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Straw potential for energy purposes in Poland and optimal allocation to major co-firing power plants

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ABSTRACT

Agricultural waste and especially straw can provide a significant share of biomass energy. However, due to the very nature of agricultural production, as well as a need for carbon sequestration in soils and other aspects of food production, only part of the straw potential may be treated as waste and spent on energy production. Based on statistical data from the Polish Central Statistical Office (CSU) the actual production of straw was modelled on a scale of local districts (NUTS-5) as well as the needs of its local use and the possibility of redistribution of excessive quantities to regions with a deficit of straw. As a result, the straw surplus that could be used in the energy sector was obtained along with its geographical distribution. Next, a cost-minimising transport model is used to optimise the straw's allocation among main power plants all over the country, taking into account capacities and technical constraints of co-firing biomass with coal. The results are detailed at the municipal level indicating excess capacity for biomass co-firing by plant and regions to be satisfied by additional biomass sources such as biomass from forest or energy plantations.

1. Introduction

Crop residues are considered a renewable biomass source for heat and electricity in rural areas. Energy production from crop residues depends on the quantities produced as well as concentrations of available conversion technologies in addition to regional characteristics concerning supply and demand. Straw for energy is included in the European policy of renewable energy sources use [1]. In Poland, industrial use of straw for energy purposes is regulated by the current legal status of biomass [2,3]. Consequently, legal considerations play a significant role in shaping the biomass energy picture; however, effective biomass use will be determined by technical and economic efficiency. Indeed, among the documents relating to sustainable use of biomass, the European Commission [4] clearly gives priority to the efficiency of biomass conversion to energy and the technology development for reducing carbon dioxide emissions compared to conventional fuels. De and Assadi [5] have analysed pilot plant tests in existing coal fuelled utility boilers, and concluded that the co-firing of biomass with coal is an appropriate option for low investment CO_2 reduction. They also concluded that the

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economic feasibility of biomass co-firing mostly depends on the relative cost of the supplied coal and biomass. Straw, as a crop residue product, is an attractive source of biomass and can be effectively obtained from perennial crop biomass [6,7]; especially in the summer and autumn months.

Estimates of the straw potential in Europe have been carried out by the Joint Research Centre (JRC) [8] as well as during scientific projects [9,10]. However, these analyses of straw resources do not seem to be sufficiently complete because of scale inconsistencies or modelled types of assortments. This applies especially in case studies conducted for larger European countries such as Germany, France and Poland, which have a high theoretical potential for this source.

Poland has abundant bioenergy resources including the agricultural and food industries as well as forest timber waste. Cereal crops dominate arable agriculture, producing straw in large quantities. The straw potentials have to be estimated for a wide range of plants: wheat, barley, triticale, rye, oats, mixed cereals, maize, rapeseed and turnip rape. This broad list takes into account all kinds of plants leaving straw mass, which is potentially usable for energy purposes. However, not all crop residues can be used for energy purposes, for instance root crops such as potatoes and sugar beet produce a small amount of biomass. Estimates into the availability of straw must take into account its primary uses in agriculture for soil fertilisation [11,12], animal husbandry [8,11], and carbon improvers in the soil [13,14], which is now seen as one of the processes of climate change mitigation [15]. A significant proportion of the straw resources are also used for mound covering, bedding mat preparation in horticultural farms, insulation of buildings and the food industry, especially mushroom production.

As Iglinski et al. [16] mentioned, since 1983 there has been an overall surplus in straw that differs from a few million tonnes nationwide to a peak of about 10 million tonnes between 1995 and 2001. An effective way to manage this surplus has to be sought and one of the possible solutions could be for energy generation purposes. Taking into account that Polish energy plants are basically fuelled by coal and that its heating value ratio to straw biomass is roughly equal to 1.5, straw could not only heat houses and buildings in agricultural areas, but could also be used in local boilers at a community level or even bigger power plants. As Ericsson [17] points out, co-firing in the large pulverised fuel boilers is technically and economically the most realistic option for Poland, even if Combined Heat and Power (CHP) plants present an environmental advantage.

Preliminary analyses of the straw potential in Poland showed large regional differences in the availability of this material [13,18]. The larger regions with a significant deficit of straw were indicated, and there were some regions with a high local (intra-regional) variability, i.e. containing local districts with a surplus or deficit in straw. Ghilardi [19] pointed out that analysed fuelwood supplies or demand imbalances in Mexico must be calculated at the closest possible level (on a locality by locality basis) in order to avoid gross under or over-estimations of biomass potential for energy purposes. Recent studies on straw use for energy are either site specific [13] or aggregated at a country level [11,20,21]. Berggren et al. [22] have conducted a comprehensive analysis on solid biomass for heat and electricity in Poland through mathematical programming, using data on the quantity of biomass at a regional level named NUTS-2 (NUTS – Nomenclature of Territorial Units for Statistics – defined by eurostat). Bearing this in mind and taking benefit from original work undertaken in Institute of Soil Science and Plant Cultivation (IUNG) on straw surplus and the deficit at a municipal level (NUTS-5), the present study aims at estimating the share of straw for satisfying biomass demand by major power plants. For this purpose the optimal redistribution among neighbouring local districts straw deficit and surplus is calculated first. For the remaining surplus straw, once local use for energy in grate boilers is deducted, a cost-minimising model redirects it to power plants in order to match supply to demand. The degree of satisfaction is estimated for each demand unit, indicating requirements for other biomass sources such as wood and perennial plantations.

