) the location of demand points (obtained from the “Demand module”) and (b) the cost of traversing different surfaces (see the section on cost). The “Cost Allocation” tool in ArcGIS pro was used to allocate individual cells to the power plant that is the least costly to supply with biomass (see Figure 3). The maximum transport distance from which residues can be sourced is set to a transport cost equivalent to 300 km on paved roads. Nivala et al. (2016), for instance, used 200 km as the maximum procurement distance of each power plant based on practical experiences in Finland. By defining a maximum supply distance, we consider that available biomass outside the procurement distance can be used for other purposes or mobilized by other transportation modes.
2. *Cost assessment:* Total cost includes the cost of extracting, collecting, and transporting biomass. The cost of transporting biomass from each cell to the corresponding power plant is estimated using the existing road infrastructure, as seen above.
3. *Supply and demand balance for each plant:* For each power plant, the least costly biomass supply is determined by claiming the least costly biomass available in the area allocated to the plant. First, the “cheapest” cells (i.e., the ones that can supply biomass at the lowest total cost) are used, and then, increasingly more “costly” cells are used until the supply is met. This ensures that the demand is met at the lowest total cost in case of an oversupply in the allocated area. Oversupply in an allocated area is made available in the next iteration to power

plants for which demand could not be met by the supply in their allocated area. It is thus ensured that any given cell will supply the plant that is the least costly to supply among the plants that cannot be fully supplied in cheaper ways. Due to modeling limitations, there can be a slight oversupply (up to 8%) to a power plant because all cells with the same cost are used to meet the demand even though they exceed it.

### 3 | RESULTS

#### 3.1 | Biomass demand

Supporting Information Table S4 shows the total biomass demand for co-firing with coal in existing European plants and the corresponding reduction in CO<sub>2</sub> emissions. The total demand in 2020 is estimated at 184 PJ, corresponding to 21 TWh of electricity and an emission reduction of 18 Mt CO<sub>2</sub>. Germany has by far the largest potential capacity for co-firing, followed by Poland. About 70% of the total demand in 2020 (80% in 2030 and 2040) is found in these two countries. As it is assumed that retrofitting for co-firing will not extend the plant lifetime beyond the default technical lifetime for coal plants, the biomass demand for co-firing decreases over time as plants are decommissioned due to age.

#### 3.2 | Residue supply potentials

The total annual generation of forest and agricultural residues is estimated at about 6.7 EJ. Figure 4 shows the distribution of the residues in Europe (Figure 4a,b) as well as the amounts available for co-firing (Figure 4c,d). The largest amounts of agricultural residues are found in France, Germany, the UK, and Poland, while the largest amounts of forest residues are found in Sweden, Finland, France, and Germany (Figure 5). Agricultural residues represent more than 75% of the total amount of residues in Europe and also in most individual countries. However, Finland, Sweden, Norway, Latvia, Estonia, and Switzerland have more forest residues than agricultural residues.

The total residue supply potential is estimated at about 2.9 EJ/year (Figure 6). Some 30–58% of the total amounts of agricultural residues were available for co-firing, depending on site conditions (determining how much is left in the field, see the section *Agricultural residue supply*) and straw use for bedding. Low soil carbon content was most constraining in Spain, Portugal, France, Italy, Greece, and Belgium. The lowest availability (30%) was found in Ireland, where straw demand for bedding was an important factor.

