Energy 36 (2011) 2017–2028

Contents lists available at ScienceDirect

Energy

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

Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: Case study Croatia

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A R T I C L E I N F O

Article history:
Received 8 March 2010
Received in revised form 28 August 2010
Accepted 6 October 2010
Available online 7 December 2010

Keywords:
Biomass
Forestry residues
Wheat straw
Corn stover
Energy potential

A B S T R A C T

This paper provides methodology for regional analysis of biomass energy potential and for assessing the cost of the biomass at the power plant (PP) location considering transport distance, transport costs and size of the power plants. Also, methodology for determination of an upper-level price of the biomass which energy plant can pay to the external suppliers has been proposed. The methodology was applied on the case of Croatia and energy potential of biomass in the Croatian counties was calculated, using different methodologies, for wheat straw, corn stover and forestry residues, types of biomass considered economically viable at the moment. Results indicate that the average energy potential of wheat straw is 8.5 PJ, corn stover 7.2 PJ and forestry residues 5.9 PJ.

1. Introduction

In order to reduce greenhouse gas (GHG) emissions, increase domestic industry development, secure and diversify the supply of energy, biomass as a renewable energy resource plays an important role for reaching these goals in the industrial countries [1–7]. Because of its widespread non-commercial use, biomass is covering more than 10% of the total world primary energy supply of 479 EJ [8]. Compared to other renewable energy sources biomass has the ability to store feedstock and use it when it is required [9]. Due to diversity of biomass residues and different products that can be obtained, there are several processes that allow transforming biomass in high energy fuels that are easy to transport and handle [10,11]. Furthermore, using biomass for production of energy can significantly contribute to the job creation and economic development of rural economies and slow down migrations from these areas to cities [12–17]. Because of that, detailed and accurate estimation of the different biomass resources and their energy potential is needed.

A number of studies for estimating the potential of agricultural [18–21] and forestry residues [22–25] based on the yield, forest area, residues coefficient (i.e., straw to grain ratio), and availability factors (i.e., mechanisation losses, fraction of the residue that can't be removed from the area) have been published. Potential of agricultural and forestry residues in those studies was calculated for the regions [26–28], countries [29–32] or worldwide [33,34] and in the most cases, geographic information system (GIS) has been used to calculate the potential of agricultural and forestry residues [35,36]. In order to provide fast and precise assessment of the potential, regional distribution and economic performance of the biomass, based on the location which is the key factor for the economic viability and environmental performance, the new methodology has been proposed. Because economic benefit is the major incentive for selection of the energy plant location and biomass fuels, this paper focuses on the competitive advantage of the agricultural and forestry residues in relation to energy plant location in order to increase understanding which part of the resource base is economically attractive for use in energy plants.

In the case of the biomass feedstock, the greater the output of the plant, the greater the biomass required and the greater the average distance required to transport the biomass [37]. At the end all this results with the increase of the energy plants fuel costs and electricity generation costs. These costs can be minimised by

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doi:10.1016/j.energy.2010.10.009

Table 1
Characteristics of different types of biomass [48–55].

		Wheat straw	Corn stover	Forest residual
Straw (stover) to grain ratio [−]		0.9–1.6	0.68–1.07	–
Straw cover required for soil protection [t/ha]	Wind erosion	1.0–2.0	–	–
	Water erosion	0.5–continues grass	–	–
Biomass for livestock production [t/cattle]		0.5–1.0	–	–
Mechanisation losses in the collecting process [%]		–	20–30	–
Soil protection factor [%]		–	30–60	–
Forest residue factor [%]		–	–	12–20
LHV [GJ/t]		13.74–17.86	11.5–15.3	15.06–5.34
Humidity of biomass [%]		20–100	30–15	10–60

optimal utilisation of the vehicle payload, by optimal location and size of the energy plant and by choice of the shortest travel paths [38–42].

This paper focuses on the identification and quantification of the available biomass in the regions and analysis of the biomass costs at the power plant locations. Firstly, methodology for assessment of regional biomass potential and the cost of the biomass at the plant location was developed. Also a model for the determination of an upper-level price for the biomass which energy plant can pay to the external suppliers is proposed. Secondly, the characteristics of the case study area have been elaborated and the results of the assessment and economic analysis are presented.

2. Methodology

In order to provide a comprehensive overview on the domestic potential of the biomass for different regions, the study aimed to investigate all economically viable biomass resources based on the region needs and applicable technology. To select all economically viable biomass resource the RenewIslands/ADEG methodology has been used. This methodology was firstly developed for use on the islands [43,44] but during time, it has been upgraded for use in other regions [45], in ADEG project [46,47]. A very detailed description of RenewIslands methodology has been given in [43] and RenewIslands/ADEG methodology in [44]. Using this methodology three types of biomass were selected for further analysis, based on the region needs, its resources and the applicable technology. Selected biomass types are:

- Biomass from wheat straw
- Biomass from corn stover
- Biomass from forestry residues

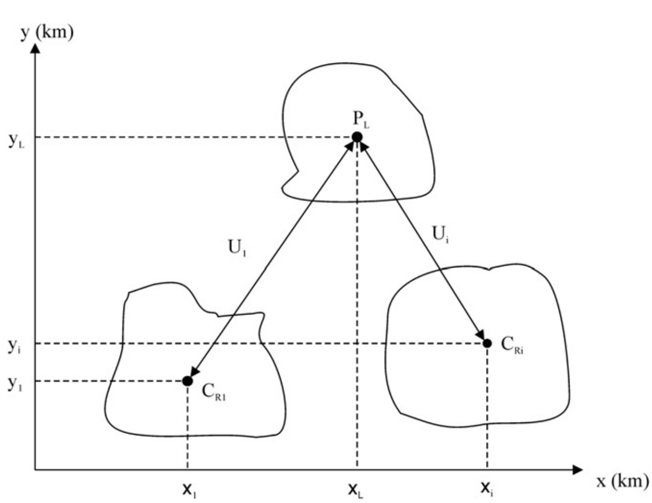

Fig. 1. Visual representation of the optimal transport distance methodology.

2.1. Technical available potential of biomass

The total potential of biomass is defined as the total annual production of agricultural and forestry residues in the regions. The total potential of biomass cannot be utilized as an energy source, because the part of the residuals needs to be left on the field for soil protection, feeding and bedding of animals and because of mechanisation losses during collecting and transportation process. Technical available potential of biomass for energy purpose is determined by subtracting quantities of residuals needed for soil protection, animal feeding and bedding from the total production of each biomass residue.