In the next section materials and methods are presented including algorithms and statistical and spatial data. Section 3 contains results on straw surpluses and deficits as well as on straw for co-firing by NUTS-5 level country wise and by major power plant. Then specific issues are discussed in more detail followed by concluding remarks and suggestions for future research.

2. Materials and methods

2.1. *Estimating straw biomass potential for energy*

The yield of straw for each area and type of crop is estimated using data for the cultivation area, cereals yield and the grain-straw ratio in a particular year. The ratio between grain and straw varies for different crops. It is assumed that the ratio for rye and oat equals 1.1; for triticale, spring triticale, maize for grain, oilseed rape and turnip rape plants to seeds 1.0, and for winter wheat, spring wheat, spring cereal mixtures 0.9 [13]. Then the quantity of straw is determined as a result of multiplying the straw yield by the planted area. Those calculations are performed for each group of plants, and are presented as the theoretical straw potential.

The theoretical straw potential cannot be used exclusively for energy purposes, since a significant proportion of this bioenergy source is used for various other purposes. A part of the available straw resources have to be used for animal feeding, animal bedding and another has to be incorporated into the soil for conservation purposes. In addition, other uses are site or country specific and have to be taken under consideration, for example mushroom production. To assess the amount of straw needed for livestock purposes the Large Heads Index (LHI) can be used. LHI is a standard measurement unit that allows the representation of the various types of livestock in order to enable them to be comparable. For the calculations, it is assumed that the use of straw for bedding is 1.5 tonne; whilst for feed consumption of one LHI per year is 1.0 tonne [13].

A proportion of the straw must also be allocated for the conservation of the soil's organic matter (SOM). This can be achieved by fertilisation with manure or other organic fertilisers as well as by incorporating straw in the soil. The benefits of straw fertilisation include enriching the soil's organic matter, increasing the nutrient content of the soil, increasing the soil's microbial activity, reducing nitrate leaching, improving the sorption capacity of the soil, having beneficial impacts on the structure of soil and on the efficiency of water management and reducing the risk of soil erosion [18]. For these reasons, attempts should be made to the primary straw use in agricultural production. Moreover, in Poland the dominant share of the territory is composed of light and very light soils. Consequently, the use of straw as a fertiliser significantly improves the quality and fertility of the soil. In the last 15 years, the balance of organic matter in Polish arable land has noticeably deteriorated reaching negative values. This is due to a decrease in cultivation of crops that enrich the soil with organic matter (plants, legumes, grasses) and in the volume of production of manure.

2.2. *Surplus and deficit of straw in NUTS-5 level in Poland*

The calculation was based on data coming from the Central Statistical Office (CSO) of Poland, which were collected during the Agricultural Census in 2002. In 2010, the census was updated, but data at a NUTS-5 level is still not available. However, a comparison of statistical data on agricultural production in 2002 and 2010 for NUTS-2 shows no significant differences that would affect the result obtained in the performed modelling. The data about the planted area and livestock were collected for NUTS-5 and the average yield was collected for NUTS-2 level. NUTS-5 in Poland is the smallest administration unit called 'gmina' (local authority). In total, there are 2489 'gmina' belonging to 16 regions. The regional administrative unit called 'województwo' (voivodeship or region) is equivalent of NUTS-2 in the European coding. Table 1 presents descriptive statistics of NUTS-2 and NUTS-5. Statistical and spatial analysis were conducted for all the 2171 rural NUTS-5 regions in Poland. A schematic modelling process of surplus and deficit of straw for each NUTS-5 unit is shown in Fig. 1.

Straw quantities produced are calculated at the NUTS-5 level combining data from different aggregation strata. After deducting straw requirements for SOM, animal feeding and bedding, the last stage of the calculation the technical straw potential is to reduce the potential of the available biomass by the straw used for the production of substrates for mushroom production. The agricultural data were obtained from the CSO database. Values of NUTS-2 were proportionally redistributed to arable areas in each NUTS-5. An example is illustrated in Table 2 for one NUTS-5 area (id: 0201022). Table 3 summarises calculations and straw usage by category aggregated at the NUTS-2 level.

Table 1 – Spatial and statistical characteristic of NUTS-2 and NUTS-5.

Indicator	NUTS-2	SD[a]	NUTS-5	SD
Number of units	16		2171	
Average area (km^2)	19,480	6597	134	74
Average arable area (km^2)	7670	3496	40	28
LHI	460,000	327,700	3400	2800

a Standard deviation.