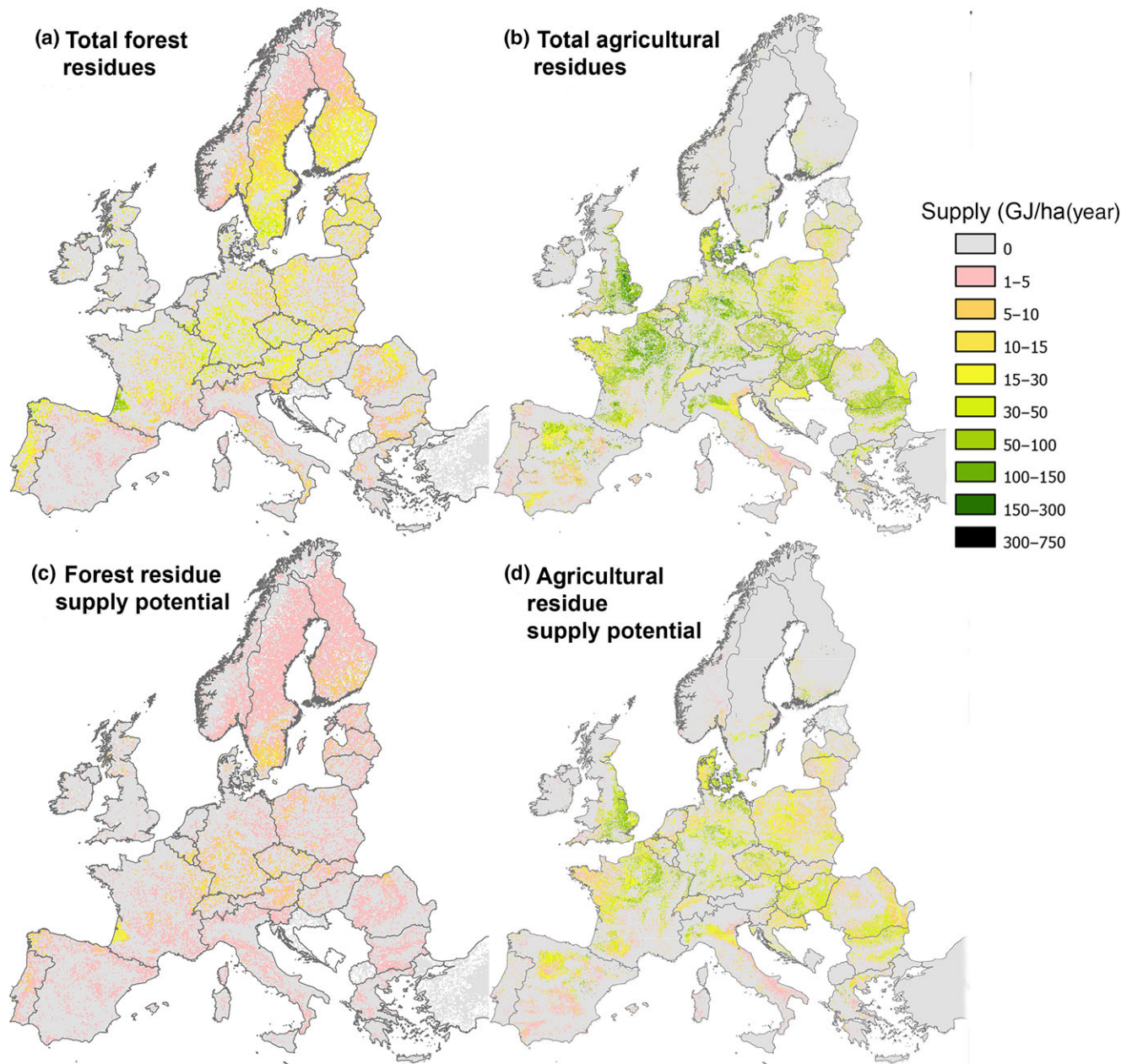
The estimated total amounts of residues are similar to those in Esteban and Carrasco (2011), and the estimated total agricultural residues are similar to the higher-end

values in Scarlat et al. (2010), except for Italy where our estimates are ca. 40% lower. The estimated residue supply potentials are consistent to those estimated by Esteban and Carrasco (2011) for all countries; note that their study did not consider other uses for straw. Estimates of forest residue supply potentials by Di Fulvio et al. (2016) are higher for many countries, for example, about 50% higher for Sweden, Finland, France, and the UK, but similar for the Czech Republic, Germany, Poland, Romania, Latvia, and Austria. Our estimated forest residue supply potential for Finland is in-between the *BAU* and *Max* scenarios in Nivala et al. (2016), while the estimate for Sweden is higher than that by de Jong, Akselsson, et al. (2017), despite using the same residue harvest rates.

#### 3.3 | Balancing biomass supply and demand

Figure 7a,c shows the supply costs and locations of the residues that match the biomass demand for co-firing in the two scenarios in year 2020. Figure 7b,d shows where residue biomass is still available (and how much per hectare) after the biomass demand for co-firing has been met (surplus supply). In Scenario 2, where all boilers can use both agricultural and forest residues, almost all the demand can be met based on residues available at distances below 300 km (see Supporting Information Table S4). In Scenario 1, such residues can meet roughly half the demand. The variation in supply cost mainly depends not only on the transport distance, but also on the price indices and labor cost (see average biomass supply cost at the country level, in Figure 8). As expected, the surplus supply is larger in Scenario 2 (cf. Figure 7b,d), and the supplies that match demand are generally closer to the power plants (cf. Figure 7a,c), resulting in a lower supply cost (Figure 8).