2.1.1. Agricultural residual – wheat straw

Wheat straw is an agricultural residual that remains on the soil surface after grain harvest. The amount of the residue produced on the field varies considerably with growing conditions and the amount of crop grown. Total quantity of this residual, generated during the grain harvest, is not possible to find in statistic yearbook and because of that total production of the wheat straw in the regions i (expressed in t) will be obtained as:

$$T_{WS(i)} = W_{P(i)} \times STGR_{W(i)} \quad (1)$$

where $W_{P(i)}$ represents the wheat production in region i (t) and $STGR_{W(i)}$ the wheat straw to grain ratio, which depends on the type of wheat, time of wheat seeding, cultivation of soil and total amount of nitrogen used for soil fertilization in region i (see Table 1)

Straw produced in regions should not all be removed from the fields. One part must be left on the field for the wind and water erosion control and one part of straw is used for bedding and feeding of livestock. The total amount of wheat straw required for soil protection depends on the soil texture and field slope. Coarse soil textures require large quantities of residue for control of wind erosion, and quantities needed for water erosion protection increase with the field slope. Straw needed for soil protection in the regions (expressed in t) will be obtained as:

$$S_{PW(i)} = SCP_{(i)} \times C_{A(i)} \quad (2)$$

where $SCP_{(i)}$ represents the straw cover required for soil protection in region i (t/ha) (see Table 1) and $C_{A(i)}$ the cultivated area of wheat in region i (ha).

Straw required for bedding and feeding of livestock varies from region to region and mainly depends on the duration of winter season and the number of cattle in the particular region. In regions with a large number of cattle this residue can be even higher than the potential of wheat straw in the region. Because of that these regions need to import straw from other regions which have high production of straw and small number of cattle. Requirements of wheat straw for feeding and bedding of livestock in the region i (expressed in t) will be obtained as:

Table 2
Croatian state owned forest parameters [52].

Counties	Forest area and forest land	Wood stock	Yearly growth	Yearly felling
	1000 ha	1000 m^3	1000 m^3	1000 m^3
Zagreb county	62	15,000	400	272
Sisak-Moslavina	151	36,700	1100	686
Karlovac county	111	23,800	566	470
Koprivnica-Križevci	42	11,650	305	265
Bjelovar-Bilogora	86	24,200	635	500
Primorje-Gorski Kotar	170	35,450	682	605
Lika-Senj	306	44,920	1050	680
Virovitica-Podravina	64	18,140	520	400
Požega-Slavonija	78	16,660	450	290
Brod-Posavina	53	13,680	380	300
Osijek-Baranja	114	23,000	770	620
Vukovar-Syrmia	69	20,240	545	450
Total “Hrvatske Šume” d.o.o.	2020	302,420	7960	5800

$$S_{RL(i)} = SLP_{(i)} \times N_{C(i)} \quad (3)$$

where $SLP_{(i)}$ represents the straw used for livestock production in region i (t/cattle) (see Table 1) and $N_{C(i)}$ the number of cattle in the region i.

Technical available potential of straw is obtained after subtracting the current quantities of straw needed for soil protection and for feeding and bedding of livestock in the region from the total production of wheat straw in region. In some regions this potential can be even lower than zero due to small production of wheat and

Table 3
Croatian cereals parameters for a period of 4 years (2002–2006) [58].

Counties		Wheat			Corn		
		Cultivated area, ha	Production, t	Yield, t/ha	Cultivated area, ha	Production, t	Yield, t/ha
Total Croatia	Avg.	190,382	750,946	3.97	357,278	2,053,043	5.86
	Max.	233,611	988,175	4.58	407,455	2,501,774	6.92
	Min.	146,411	601,748	2.96	296,521	1,569,150	3.86
Zagreb county	Avg.	8916	27,216	3.16	31,760	149,846	4.92
	Max.	13,929	45,967	3.67	39,522	211,441	5.90
	Min.	4830	17,726	2.36	20,619	106,319	2.72
Sisak-Moslavina	Avg.	5693	18,609	3.32	24,404	130,232	5.39
	Max.	8978	32,679	3.70	25,793	153,525	6.51
	Min.	2954	5444	2.35	22,822	92,339	3.58
Varaždin	Avg.	4864	17,070	3.60	19,241	93,520	5.08
	Max.	6317	23,625	4.29	22,627	108,600	6.64
	Min.	3309	12,576	2.56	15,576	63,185	2.82
Koprivnica-Križevci	Avg.	11,731	41,803	3.65	33,669	193,181	5.82
	Max.	14,331	53,886	4.27	36,759	231,531	7.13
	Min.	8693	34,076	2.63	29,367	142,625	3.88
Bjelovar-Bilogora	Avg.	10,417	31,599	3.17	35,215	220,695	6.23
	Max.	15,407	47,916	4.28	38,375	282,442	7.44
	Min.	7112	23,927	2.05	33,387	143,906	4.21
Virovitica-Podravina	Avg.	18,063	73,716	4.03	28,248	165,572	5.89
	Max.	21,577	96,882	4.56	31,908	197,631	6.82
	Min.	13,394	51,566	3.21	24,220	136,356	4.53
Požega-Slavonija	Avg.	9242	37,202	4.05	12,908	80,803	6.24
	Max.	11,254	50,079	4.46	13,834	102,783	7.43
	Min.	7640	32,012	3.11	11,379	58,152	4.53
Brod-Posavina	Avg.	12,238	47,207	3.85	21,597	128,731	6.07
	Max.	14,698	59,527	4.17	25,702	165,006	7.16
	Min.	10,586	36,789	3.13	17,613	96,381	3.98
Osijek-Baranja	Avg.	54,038	237,067	4.36	63,942	401,530	6.37
	Max.	60,171	293,034	5.01	73,554	517,512	7.34
	Min.	47,469	174,534	3.28	55,197	311,134	4.23
Vukovar-Syrmia	Avg.	34,415	154,500	4.49	38,352	270,261	7.16
	Max.	38,138	184,590	4.97	49,070	376,369	8.38
	Min.	28,562	122,642	3.50	26,990	230,093	5.15
Međimurje	Avg.	5473	22,586	4.20	15,556	101,089	6.64
	Max.	6971	31,161	4.56	17,994	123,799	7.96
	Min.	4062	18,524	3.19	12,964	72,022	4.14

Table 4
Characteristics of different types of biomass in Croatia.