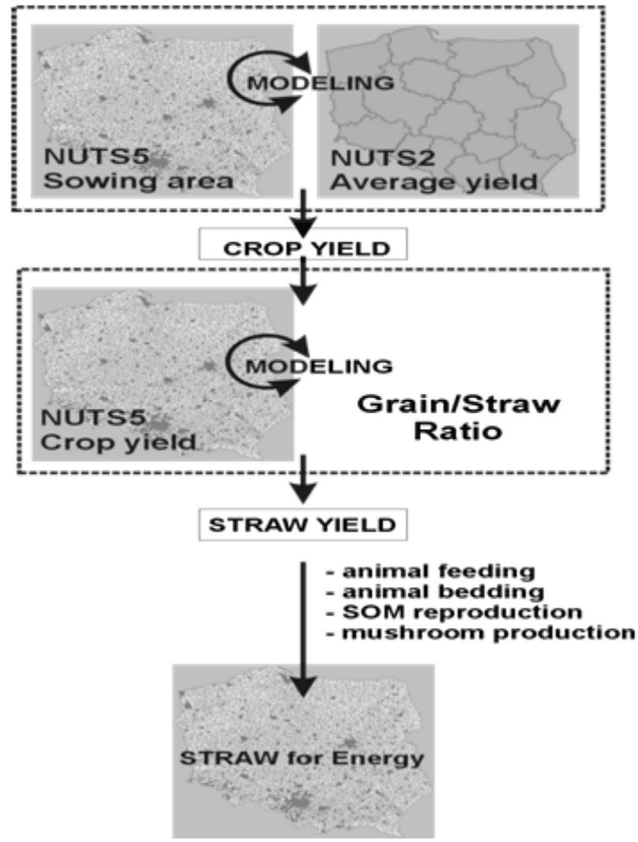

Fig. 1 – Flowchart of straw for energy calculation.

2.3. *Collection, handling and transport costs for straw*

Four major types of costs can be distinguished, namely opportunity cost, collection, road-siding and pre-storage cost. In order to estimate the cost of delivered biomass at the power plant gate, the transportation cost from the storage site to the conversion plant has to be added to the previous elements.

The opportunity cost expresses payments required to make residues available for collection. This cost is one of the most uncertain items involved in the feasibility study of agricultural residues for energy purposes. Its value is related to the willingness of the farmer to offer the straw residue and it is related to alternative uses and expected benefit from them. As explained in the previous section we consider that all other than energy straw uses pay a higher price and only spare straw can be available for energy. Thus, we assume zero opportunity cost for the remaining straw that eventually may be utilised for energy purposes.

To estimate the cost of handling residues, it is assumed that a machine pool performs the required operations. Main features of the machinery costs are fixed costs (interest, purchase value, insurance and shelter) and operating costs (fuel and lubricants, maintenance, repairs and labour). Fixed cost reported in units (hectares or tonnes) is dependent on the available time for handling operations. Material losses or

Table 2 – Illustration of calculation of straw surplus/deficit at the NUTS-5 level (id: 0201022).

Crops	Sown area (ha)	Yield (Mg ha^{-1})	Ratio grain/straw	Straw yield (Mg ha^{-1})	Straw required for SOM reproduction (Mg ha^{-1})	Straw (from fields) (Mg ha^{-1})
Rye	837.4	2.98	1.1	2741	1789	952
Oat	582.0	2.95	1.1	1890	1233	656
Mixed cereals	378.5	3.02	0.9	1028	671	357
Wheat	3712.8	4.48	0.9	14,976	9774	5202
Barley	908.8	3.54	0.8	2571	1678	893
Triticale	173.6	3.55	1	616	402	214
Rape	713.0	2.61	1	1863	1216	647
Maize	839.4	6.25	1	5245	3423	1822
					Total for 0201022	**10,744**
				t/LHI		
LHI (heads)	1472	Animal feeding ratio		1	Animal feeding	1472
		Animal bedding ratio		1.5	Animal bedding	2208
					Mushroom production	1504
					NET total for 0201022	**5560**

Note: Straw required for SOM reproduction is calculated taking into account field losses.

benefits (decrease of wet matter in biomass) during pre-storage have to be taken into account. For a full account of pre-treatment costs of biomass designated to energy and especially co-firing, please see Maciejewska et al. [23].

Different factors analysed in more detail later in the discussion section such as meteorology, farm size and means of transport available, affect the cost of straw. Having calibrated the previous figures to Polish conditions we can assume an overall variable transport cost of 0.15 € Mg^{-1} km^{-1} (DM). Prices paid for solid biomass in Poland amount at about 2.5 € GJ^{-1} at the plant gate [20]. Taking in consideration the fact that straw in Poland has a lower heating value (LHV) of around 14–15 GJ Mg^{-1} (15% moisture), it corresponds to 35–37.5 € Mg^{-1} which represents around 40 € Mg^{-1} in current prices.

For short distances, transportation can be carried out by existing tractor-trailers. Its cost also comprises of a loading on the engine and it is decisively affected by distances from the origin point to destination. The calculation of the transportation cost can become very detailed and a good example can be found at Rogers and Brammer [24].

2.4. *Redistribution and transport model*

The transportation of the biomass available for energy to the intermediate or final locations is a significant part of the modelling process for any biomass to energy project. The transportation modelling is project-specific and many different variations exist in literature [24–26]. Generally, the

Table 3 – Straw potential and competitive uses in 2002 (in Gg).