Figure 9 shows the modeled biomass supply cost (€/GJ) for the countries where there is a biomass demand for co-firing in 2020. In Scenario 1, about 21% of the total biomass demand for co-firing is met at a cost below 2.5 €/GJ biomass (100% of the demand in Portugal, Romania, Estonia, and Slovakia, 95% in Bulgaria, 80% in the Czech Republic, and 38% in Poland). This is due to low price indices and labor costs as well as the possibility to source the needed biomass rather locally. About 18% of the demand is met at costs in the range 3–3.5 €/GJ (100% of the demand in Croatia, Slovenia, and Finland, 30% in Germany, 20% in the Czech Republic, and 16% in Poland). About 7% of the demand is met at costs in the range 3.5–5 €/GJ (power plants in Belgium, the UK, Germany, and Poland), mainly due to high price indices and labor costs. The remaining 54% of the total demand cannot be met unless biomass is transported over longer distances than 300 km. This is the situation in Greece, Italy, Spain, the Netherlands, Denmark, and Norway, due to the limited and scattered forest residue

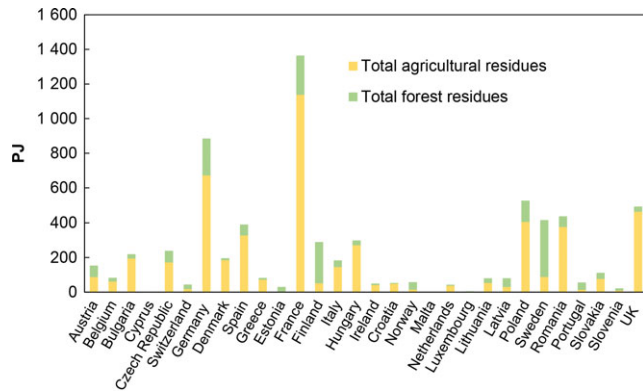


**FIGURE 4** Total amounts of forest and agricultural residues and the modeled residue supply potentials

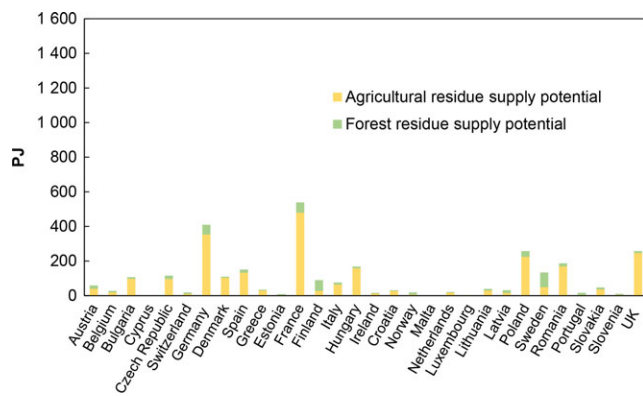
supply potential, and also in Poland and Germany, where the demand for biomass for co-firing in 2020 is larger than the domestic forest residue supply potential. In Poland and Germany, the power plants with lower co-firing capacity can meet their demand and they outcompete plants with greater capacity (remaining 23% and 70% of the demand for biomass in Poland and Germany, respectively), which would need to transport biomass over longer distances, likely using other transportation modes.

In Scenario 2 (Figure 9b), in which all boilers can use both agricultural and forest residues, about 43.5% of the total biomass demand can be met at costs below 2.5 €/GJ biomass, due to relatively high agricultural residue supply

potentials and low price indices and labor costs (Portugal, Poland, Bulgaria, Romania, Estonia, Slovakia, and Slovenia). About the same share (43.5%) can be met at a cost of 3–3.5 €/GJ biomass. The associated power plants are located in the UK, Belgium, Croatia, Greece, Finland, Germany (85% of total demand), and Spain (10%). About 5% of the biomass demand could be met at costs of 3.5–5 €/GJ biomass. In Denmark and the Netherlands, the domestic biomass supplies are costlier than those in other European countries due to high price indices and labor costs. In Norway, biomass resources around the power plant are rather scattered, and in Germany, the remaining demand (15%) is from the largest plants, requiring transport over longer



**FIGURE 5** Total amounts of forest and agricultural residues by country



**FIGURE 6** Residue supply potentials by country

distances. About 8% of the demand (in Italy and Spain) could be met by domestic biomass transported over longer distances than 300 km and most likely using other transportation modes.