	Wheat straw	Ref.	Corn stover	Ref.	Forest residues	Ref.
Straw (stover) to grain ratio [–]	1.6	[48,62]	0.8	[48,62]	–	
Straw cover required for soil protection [t/ha]	1.5	[59,62]	–		–	
Biomass for livestock production [t/cattle]	0.6	[60,62]	–		–	
Mechanisation losses in the collecting process [%]	–		20	[48,61,62]	–	
Soil protection factor [%]	–		50	[48,59,61]	–	
Forest residue factor [%]	–		–	–	12	[52,63]
Lower heating value of biomass [GJ/t]	13.74	[62]	14.7	[62]	8.5	[62]
Humidity of biomass [%]	20	[62]	20	[62]	50	[52,62]

large number of cattle in the region. This means that wheat straw needs to be imported in the region. Technical available potential of wheat straw in the region i (expressed in t) will be obtained as

$$E_{PW(i)} = T_{WS(i)} - S_{PW(i)} - S_{RL(i)} \quad (4)$$

where $T_{WS(i)}$ represents the total wheat straw production in region i (t), $S_{PW(i)}$ the straw needed for soil protection in region i (t) and $S_{RL(i)}$ the straw requirements for feeding and bedding of livestock in the region i (t).

2.1.2. *Agricultural residual – corn stover*

Corn stover is an agricultural residue defined as the portions of the corn plant aside from the corn kernels that remain on the soil surface following grain harvest. Same as with the wheat straw, total quantity of the corn stover, generated during the grain harvest, is not possible to find in statistic yearbook and because of that total potential of corn stover needs to be calculated using corn stover to grain ratio. Total production of the corn stover in the region i (expressed in t) will be obtained as:

$$T_{CS(i)} = C_{P(i)} \times STGR_{C(i)} \quad (5)$$

where $C_{P(i)}$ represents the corn production in the region i (t) and $STGR_{C(i)}$ the corn stover to grain ratio, whose value mainly depends on grain humidity in the time of harvesting (see Table 1)

It is not possible to collect all corn stover from the field because of the losses generated during the process of harvesting and

Table 5
Technical available potential of corn stover in Croatian counties.

Counties		Total potential of corn stover, [t]	Corn stover needed for soil protection, [t]	Harvesting and collection losses, [t]	Technical available potential of corn stover, [t]
Total Croatia	Avg	1,642,434	821,217	328,487	492,730
	Max	2,001,419	1,000,710	400,284	600,426
	Min	1,255,320	627,660	251,064	376,596
Zagreb county	Avg	119,876	59,938	23,975	35,963
	Max	169,153	84,576	33,831	50,746
	Min	85,055	42,528	17,011	25,517
Sisak-Moslavina	Avg	104,186	52,093	20,837	31,256
	Max	122,820	61,410	24,564	36,846
	Min	73,871	36,936	14,774	22,161
Varaždin	Avg	74,816	37,408	14,963	22,445
	Max	86,880	43,440	17,376	26,064
	Min	50,548	25,274	10,110	15,164
Koprivnica-Križevci	Avg	154,544	77,272	30,909	46,363
	Max	185,225	92,612	37,045	55,567
	Min	114,100	57,050	22,820	34,230
Bjelovar-Bilogora	Avg	176,556	88,278	35,311	52,967
	Max	225,954	112,977	45,191	67,786
	Min	115,125	57,562	23,025	34,537
Virovitica-Podravina	Avg	132,458	66,229	26,492	39,737
	Max	158,105	79,052	31,621	47,431
	Min	109,085	54,542	21,817	32,725
Požega-Slavonija	Avg	64,642	32,321	12,928	19,393
	Max	82,226	41,113	16,445	24,668
	Min	46,522	23,261	9304	13,956
Brod-Posavina	Avg	102,985	51,492	20,597	30,895
	Max	132,005	66,002	26,401	39,601
	Min	77,105	38,552	15,421	23,131
Osijek-Baranja	Avg	321,224	160,612	64,245	96,367
	Max	414,010	207,005	82,802	124,203
	Min	248,907	124,454	49,781	74,672
Vukovar-Syrmia	Avg	216,209	108,104	43,242	64,863
	Max	301,095	150,548	60,219	90,329
	Min	184,074	92,037	36,815	55,222
Međimurje	Avg	80,871	40,435	16,174	24,261
	Max	99,039	49,520	19,808	29,712
	Min	57,618	28,809	11,524	17,285

Table 6
Technical available potential of wheat straw in Croatian counties.

Counties		Total potential of wheat straw, [t]	Wheat straw needed for soil protection, [t]	Wheat straw needed for feeding and bedding of livestock, [t]	Technical available potential of wheat straw, [t]
Total Croatia	Avg	1,201,513	285,573	293,188	622,752
	Max	1,581,080	350,417		937,476
	Min	962,797	219,617		449,993
Zagreb county	Avg	43,545	13,373	32,786	–
	Max	73,547	20,894		19,867
	Min	28,362	7245		–
Sisak-Moslavina	Avg	29,774	8539	17,305	3930
	Max	52,286	13,467		21,514
	Min	8710	4431		–
Varaždin	Avg	27,312	7296	13,876	6140
	Max	37,800	9476		14,449
	Min	20,122	4964		1283
Koprivnica-Križevci	Avg	66,885	17,597	47,222	2066
	Max	86,218	21,497		17,499
	Min	54,522	13,040		–
Bjelovar-Bilogora	Avg	50,559	15,625	43,448	–
	Max	76,666	23,111		10,107
	Min	38,283	10,668		–
Virovitica-Podravina	Avg	117,945	27,095	11,551	79,299
	Max	155,011	32,366		111,095
	Min	82,506	20,091		50,863
Požega-Slavonija	Avg	59,523	13,863	7141	38,519
	Max	80,126	16,881		56,104
	Min	51,219	11,460		32,618
Brod-Posavina	Avg	75,530	18,356	10,210	46,964
	Max	95,243	22,047		62,986
	Min	58,862	15,879		32,773
Osijek-Baranja	Avg	379,307	81,057	30,806	267,443
	Max	468,854	90,257		347,792
	Min	279,254	71,204		177,245
Vukovar-Syrmia	Avg	247,200	51,623	15,802	179,775
	Max	295,344	57,207		222,335
	Min	196,227	42,843		137,583
Međimurje	Avg	36,138	8209	10,250	17,679
	Max	49,858	10,457		29,151
	Min	29,638	6093		13,295

collecting. These losses mainly depend on the mechanisation used in the harvesting and collecting process [48,49]. Total amount of corn stover which cannot be removed from the field (expressed in t) will be obtained as:

$$U_{CS(i)} = T_{CS(i)} \times M_L \tag{6}$$

where $T_{CS(i)}$ represents the total potential of corn stover which is produced on the field in the region i (t) and M_L the mechanisation losses (%), which mainly depend on the field machinery used (see Table 1).

Corn stover residues left on the field protect soil from water and wind erosion and increase soil organic carbon (SOC) dynamics. For higher corn yield and lower soil erosion, greater presence of stover is needed. Therefore, adequate residue cover must be left on the field to prevent erosion losses and to increase total SOC [56]. Total amount of corn stover required for soil protection in the region i (expressed in t) will be obtained as:

$$S_{PC(i)} = T_{CS(i)} \times S_{PP(i)} \tag{7}$$

where $T_{CS(i)}$ represent the total amount of corn stover produced on the field in region i (t), and $S_{PP(i)}$ the soil protection factor in the region i (%).