NUTS-2	Straw yield[a]	Straw for animal feeding[b]	Animal bedding[b]	Straw for soil conservation[c]	Straw for food industry[b]	Straw for energy purposes
Dolnośląskie	2358	194	292	1342	100	429
Kujawsko-pomorskie	2328	665	997	0	100	565
Lubelskie	2403	589	883	268	0	662
Lubuskie	606	103	155	232	100	15
Łódzkie	1586	572	858	0	200	−44
Małopolskie	729	335	503	0	0	−109
Mazowieckie	2657	1063	1595	0	100	−102
Opolskie	1592	209	314	436	0	631
Podkarpackie	734	244	367	4	0	119
Podlaskie	1237	695	1042	0	0	−500
Pomorskie	1447	325	487	0	0	634
Śląskie	602	162	343	0	0	196
Świętokrzyskie	682	254	382	0	0	45
Warmińsko-Mazurskie	1554	458	688	0	100	307
Wielkopolskie	3800	1287	1931	0	200	382
Zachodniopomorskie	1762	191	286	757	100	427

a Central Statistical Office (CSO).
b Calculated based on CSO.
c Ref. [13].

transport costs are minimised subject to supply, flow and demand constraints.

Since the estimated straw biomass potential is positive in some areas (NUTS-5) whereas in others it is negative, it is reasonable to assume that neighbouring areas will balance their surpluses and deficits of straw biomass. This balancing will take place by transporting straw quantities from surplus areas to nearby deficit areas. Assuming that trailers pulled by tractor are used, transportation up to a distance of 30 km is a reasonable limit for transferring straw between farms in the redistribution phase. We thus assume that for the current phase the unitary cost per kilometre is constant, since the transportation is expected to take place with equipment that is already owned by the farm and used in various other activities. Afterwards the remaining straw biomass will be available for transportation to energy plants. Straw will be transported by lorries increasing the distance limit to 100 km. We refer to these two phases as the redistribution and transportation phases. The factories that can accept the surplus straw on the transportation phase are either small plants with grate boilers (phase 2.1) or coal/lignite powered power plants (phase 2.2).

Both phases can be simulated using stylised transportation models. Algebraic representation of the transportation problem is typically presented in a format similar to the following:

$$\min \sum_j h \cdot R_j + \sum_j \mathrm{CHC}_i \cdot x_{ij} + \sum_i \sum_j l \cdot v_{ij} \cdot c_{ij} \cdot d_{ij} \cdot x_{ij}$$

$$\mathrm{CHC}_i = \begin{cases} \mathrm{CHC}_{\min}\text{\_if\_area}_i \geq \mathrm{area}_{\mathrm{ceiling}} \\ \mathrm{CHC}_{\max} - \frac{\mathrm{area}_i - \mathrm{area}_{\min}}{\mathrm{area}_{\max} - \mathrm{area}_{\min}} \cdot (\mathrm{CHC}_{\max} - \mathrm{CHC}_{\min})\text{\_if\_area}_i \leq \mathrm{area}_{\mathrm{ceiling}} \end{cases}$$

s.t.

$$\sum_j v_{ij} \cdot q_{ij} \leq S_i, \quad \forall i$$

$$\sum_i v_{ij} \cdot q_{ij} = D_j - R_j, \quad \forall j$$

$$x_{ij} \geq 0, \quad \forall x_{ij}$$

where

Objective function: minimize {total cost}
total cost = Cost for failing to meet demand + Collection and handling cost + Transport cost
Sets
- i, areas (NUTS-5) with a straw surplus
- j, destinations (areas with a straw deficit in the redistribution phase/power plants in transportation phase)

Parameters
- CHC, collection and handling costs for each area i (€)
- Area_i, average arable area by farm for each area i (ha)
- v_{ij}, binary coefficient that is equal to 0 when the distance between areas i and j is reasonable enough for transportation, otherwise it is valued 1
- c_{ij}, cost for transporting straw from area i to area j per km (€ km^{-1})
- d_{ij}, distance between area i and area j (km)
- D_j, demand for straw on area j

Constants
- h, artificially large penalty (€) for not meeting demand
- l, scaling constant taking eps value

Variables
- x_{ij}, quantity transported from area i to area j (Mg)
- R_j, residual deficit (Mg) of area j

Notice that the arbitrary constraint of 30 km radius straw transport limit resulted in model infeasibilities (in some NUTS-5 agglomerations surplus could not meet adjacent deficit for straw). In order to overcome this problem we introduced the residual variable (R_j) along with h and l constants.

For conducting spatial modelling the ArcGIS 9.3 software was used to feed a database that supports the optimisation module of the Decision Support System (DSS) for bio-energy decision-making which was adapted to Polish conditions [27]. The DSS is programmed in GAMS (General Algebraic Modelling System).

The distance between NUTS-5 area centroids was computed on the GIS system. We have also computed the national road network distances from the surpluses to the 20 factories using the ArcGIS network module. There is strong evidence for using this kind of measurement instead of Euclidean distances. Distances of up to 200 km that have been calculated in Poland resulted in road distances on average 15% higher than the Euclidean distance [28]. This is a significant difference in distances computed, so we adopted the shortest path method using the road network layer.

3. Results

3.1. *Surplus and deficit of straw at the NUTS-5 level*

The technical potential of straw for Poland amounted at 3.7 Tg (Table 3). The good management of straw, ensuring its sustainable utilisation for agriculture and non-farm usage requires a redistribution of about 2.5 Tg between neighbouring NUTS-5.