By 2030, biomass demand for co-firing is reduced to 90 PJ (see Supporting Information Table S4) as 61 power plants have been decommissioned by then. Biomass supplied within 300 km can meet more than 67% and 100% of the demand for biomass in 2030 in Scenario 1 and Scenario 2, respectively. Using the current cost factors, slightly more than 59% of the total demand can be met at supply costs below 3.5 €/GJ biomass (Bulgaria, Estonia, Romania, and the Czech Republic below 2.5 €/GJ, Slovenia, the UK, Poland, Finland, Italy, Spain, and 44% of the biomass Germany demand) in Scenario 1. 33% of the total demand (Norway, 71% of biomass demand in Greece and 56% in Germany) cannot be met with biomass supplies within the 300 km distance. In Scenario 2, almost the entire demand can be met at costs below 3.5 €/GJ biomass (Bulgaria, the Czech Republic, Estonia, Greece, Poland, Romania, and Slovenia below 2.5 €/GJ). Norway and 12% of the biomass demand in Germany require biomass at costs in the range 3.5–4 €/GJ biomass.

By 2040, an additional 21 plants have been decommissioned and the biomass demand for co-firing is 70 PJ. Biomass supplied within 300 km can meet about 60% and 100% of the demand for biomass in 2030 in Scenario 1 and Scenario 2, respectively. With the current cost factors, about 55% of the total demand can be met at costs below 3.5 €/GJ in Scenario 1. Norway and 9% of the German demand would require biomass at costs in the range 4–5 €/GJ biomass. 40% of the total demand (Greece and 60% of the biomass demand in Germany) cannot be met with biomass supplies within the 300 km distance. In Scenario 2, almost the entire demand can be met at costs below 3.5 €/GJ biomass, except in Norway, where the cost would be 4 €/GJ biomass.

### 3.4 | Sensitivity analysis of biomass supply cost

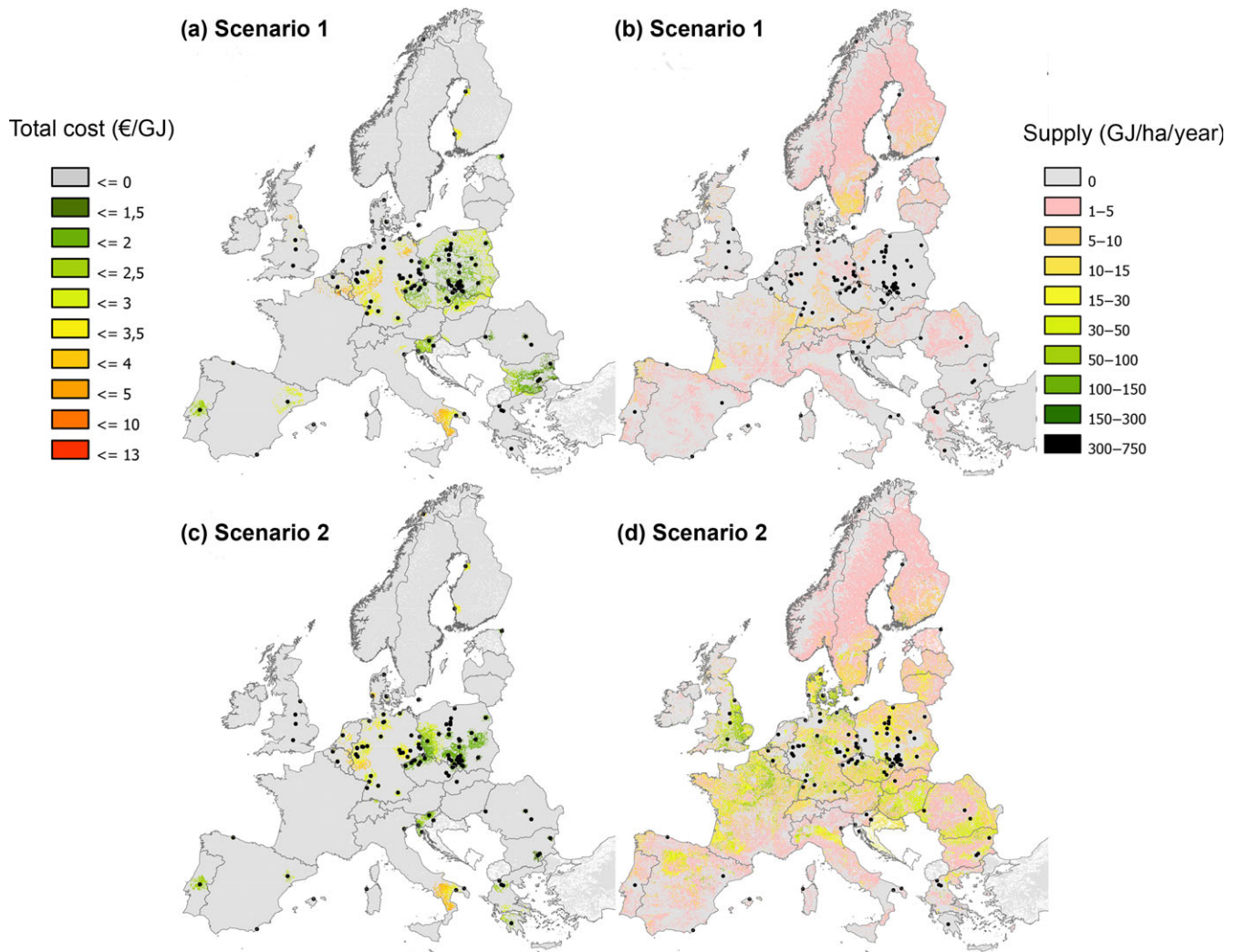
Figure 10 shows the alternative scenarios used to assess how sensitive the results are to the assumptions on costs and forest residue harvesting rates. The results in both scenarios are sensitive to changes in the assumed harvest costs, as the harvest cost represents a large share of the total supply cost, especially in Scenario 2 (See Figure 8a, b). Results are slightly less sensitive to the transport cost assumptions. Scenario 1 is also sensitive to the assumed harvesting rate for forest residues and to the distance limit for biomass transport that is used in the supply–demand matching.