Technical available potential of corn stover is obtained after subtracting the quantities of stover needed for soil protection and losses due to collecting and harvesting process from the total production of corn stover in region. These mechanisation losses in the process of harvesting and collecting of corn stover are higher than the losses in collecting of straw. Main reason for this is the specific shape of the corn stover. Technical available potential of corn stover in the region i (expressed in t) will be obtained as:

$$E_{PC(i)} = T_{CS(i)} - S_{PC(i)} - U_{CS(i)} \tag{8}$$

where $T_{CS(i)}$ represents the total corn stover production in region i (t), $S_{PC(i)}$ the corn stover required for soil protection in region i (t) and $U_{CS(i)}$ the uncollected corn stover from the field in the region i (t).

2.1.3. Forestry residues

Biomass usable for energy purpose is produced during silvicultural operations aimed at producing firewood and industrial wood and from sustainable sawlog harvest. These residues represent the most economical and technical fraction to be used in a bioenergy system. The methodology followed is based on the current national yearly felling and biomass fraction, but only for tree branches over 7 cm in diameter. Technical available potential

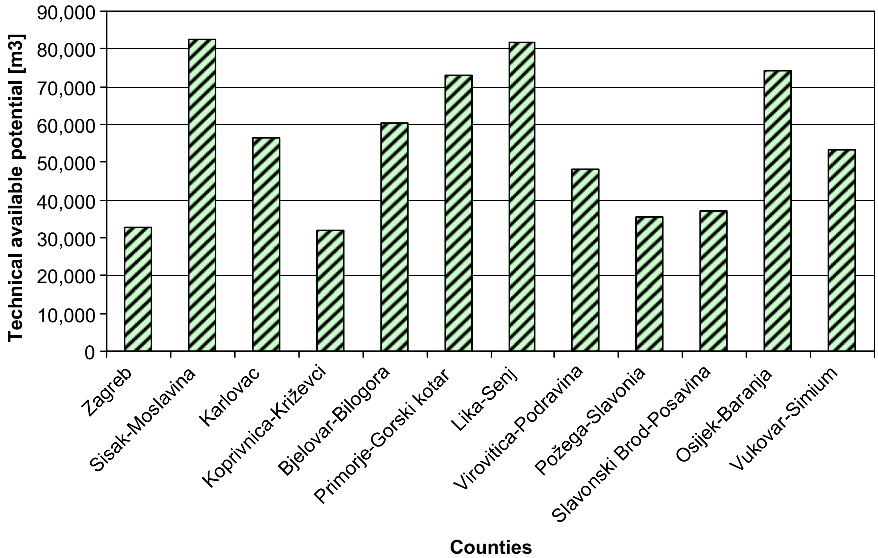

Fig. 2. Technical available potential of forestry residues in Croatian counties.

Table 7
Energy potential of agricultural residuals in Croatian counties.

Counties		Energy potential of corn stover, 1000 GJ	Energy potential of wheat straw, 1000 GJ
Total Croatia	Avg	7243	8557
	Max	8826	12,881
	Min	5536	6183
Zagreb county	Avg	529	–
	Max	746	273
	Min	375	–
Sisak-Moslavina	Avg	459	54
	Max	542	296
	Min	326	–
Varaždin	Avg	330	84
	Max	383	199
	Min	223	18
Koprivnica-Križevci	Avg	682	28
	Max	817	240
	Min	503	–
Bjelovar-Bilogora	Avg	779	–
	Max	996	139
	Min	508	–
Virovitica-Podravina	Avg	584	1090
	Max	697	1526
	Min	481	699
Požega-Slavonija	Avg	285	529
	Max	363	771
	Min	205	448
Brod-Posavina	Avg	454	645
	Max	582	865
	Min	340	450
Osijek-Baranja	Avg	1417	3675
	Max	1826	4779
	Min	1098	2435
Vukovar-Syrmia	Avg	953	2470
	Max	1328	3055
	Min	812	1890
Medimurje	Avg	357	243
	Max	437	401
	Min	254	183

of forestry residues in the region i (expressed in m^3) will be obtained as:

$$E_{PF(i)} = Y_{F(i)} \times F_R \tag{9}$$

where Y_F represents the yearly felling of the forest in the region i (m^3) and F_R the forestry residues factor (%), the amount of the total mass of the tree which can be used for the energy purpose (see Table 1).

2.2. Energy potential

The assessment of the biomass energy potential is based on the total biomass potential and the respective lower heating value of each biomass type available for energy purposes. Lower heating value is different for each type of biomass, its value depends on the chemical structure of biomass, contents of moisture in the biomass and content of the hydrogen in the biomass. Energy potential for different types of biomass (expressed in 1000 GJ) will be obtained as:

$$B_{ep(n)} = E_{p(n)} \times \mathrm{LHV}_{(n)} \tag{10}$$

where $E_{p(n)}$ represents the technical available potential of biomass type n (expressed in tons) and $\mathrm{LHV}_{(n)}$ the lower heating value of biomass (expressed in GJ/ton) (see Table 1), which depends on humidity and type of wood.

2.3. Cost of biomass at the power plant location

Cost of biomass at the power plant location depends on the cost of biomass at the forest road or agricultural field, transportation cost, distance between biomass location and plant location and on the size of the energy plant. The main impact on the cost of the biomass has biomass feedstock costs and transport distance of the biomass which mainly depends on the size of the power plants and on the available biomass in the regions. Cost of biomass at the power plant locations (expressed in €/tons) will be obtained as:

$$G_C = \sum_{i=1}^{n} \frac{[C_B + (T_P \times U_i)] \times K_{Bi}}{P_B} \tag{11}$$

where:

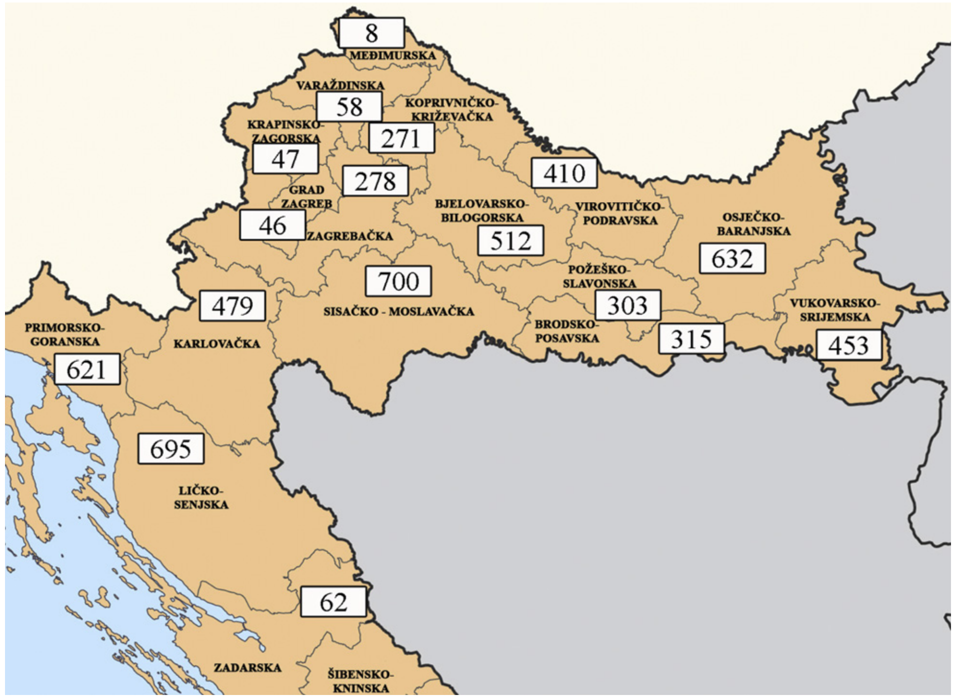

Fig. 3. Energy potential of forest residues in Croatian counties [1000 GJ].

- G_C: Average price of biomass at the plant location (€/ton)
- C_B: Biomass feedstock costs (€/ton)
- T_P: Biomass specific transport costs (€/ton/km)
- U_i: Distance between administrative center of the region and the plant location (km)
- K_{Bi}: The total amount of biomass delivered from the region i (ton)
- P_B: Annual fuel consumption of the power plant (ton)

Methodology for determining the distance (U_i) between the plant location (P_L) and center of the region (C_{Ri}) is illustrated in Fig. 1. In Fig. 1 distance between plant location and center of the region is illustrated as a straight line but for more precise results, Geographical Information System (GIS) is recommended to be used.

2.4. Upper-level price of the biomass and electricity generation cost

Methodology for the evaluation of upper-level price of the biomass and economic prospect of biomass-fired power plants has been performed based on electricity generation cost and feed-in tariffs. Upper-level of the biomass price will be obtained as:

$$\mathrm{COB}_{\max} = \left[\mathrm{FIT} - \left(\frac{C_I}{\mathrm{LF}} \times \frac{i \times (1+1)^n}{(1+i)^n - 1} - C_{\mathrm{OM}}\right)\right] \times \mathrm{LHV} \times \eta_{\mathrm{PP-E}} \times \frac{1000}{3.6} \quad (12)$$

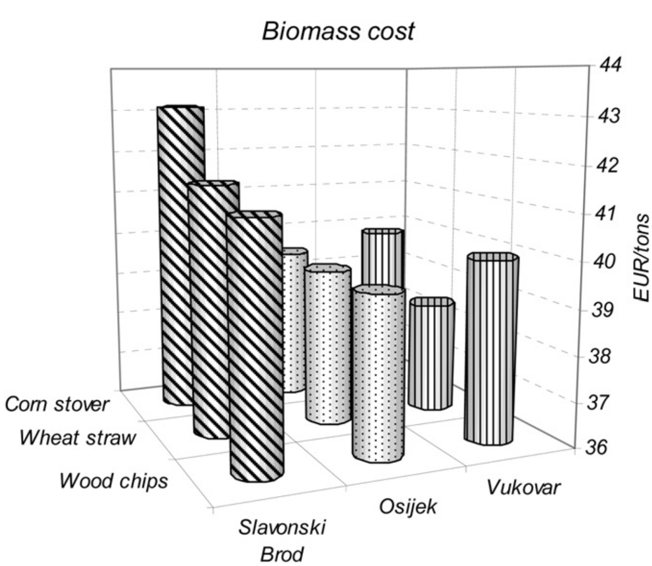

Fig. 4. Cost of biomass at the selected location for the power plants with the capacity of 100,000 t/year and biomass transport cost of 0.1 €/t/km.

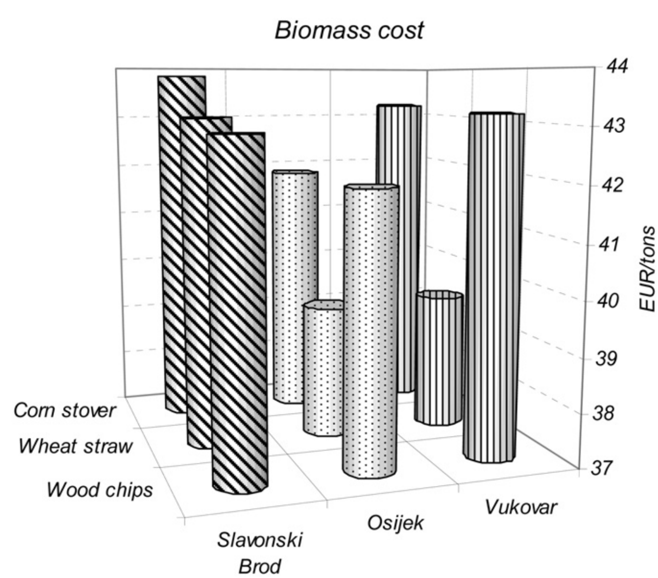

Fig. 5. Cost of biomass at the selected location for the power plants with the capacity of 200,000 t/year and biomass transport cost of 0.1 €/t/km.

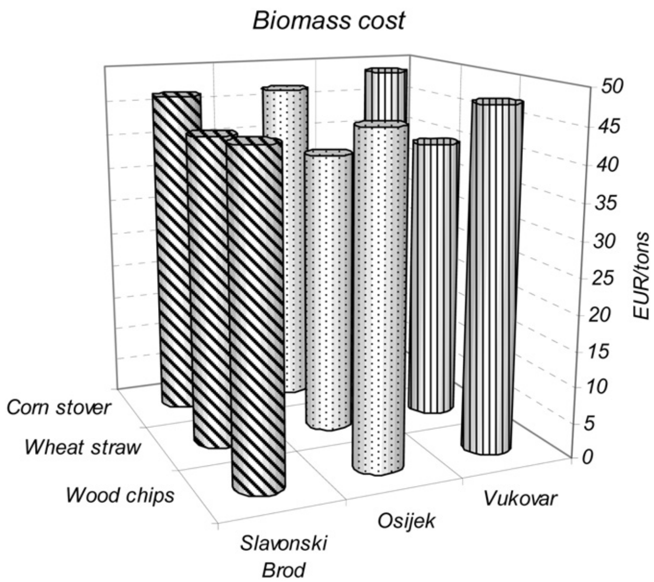

Fig. 6. Cost of biomass at the selected location for the power plants with the capacity of 300,000 t/year and biomass transport cost of 0.1 €/t/km.