The local districts with excess straw correspond to regions dominated by crop production with little participation in animal husbandry (Wielkopolskie, Kujawsko-Pomorskie, Pomorskie, Dolnośląskie). These regions contain mainly large-scale farms that facilitate straw handling logistics. A large surplus of straw is also observed in Lubelskie. However, in this region, farms are much smaller. The map shows high spatial variability of straw distribution as there are 825 out of 2171 NUTS-5 areas with straw deficit (Fig. 2).

3.2. *Redistribution of straw towards deficitary neighbouring areas*

The model proposed transport paths and quantities between surplus and deficitary NUTS-5 land units minimising distances and taking into account maximum distance constraint. At the optimum 1.2 Tg was relocated to the closest NUTS-5 with straw deficits. That represents approximately 20% of the total quantity of straw surplus.

After solving the model minimising the total transport cost, available straw for energy purposes at the NUTS-5 level is determined. The map in Fig. 3 is generated based on surplus and deficit values that were obtained at the optimum. After the redistribution process there is still remaining straw, which can be transferred to energy plants for co-firing and electricity generation.

The calculation of spatial differences in the availability of straw after the redistribution phase has allowed the identification of clusters of straw availability. Five major concentrations of straw surplus (R1, ..., R5) were determined as well as three smaller ones which are still important because of their location (r1,...,r3). In more detail:

- R1 – this region is situated in the close neighbourhood of the Upper Silesian Industrial Region. Because of this, there is the great demand for biomass by the power generation system and CHP power plants. All surpluses of straw from western NUTS-5 areas at Opolskie will probably be allocated to the eight power plants, which are located within a radius of up to 80 km.
- R2 – almost the whole area of 'Lubelskie' voivodeship. This NUTS-2 area is characterised with good soil conditions, but the farms are quite small (average 6.4 ha) and dispersed. In this region, there are four medium sized (50–400 thousand people) cities (Lublin, Zamość, Chełm, BiałaPodlaska) which can be potentially interested in obtaining straw for heat and power production.
- R3 – Wielkopolskie and Kujawsko-Pomorskie are agricultural regions of Poland specialising in wheat, rape and potato production. R3, R4 and R5 regions are good for locating local power plants.

The other three small regions (r1, r2, r3) are located in the immediate vicinity of important power plants, representing the potential resource bases for them.

3.3. *Matching straw potential for energy purposes with demand for co-firing*

Two options are possible for co-firing the remaining straw for electricity generation primarily local small grate boilers and then larger coal fuelled power plants [17]. The total grate boiler capacity for burning biomass has been obtained from Berggren et al. [22] at a resolution of NUTS-2 level. At this stage, we proportionally allocate the surplus of each NUTS-5 area to its NUTS-2 local boilers. This latter use concerns about 170 Gg nationwide though it is unequally distributed as can be seen in Table 4.

The remaining straw will be sent to large coal or lignite power plants minimising the total cost of the biomass at the factory gate. This cost is the sum of two components. First, the cost of straw at the farm gate that increases with decreasing farm average arable area of a corresponding NUTS-5 land unit. It represents harvesting collection and handling costs and varies from 30 to 40 € Mg^{-1}. The second component is the transport cost to the factory that depends on the distance from the surplus area. This cost is calculated at 0.15 € km^{-1} Mg^{-1}. The farm gate cost for NUTS-5 areas that are more effective on producing straw results in higher ratios for selling straw even at longer distances. In Table 5, we can see the total cost of straw at the power plant gate. This cost comprises average farm gate cost and transport cost, this latter varies from 1% to 12% of total cost.

The capacity for burning straw allocated in the 20 major power plants [29], the effective quantity of straw to be moved to each plant (source: model results), as well as capacity coverage in percentages (source: own calculations) are shown also in Table 5. One can observe that about half of the power plants are fully exploiting their capacity, whereas six of them exploit 40–70% of their capacity and the rest process only limited quantities of straw. The spatial properties of the coverage are shown in the following map in Fig. 4.

The comprehensive results of this exercise are also aggregated by region (NUTS-2 level) as shown in Table 4. There is spatial variability between areas that is explained by straw concentration and by plant location. Five NUTS-2 regions provide a straw surplus to power plants whereas four of them provide low quantities and the rest are in an intermediate situation.

Overall a quantity of about 1.2 Tg is transported to power plants for co-firing with coal leaving about half of the gross straw potential (initial straw availability, see Fig. 1 and Table 2) unused, probably available for decentralised energy use to be developed in the future. This holds in particular for Lubelskie and Pomorskie voivodeships and for a few other regions because of actual location of power plants remain with most of harvested straw unused. By avoiding burning in the fields, the co-firing of this straw would contribute to a reduction of gases emissions. For similar reasons, some power plants do not satisfy their needs in biomass, so that in order to respect quotas means paying environmental taxes and the management has to search for other sources of biomass possibly from timberwood waste or perennial plantations. Thus, in the Upper Silesian Industrial Region only 46% of the capacity earmarked for straw has been satisfied because of high demand concentration (about 1 Tg). The models results minimising straw cost at the plant gate show full (100%) coverage for four plants, whereas the other six especially Jaworzno II and III as well as the one located in Siersza fall short in their totals of straw (Table 4). In addition, plants in the East of Poland (located in Ostrołęka, Turówand Bełchatow) and in the South West (Kozienice) are not provided with straw