Alternative cost conversion factors are applied to obtain alternative country-specific transport costs. We now let fuel prices (Eurostat, 2016d) represent 50% of the weight of the index, with the other 50% represented by labor costs (Eurostat, 2015) as before (see Section 8). The alternative transport cost estimates are very similar to the transport costs calculated with conversion factors based on price indices and labor costs.

## 4 | DISCUSSION

The assessed demand for biomass for co-firing in 2020 (184 PJ) corresponds to 21 TWh of electricity generation or 20% of the electricity generation from solid biofuels in 2016 in the EU. In some countries, the estimated domestic forest residue supply potential was lower than the biomass demand for co-firing. But the total (forest + agricultural) residue supply potential is greater than the assessed biomass demand for co-firing in all countries. The cost of meeting the demand is reduced when agricultural residues are available, due to shorter transport distances.

High biomass supply cost or inability to fully meet biomass demand for co-firing should not be understood as a strong indication that resource limitations will constrain



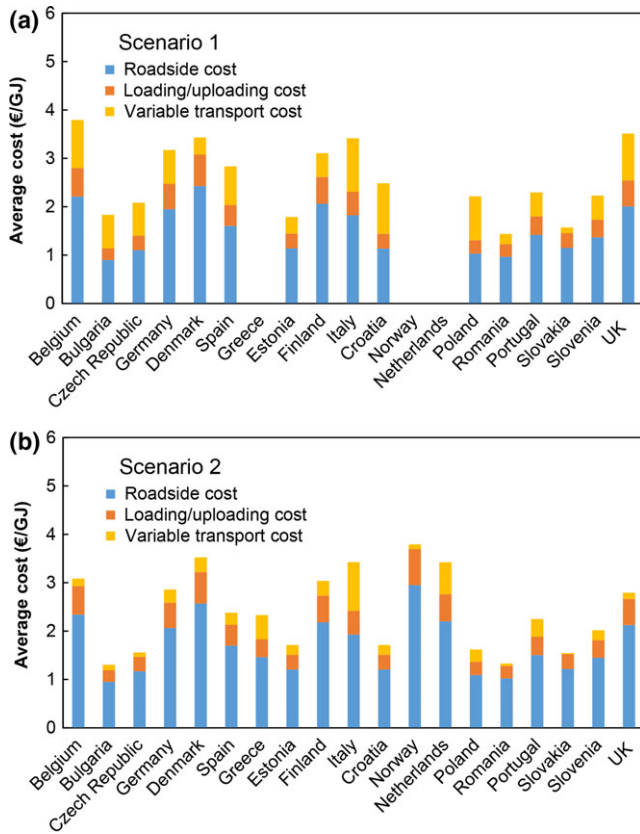
**FIGURE 7** Pattern of available biomass supply (used and unused) in the two scenarios in year 2020. Maps (a) and (c) show plant gate cost (€/GJ) and locations of residues that match the biomass demand for co-firing; maps (b) and (d) show the locations of available biomass supply that remains after the demand is met