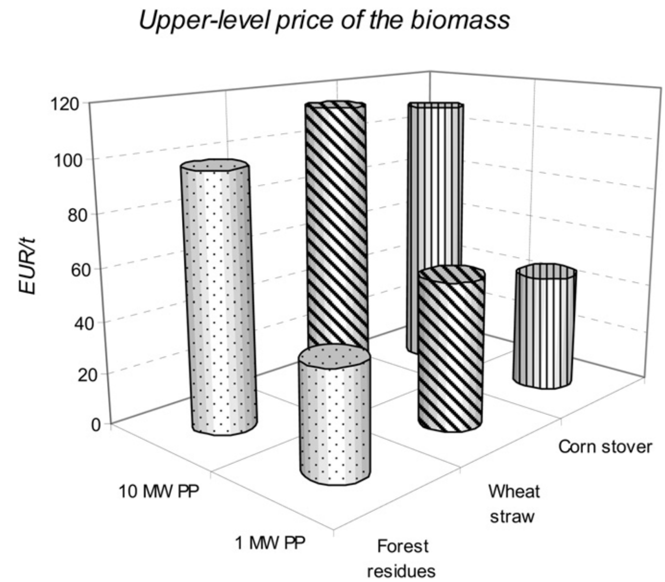

Fig. 7. Upper-level price of the biomass for different sizes of the power plants and biomass types in Croatia.

where COB_{max} represents the maximal cost of the biomass at the power plant location during the whole year (€/t), FIT the feed-in tariffs for produced electricity from biomass-fired power plant (€/kWh), C_I the specific investment cost (€/kWh), LF the annual load factor (h/a), i the discount rate (%), n the economic life time of power plant, $C_{O\&M}$ the specific operation and maintenance cost of the power plant, LHV the lower heating value of the biomass (GJ/t) and $\eta_{PP\text{-}E}$ the net electric efficiency of the energy plant (−).

Model for the assessment of electricity generation costs from the biomass has been proposed. The cost of generated electricity depends on the operating and maintenance cost, investment cost, cost of the biomass at the agricultural field or forest road, specific transport cost and on the transport distance of the biomass. Electricity generation cost will be obtained as:

$$C_E = C_{OM} + \left(\frac{C_I}{LF} \times \frac{i \times (1+1)^n}{(1+i)^n - 1}\right) + \left[\left(\frac{3.6}{1000} \times \frac{1}{LHV \times \eta_{PP-E}}\right) \times (F_S + T_R \times D)\right] \quad (13)$$

where C_E represents the electricity generation cost (€/kWh), F_S the cost of the biomass at the agricultural field or forest road (€/t), T_R the biomass specific transport cost (€/ton/km/) and D the distance to plant (km).

Table 8
Characteristics of the biomass-fired power plants [7,62,66,67].

P (MW$_e$)	C_I (€/kW)	$C_{O\&M}$ (c€/kWh)	η_{PP-E} (%)	LF (h/a)	LHV (GJ/t)	Biomass price (€/t)
Forest residues (FR)						
1 MW	4100	1.54	29	7971.6	8.5	36.9
10 MW	1300	0.56	35	7884	8.5	40
Wheat straw (WS)						
1 MW	4200	2.11	29	7971.6	13.74	36.4
10 MW	1700	1	29	7884	13.74	38.5
Corn stover (CS)						
1 MW	4400	2.21	27	7971.6	14.7	36.1
10 MW	1850	1.01	25	7884	14.7	39.85

3. Study area: Croatia

3.1. Production of cereals and forest potential in Croatia

Land surface of the Republic of Croatia spreads over a total of 56,542 km^2, out of which 42% is under forests, 19% is available for cultivation, 19% is limitedly suitable for cultivation, and 14% is not available for cultivation and can be used for cultivation of energy crops [57]. Republic of Croatia is divided into counties, primary territorial subdivisions. There are total 21 counties, counting in the City of Zagreb which has status equal to a county. Croatia produces more than 2.8 Mt of wheat and corn grain annually and cuts over 4.5 million cubic meters of state owned forest [52,58]. Planed yearly felling in the period of 2006–2015 is around 5.8 million cubic meters of tree and for the period 2016–2025 planed yearly felling will be between 5.8 and 6.4 million cubic meters [52]. In Table 2

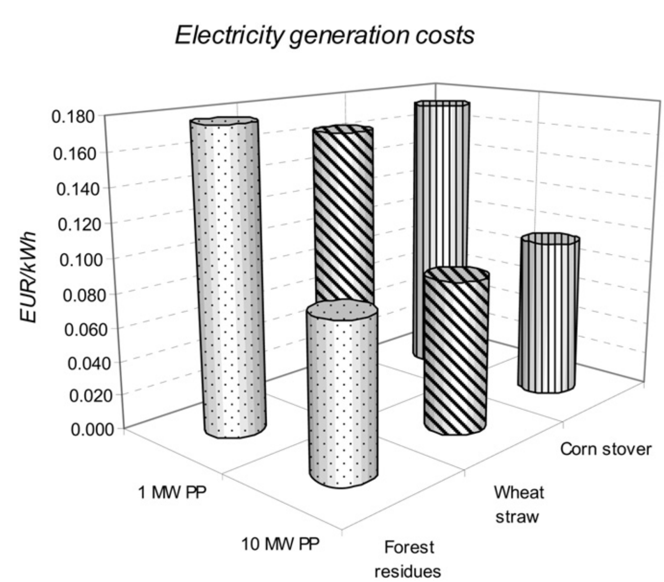

Fig. 8. Electricity generation costs for the biomass-fired power plants.