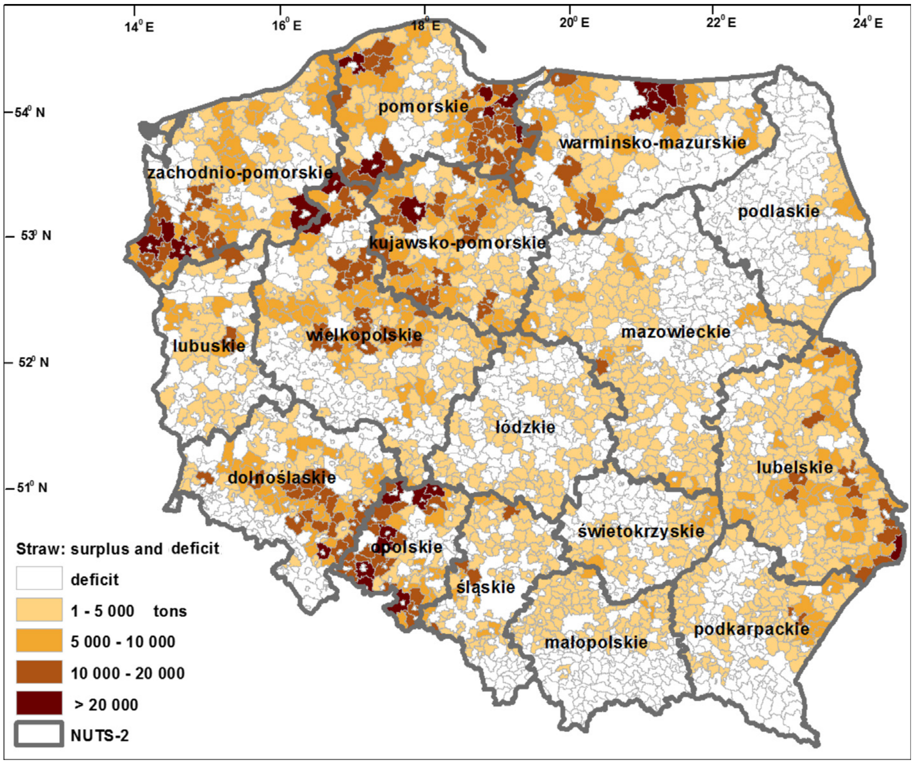

Fig. 2 – NUTS-5 areas with surplus or deficit of straw in Poland.

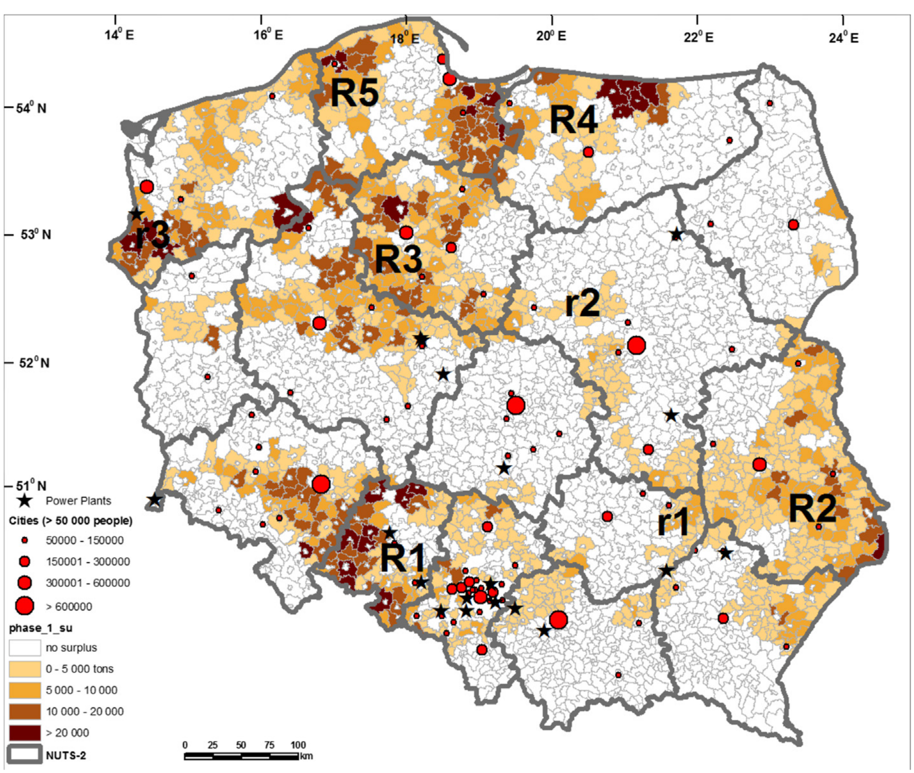

Fig. 3 – Straw availability for energy purposes at the NUTS-5 level.

Table 4 – Surplus of straw by region (NUTS-2) at different phases.