biomass co-firing in some power plants. Rail and waterways provide alternative transport options that can make sourcing over longer distances economically viable, as demonstrated by existing long-distance supply chains (Dale et al., 2017; Englund et al., 2015; Hamelinck, Suurs, & Faaij, 2005; Hansson et al., 2009; Hoefnagels, Resch, Junginger, & Faaij, 2014; Lamers, Hoefnagels, Junginger, Hamelinck, & Faaij, 2015; Thraen et al., 2017).

Most coal power plants in the EU are located relatively close to ports (Figure 11) and use imported coal; that is, long-distance supply infrastructure for solid fuels has been established. For example, the German power plants with the highest supply costs are within 50 km from ports, providing access to international biomass markets. In Spain, the plant with limited access to biomass resources is only 2 km from a port. In Poland, the plants with higher capacity, which have higher biomass supply costs for meeting the demand, are within 50–200 km from ports. Possible

constraining factors include competition from other biomass markets, trade barriers, and challenges in meeting sustainability requirements in the importing countries. The amount of internationally available biomass obviously also depends on the biomass strategy of the exporting countries.

Biomass from nearby energy crops is an option that might be especially attractive where long-distance supplies are costly or constrained for other reasons, for example, by sustainability requirements. For example, Poland and the Czech Republic primarily use domestic coal resources (Hansson et al., 2009) and may consider energy crops rather than develop long-distance bioenergy supply chains. There is also an interest in developing domestic biomass supply chains to improve energy security, provide jobs, and make economic use of marginal lands where agriculture and forestry is challenging (Berndes & Hansson, 2007; Dauber et al., 2012; Domac, Richards, & Risovic, 2005). Further, studies have shown that the integration of

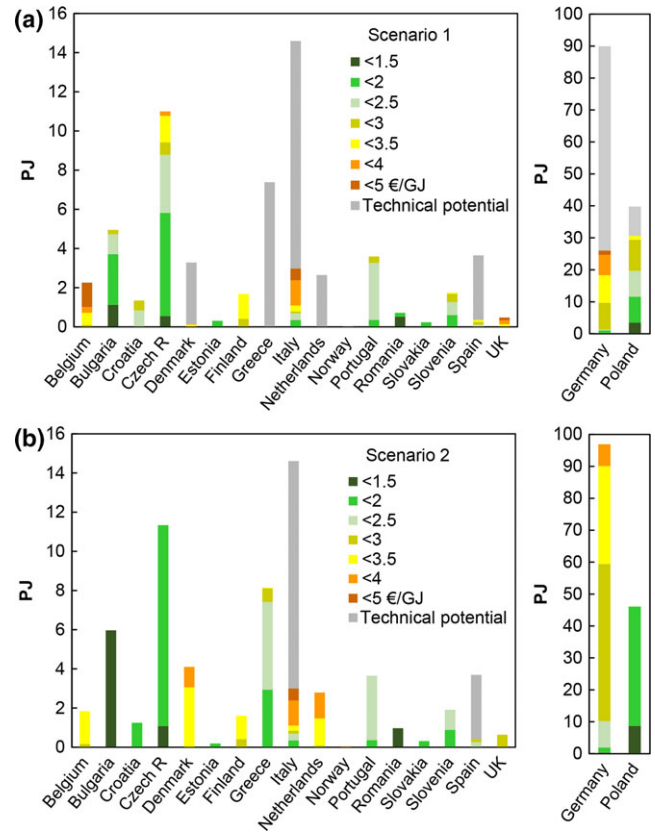


**FIGURE 8** Average residue supply cost (€/GJ) at the power plant gate in the countries with assessed biomass demand for co-firing in 2020, in (a) Scenario 1 and (b) Scenario 2