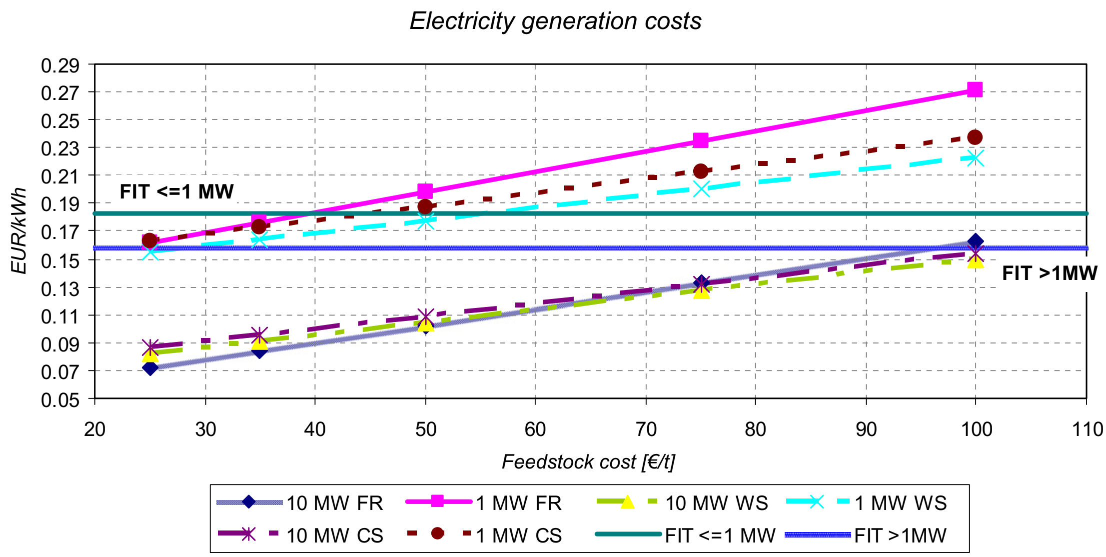

Fig. 9. Influence of the feedstock cost on the electricity generation cost, $T_R = 0.1$ €/t/km, $D = 50$ km for 10 MW PP and $D = 15$ km for 1 MW PP.

characteristic data for state owned forests in Croatian counties for period 2006–2015, is presented. Total cultivated area, production of cereals and yield in Croatian counties, which have reasonable potential are shown in Table 3.

3.2. Technical available potential of biomass

The availability of biomass from the forest and main crops in Croatia has been evaluated. The potential of biomass in counties was calculated by using appropriate value from Table 4.

Agricultural biomass has been identified and calculated for two categories, wheat straw and corn stover. Traditionally agricultural counties in the east part of Croatia, Osijek-Baranja and Vukovar-Syrmia, have the highest potential of the agricultural residues. To calculate technical available potential of wheat straw, number of cattle in counties has been used. These numbers vary from county to county and in case of Croatia this data has been obtained from [64]. Technical available potential of wheat straw in Croatia ranges from the maximum 930 kt year^{-1} to the minimum 450 kt year^{-1} and corn stover ranges from the maximum of 600 kt year^{-1} to the minimum of 370 kt year^{-1}. Technical available potential of corn stover is presented in Table 5 and potential of wheat straw is presented in Table 6.

Calculated potential of forestry residues in Croatia is over 700,000 cubic meters. Counties with the large quantities of forestry residues are Sisak-Moslavina and Lika-Senj, over 80,000 cubic meters. Technical available potential of forestry residues in Croatian counties is shown in Fig. 2.

3.3. Energy potential of biomass

The energy potential of the biomass in Croatia was estimated by using LHV for different types of biomass. Characteristics of various biomass types, in Croatia, have been reported in Table 4. Highest energy potential has the east part of Croatia and minimal potential have counties in the south part of Croatia so that potential can be

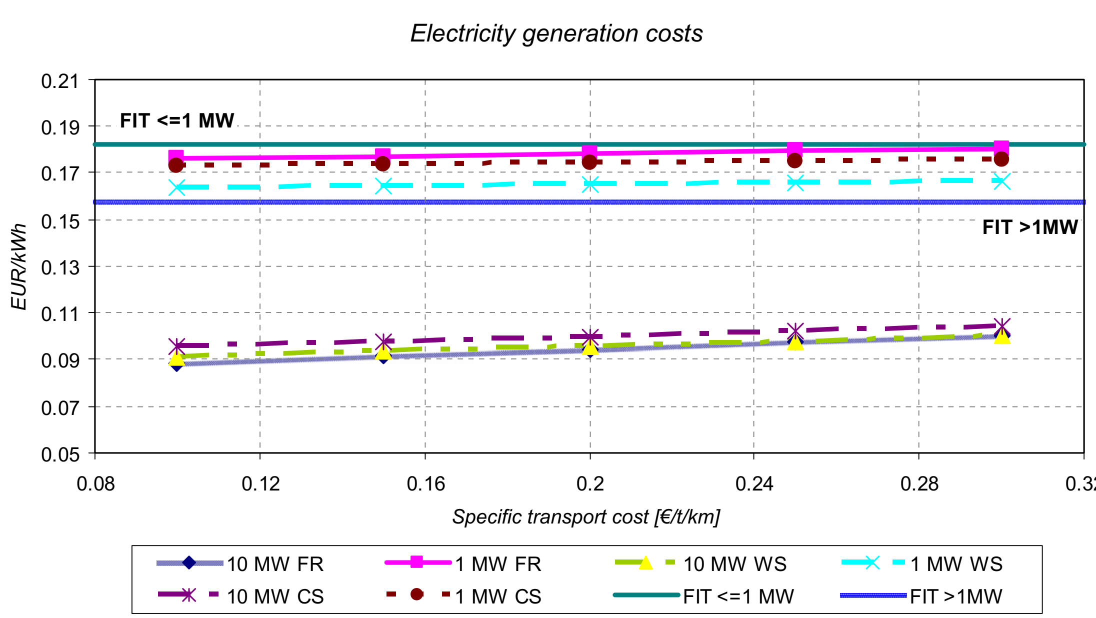

Fig. 10. Influence of the specific transport cost on the electricity generation cost, $F_S = 35$ €/t, $D = 50$ km for 10 MW PP and $D = 15$ km for 1 MW PP.

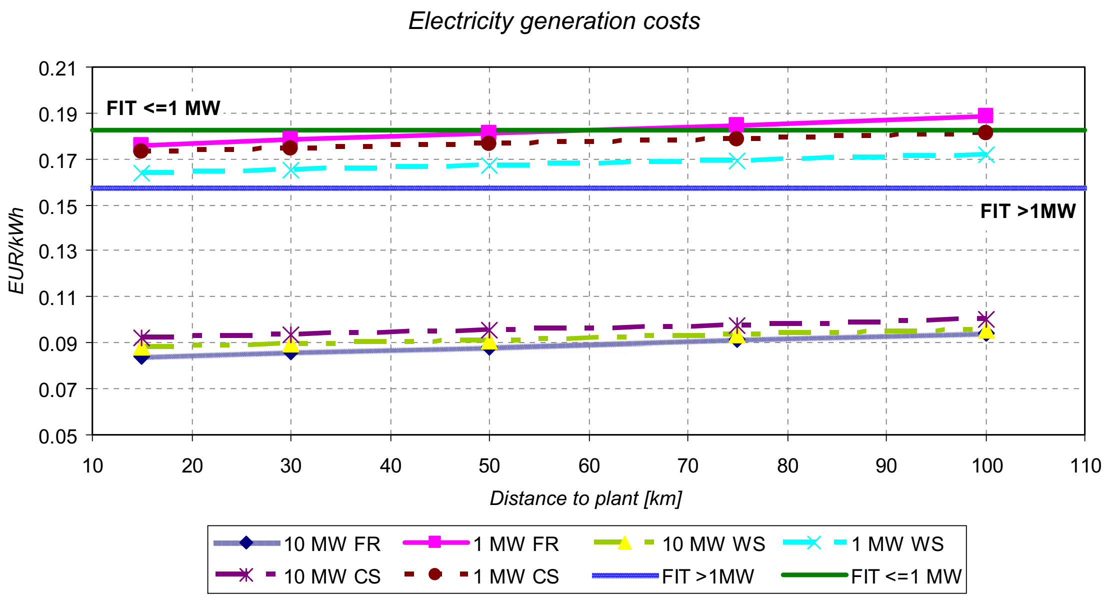

Fig. 11. Influence of the collecting radius of the biomass on the electricity generation cost, $T_R = 0.1$ €/t/km, $F_S = 35$ €/t/km.