NUTS2 regions	Initial straw quantity		After redistribution (Phase 1)		Transportation to local small factories (Phase 2.1)		Transportation to CHP factories (Phase 2.2)		% Surplus left
	Surplus (Gg)	Deficit (Gg)	Sum of surplus (Gg)	Sum of deficit (Gg)	Grate Boilers capacity (Gg yr^{-1})	Straw moved (Gg)	Factories	Quantity moved to factories	
Dolnośląskie	548	−118	435	−20	0	0	1	67	67
Kujawsko-Pomorskie	618	−52	558	0	51	51	0	137	60
Lubelskie	706	−44	675	−11	6	6	0	56	87
Lubuskie	120	−105	32	−6	16	16	0	0	13
Łódzkie	143	−187	25	−11	235	25	1	0	0
Małopolskie	134	−243	74	−193	6	6	2	68	0
Mazowieckie	345	−446	145	−276	20	20	2	67	17
Opolskie	646	−14	630	0	5	5	2	225	62
Podkarpackie	175	−56	140	−20	0	0	1	15	71
Podlaskie	65	−566	22	−502	0	0	0	0	33
Pomorskie	989	−54	635	0	0	0	0	0	92
Śląskie	232	−35	210	−15	20	20	6	185	2
Świętokrzyskie	95	−49	69	−8	6	6	1	62	1
Warmińsko-Mazurskie	477	−169	341	−70	0	0	0	0	71
Wielkopolskie	713	−331	505	−135	6	6	3	203	41
Zachodniopomorskie	507	−80	435	−1	6	6	1	125	60
Total	**6213**	**−2549**	**4931**	**−1268**	**377**	**167**	**20**	**1210**	**57**

Table 5 – Straw supply to main electric power plants in Poland.

	Straw capacity (kt)	Straw moved (kt)	Average cost of straw (€ kt^{-1})	% Covered
R1 region: Upper Silesian Industrial Region				
Elektrownia Opole	84.3	84.3	36.66	100
Elektrownia Rybnik SA	293.7	167.0	40.44	57
PKE SA Elektrownia Jaworzno III	151.2	0.0		0
PKE SA Elektrownia Łaziska	159.9	31.5	40.65	20
PKE SA Elektrownia Siersza	93	6.6	40.41	7
PKE SA Elektrownia Łagisza	81.3	81.3	41.44	100
Elektrownia Skawina SA	69.9	48.7	41.61	70
PKE SA Elektrownia Halemba	17.4	17.4	41.50	100
PKE SA Elektrownia Jaworzno II	29.4	5.0	41.56	17
PKE Elekrownia Blachownia SA	14.4	14.4	36.89	100
Region subtotal	**994.2**	**456.1**		
R2 region: Lubelskie voivodship				
Elektrownia Połaniec	145.2	83.6	41.03	58
Elektrownia Stalowa Wola SA	32.1	32.1	40.19	100
Region subtotal	**177.3**	**115.7**		**65**
R3 region: Wielkopolska&Kujawy				
Elektrownia Pątów	197.1	197.1	39.36	100
Elektrownia Adamów	102.9	93.3	40.00	91
Elektrownia Konin	50.1	50.1	38.61	100
Region subtotal	**350.1**	**340.5**		**97**
Other plants				
Zespół elektrowni Dolna Odra	125.1	125.1	33.05	100
Elektrownia Bełchatów	867.6	23.1	42.08	3
Elektrownia Turów	396.9	67.1	39.80	17
Elektrownia Kozienice SA	340.2	84.0	42.20	25
Elektrownia Ostrołęka SA	69.9	0.0	41.12	0
ALL plants	**3321.3**	**1211.6**		**36**

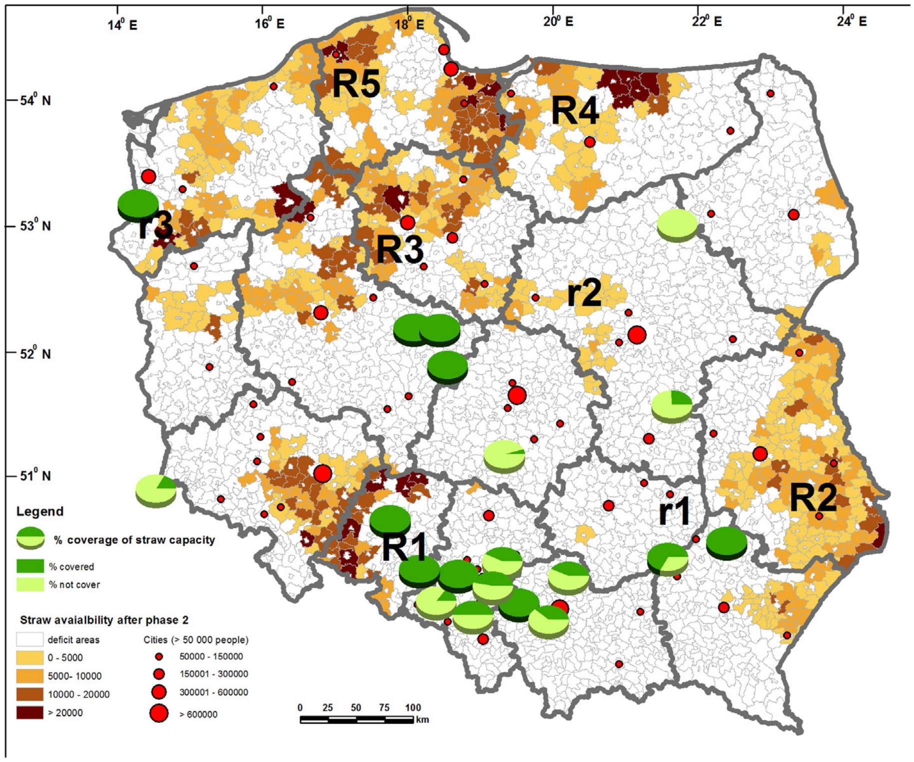

Fig. 4 – Capacity coverage in major power plants and remaining straw in NUTS-5 areas.

at considerable quantities, mainly because of the distant away from surplus regions. The latter could search for straw from neighbouring countries, as it is practically located on the Polish western border, however the former three should attain quotas either from straw sources such as miscanthus either from woody biomass or perennial crops.