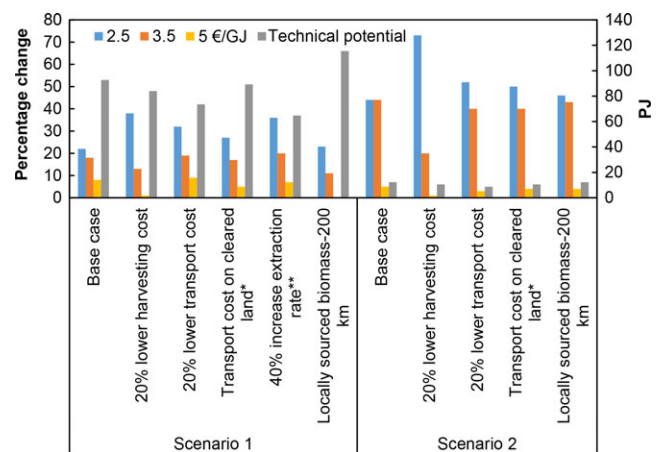
appropriate biomass production systems into agriculture landscapes can help reduce negative impacts of current land use and improve conditions for biodiversity and multiple ecosystem services (Berndes, Börjesson, Ostwald, & Palm, 2008; Berndes, Fredrikson, & Börjesson, 2004; Börjesson & Berndes, 2006; Dimitriou et al., 2011; Ferrarini, Serra, Almagro, Trevisan, & Amaducci, 2017; Pedrolí et al., 2013).

Among studies that assess biomass supply options in Europe (while considering food sector needs), Fischer et al. (2010) estimated that some 44–53 Mha of cropland and 19 Mha of pasture could be available for bioenergy feedstock production by 2030. The available land is mainly located in Eastern Europe, where crop yield improvements could free up substantial cultivated areas while meeting anticipated food demand. If energy crops were to be grown on that land, the biomass output could be up to three times the estimated possible agricultural residue output for bioenergy. Other studies [e.g., Aust et al. (2014); Hoefnagels, Resch, et al. (2014); Smeets, Lewandowski, and Faaij (2009)] also find a significant potential for energy crops in Europe.

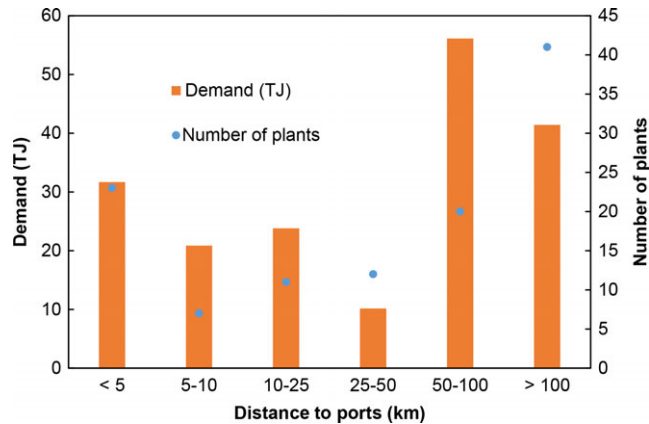
The extent to which biomass co-firing with coal is economically feasible depends on the biomass supply cost (as



**FIGURE 9** Forest and agricultural residues for co-firing at different cost intervals (€/GJ) for the countries with demand for biomass for co-firing in 2020, in (a) Scenario 1 and (b) Scenario 2. The term “technical potential” refers to residues that are not considered in the demand–supply matching due to being located more than 300 km from a demand point



**FIGURE 10** Sensitivity analysis. \*transport cost on cleared land (agricultural and forest) is set equal to transport cost on unpaved roads, and \*\*forest residue harvest rate is increased from 28% to 40%, corresponding to roughly a 50% increase in share of stands subject to residue harvest. The 20% reduction in cost was adopted to represent a degree of change that can occur as a consequence of normal variations concerning cost factors (“normal” in the sense that the variation is not due to shifts in technology used)