disregarded. Energy potential of agricultural residuals in Croatia is presented in Table 7.

Energy potential of forestry residues is calculated for all counties in Croatia and the potential is presented in Fig. 3. Highest potential has Sisak-Moslavina County, over 700,000 GJ and total energy potential of forestry residues in Croatia state owned forests is over 5.9 PJ. For transforming technical available potential of forestry residues from cubic meters to tons, density of 1 t/m^3 was used [52].

3.4. Cost of biomass at the power plant location

The cost of the biomass at the location of the power plant has been calculated based on the input data from Section 3.2 and Eq. (11). Transport distance of biomass has been evaluated using methodology from Section 2.3. For purpose of this study road distance from the plant location and center of regions (counties) was obtained from the existing road maps in Croatia. Transport cost of biomass of 0.1 €/t/km [65] and the cost of biomass of 35 €/t [52,62] on road, have been used in the calculation of the biomass costs. Also, costs of biomass have been calculated for different sizes of power plants ranging between 100,000 t and 300,000 t. Calculated results for different types of biomass, size and location of the power plants (selected by taking into account biomass potential of counties, development of the cities and polycentric development of the Republic of Croatia) have been presented in Figs. 4–6.

The comparison of the calculated biomass cost shows that the cost generally increases with the increase of the plant capacity. The illustration also shows that selected locations Osijek and Vukovar have lower calculated price of biomass compared to Slavonski Brod. Calculated costs for the biomass-fired power plant in Vukovar are in range between 38.5 €/t and 40 €/t. These costs are calculated for the biomass-fired plant with the capacity of 100,000 t/years. Also, the illustration shows that the most suitable location for the power plants with the capacity of 200,000 t/year and 300,000 t/year is Osijek, followed by Vukovar and Slavonski Brod.

3.5. Upper-level price of the biomass and electricity generation cost

To determinate upper-level price of the biomass at the plant location, Eq. (12) has been used and appropriated value from Table 8. Feed-in tariffs for electricity delivered from biomass-fired power plants are determined with respect to the power plant size. For the power plants with installed power up to and including 1 MW, feed-in tariff for 2010, in Croatia, is 1.3312 HRK/kWh (0.1824 €/kWh) and for power plants with installed power over 1 MW, feed-in tariff is 1.1537 HRK/kWh (0.158 €/kWh) [68]. The discount rate of 18% and the economic life time of 12 years were used to determinate the maximal costs of the biomass in Croatia [7,62]. Calculated results for different size of power plants and biomass types have been presented in Fig. 7.

Calculated results show that the upper-level of the biomass price for the power plants with installed power of 10 MW is 97.58 €/t for forestry residues, 114.06 €/t for wheat straw and 109.12 €/t for corn stover fired power plants. For power plants with installed power of 1 MW, upper-level price of forestry residues is 40.83 €/t, for wheat straw 56.85 €/t and for corn stover this price is 46.06 €/t.

The electricity generation costs from the biomass-fired plants have been calculated by using Eq. (13) and appropriated value from Table 8 and Section 3.4. Input data in Table 8 is for biomass-fired plants with grate combustion and steam turbines. Calculated results for different size of power plants and for three types of biomass have been presented in Fig. 8.

Calculated results show that electricity generation cost for 10 MW power plant which uses forestry residues as fuel is 0.088 €/kWh, for wheat straw fuel this cost is 0.09 €/kWh and for corn stover fuel electricity generation cost is 0.095 €/kWh. For power plants with the installed power of 1 MW which use forestry residues as fuel, electricity generation cost is 0.177 €/kWh, for wheat straw fuel 0.164 €/kWh and for corn stover fuel this cost is 0.173 €/kWh. The comparison of the calculated electricity generation costs shows that the best solution for 10 MW power plants is forestry residues as fuel and for 1 MW power plants it is wheat straw.

Since the size of the power plant, cost of the biomass at the agricultural field or forest road, biomass specific transport cost and the biomass transport distance have high influence on the electricity generation cost, a sensitive analysis has been performed. For the analysis, Eq. (13) has been used. The results have been presented in Figs. 9–11.

On the illustrations, calculated generation costs are compared with feed-in tariffs for biomass-fired power plants in Croatia. The analysis of the presented data shows that most of the biomass-fired power plants would be profitable. Also analysis shows that the highest impact on the electricity generation costs has the price of the biomass feedstock and in case when these costs are very high, electricity generation costs from the biomass-fired power plants are higher than feed-in tariffs.

4. Conclusion

In this paper, a methodology for economic evaluation of the biomass potential and the cost of the biomass at the plant location has been presented. The methodology has been applied to Croatia and with this methodology we have assessed which type of the biomass is most suitable for use in the biomass-fired power plants in Croatia. From the agricultural and forest statistical data it was possible to estimate the technical and energy potential for each type of the biomass. Results show that high quantities of the agricultural and forestry residues exist in Croatia. Average quantity of wheat straw which can be removed from the field is 600 kt and corn stover 490 kt. Available potential of forestry residues calculated in this study is 690,000 cubic meters. Average energy potential of forestry residues is 5.9 PJ, wheat straw 8.5 PJ and corn stover 7.2 PJ.

An analysis performed for the assessment of the biomass cost at the energy plant location in Croatia, indicate that these costs range between 38.5 €/t and 48.7 €/t. Analysis was performed for different biomass types, size and locations of the power plants. Also, analysis performed for the assessment of the upper-level price of the biomass on the basis of the resulting cost of the electricity, the biomass-fired plants could even pay up to 100 €/t (10 MW power plants) for the biomass bought from outside suppliers, if the payback tariff of the electricity sold to the grid equal to the feed-in tariffs. The methodology applied for the estimation of the biomass cost didn't take into consideration competing uses of the biomass with other sectors and therefore, future studies should be focused on that issue.

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