4. Discussion

4.1. *The maximum distance hypothesis*

At the optimum only a part of spare straw theoretically available is transported to deficitary land units. The average distance between the transportation areas was about 18 km. Actually, in the case for a lack of straw, organic fertilisers can

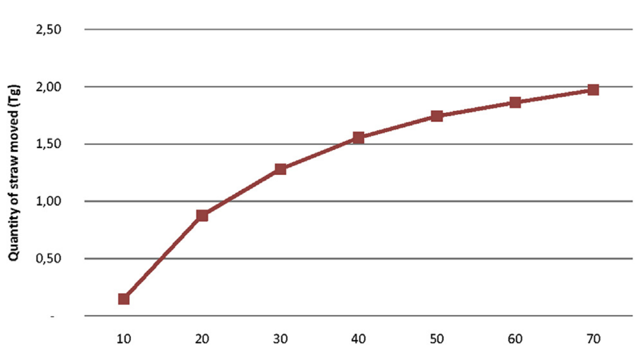

Fig. 5 – Distance factor impact on total straw quantity transported to areas with deficit.

be used for soil improvements that concern the major share of straw uses (Table 3). Alternatively, if maximum distance is raised to 40 km instead of 30 km then the quantity moved is increased from 1.2 to over 1.5 Tg of straw. About fifty percent of straw deficit is satisfied under the 30 km maximum distance hypothesis. At phase 1 (redistribution) almost equal quantities of straw available for energy is moved to the power plants under the 100 km hypothesis. In Fig. 5, the relation between the redistribution threshold distance and the quantity moved from surplus to deficit areas is depicted. Relaxation of the maximum distance constraint involves additional transport charges since more costly means are necessary instead of tractors and trailers already available on farms.

4.2. *Factors affecting cost of straw at the farm gate*

Due to various factors (meteorological conditions etc.) the available time varies across regions resulting in site-specific costs for the residues [30]. A typical cost structure calculated by these authors is baling 50%, road-siding 25%, loading 5% and average transport 20%. Besides the available time reported above that could cause up to a 30% variation in baling cost the farm size can also cause a baling cost variation. In Poland, straw is produced in various farms, sized between 10 and 20 ha (average area in NUTS-2) in Western Poland and 4–12 ha in Eastern Poland. The size of the farms affects the efficiency of collection and handling and consequently determines costs that to move downwards for large farms up to 30%, whereas the transport cost per km is negatively related to the overall travelled distance. More recently the cost of producing straw has been assessed at 85 € Mg^{-1} (Dry matter, DM) and miscanthus at about 90 € Mg^{-1} (DM) by the French research Institute Arvalis (cited by Ref. [31]). Transportation cost was estimated at 0.18 € Mg^{-1} km^{-1}. Corn stover production cost has been estimated at 42 € Mg^{-1} (DM) including collection, baling, wrapping, nutrient replacement, and storage. Details based on the US situation are analysed in Brechbill and Tyner [32]. Rogers and Brammer [24] thoroughly analysing transport costs of biomass in the UK, suggest a fixed component of about 0.85 € GJ^{-1} plus variable cost depending on distance varying within 0.18–0.22 € GJ^{-1} km^{-1}.

5. Concluding remarks

Agricultural waste represents an important source of biomass for energy, especially in large territories where abundant supplies can be made available for energy purposes. This source of biomass will be fully exploited by second-generation bio-energy technologies, thus overcoming the food-energy controversy, nevertheless it is readily available for usage in order to meet short or medium term goals and attain policy objectives. In this context, estimation of the straw potential for energy purposes has been undertaken based on well-known methods and at the same time focussing on the spatial dimension in order to closely approximate realistic numbers. A straw surplus and deficit that has been calculated at the NUTS-5 detail in Poland, has allowed the optimisation of transport models keeping priority to all other uses beside energy.

Once the quantities of straw available for energy have been determined at a municipal level, a second model allocates it among power plants after deducting straw directed to small grate boilers. Spatial resolution at a quite detailed level provides interesting results aiming at estimating straw effective potential for co-firing at the country level.

Further research is necessary to address the issue of supplying biomass to energy generation plants in order to fulfil national and European policy objectives. More specifically, advanced model building is required to integrate all possible demand for solid biomass and to select from various sources, and simultaneously maximising the industry and farmers' welfare as well as minimising transportation costs. This task goes beyond the objectives of this paper. Nevertheless state-of-the-art partial equilibrium integrated models can be exploited [31] as well as methods assisted by GIS to bridge the gap between regional statistics and local spatial information. Available spatial and economic data on Poland as well as numerous published materials can enhance such models.

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