**FIGURE 11** Number of power plants (right axis) within a certain distance to a port and corresponding total biomass demand for co-firing (left axis). Almost half of the demand is found in power plants located within 50 km from ports. The distance to ports is less than 5 km for power plants located in Denmark, Finland, Norway, and the Netherlands; 10 km in Italy; 15 km in the UK; 40 km in Belgium; and 50 km in the Czech Republic. The distance to ports is calculated using the “Generate Near Table” tool in ArcGIS Pro and spatial data on port infrastructure (Eurostat, 2013b)

well as the retrofitting cost) compared with the cost of coal, the CO<sub>2</sub> allowance price, and the implementation of other policy instruments. A carbon price of 6 €/tCO<sub>2</sub> and a coal price of 2 €/GJ (Quandl, 2016) would correspond to an estimated 2020 supply cost (at the plant gate) of 2.5 €/GJ biomass. At the same coal price and at carbon price levels of 15 €/tCO<sub>2</sub>, 20 €/tCO<sub>2</sub>, and 30 €/t CO<sub>2</sub>, biomass supply costs below 3.5 €/GJ, 4 €/GJ, and 5 €/GJ biomass, respectively, would be attractive for co-firing.

Several EU member states have introduced policies that (directly and/or indirectly) stimulate the deployment of biomass co-firing. In Denmark, a quota-like system is in place through which power companies receive bonuses for using biomass to generate electricity (IEA Bioenergy, 2016). In the UK, co-firing has been part of the renewable energy quotas, but it was recently excluded. The Netherlands subsidizes biomass co-firing up to 25 PJ per year, and Belgium has a green certificate system that incentivizes the use of biomass for co-firing (IEA Bioenergy, 2016; IEA-ETSAP, 2013; Roni et al., 2017). On the other hand, Germany and Poland currently do not have any specific economic incentives for biomass co-firing.

A gradual decommissioning of coal power plants suitable for co-firing may not result in a decline in the total demand for biomass for co-firing (Supporting Information Table S4); coal power plants retrofitted for co-firing may increase the share of biomass in the fuel supply over time, or they may switch to using only biomass as fuel. In the UK, economic incentives to stimulate biomass use for co-firing have shifted toward only supporting dedicated

bioenergy plants. This encourages the full conversion of coal power plants (Roni et al., 2017), and three power plants have been converted so far (IEA Bioenergy, 2016). Biomass co-firing could be incentivized via the feed-in tariffs that exist in many of the assessed countries and—as in the UK—promote a gradual fuel shift from coal to biomass. The extent to which a conversion from coal to biomass will take place depends on energy policy, biomass availability, and the development of the biomass supply infrastructure, rather than on technical issues associated with upgrading boilers.

## 5 | LIMITATIONS AND FUTURE RESEARCH

The forest residue supply potential was calculated assuming a constant residue harvest rate, based on the Swedish experience. However, as already noted, harvest rates will vary as they depend on local conditions. Furthermore, other types of forest biomass (e.g., stumps and forest industry residues) can be used for energy. The sensitivity analysis showed that the assumed forest residue harvest rates significantly influenced the results concerning availability of residues within different supply cost intervals. Comprehensive inventories to produce a more elaborate database on forest residue availability and cost will consequently improve the conditions for future studies with the modeling framework. Information about agricultural residues can be obtained in a similar manner. Additional supply sources, such as food industry by-products and municipal organic waste, can be added to the supply-side database.

The calculation of forest and agricultural residue availability is based on a constant level of production in the relevant industries, but land use and biomass production change in response to multiple factors, including legislation, policies, and current and expected future markets (Abt, Abt, & Galik, 2012; Miner et al., 2014; Nepal, Ince, Skog, & Chang, 2012). A growing biomass demand for co-firing and other energy applications may in itself influence how landowners manage their land. Analyses using integrated biophysical–technoeconomic models can provide complementary insights, for example, about possible competition for biomass resources, supply-side response to demand, and international biomass trade balancing supply and demand. For example, this study found a large potential for biomass co-firing in Estonia. However, Estonia already experiences demand levels exceeding the estimated availability of logging residues (Díaz-Yáñez et al., 2013), indicating that the demand for biomass for co-firing in Estonia would need to be met based on other biomass sources. Other (domestic and imported) biomass resources may then be important for the implementation of biomass co-firing.

The study presented in this paper is a first application of a GIS-based assessment framework to analyze biomass supply–demand patterns, and associated land use, in Europe. The modeling framework will be further developed to extend the scope regarding supply and demand sources and to address sensitivities discovered in this first application. Planned updates include the following: (a) more comprehensive consideration of spatial and temporal aspects of biomass supply systems, including carbon balances; (b) extension of the biomass supply database to include additional waste/residue flows and biomass from dedicated plantations; and (c) extended modeling of biomass demand to include higher biomass shares in co-firing applications, increasing biomass use in existing industries, and emergence of new biobased production.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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