Delivery of sustainable supply of non-food biomass to support a "resource-efficient" Bioeconomy in Europe

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Task 9.3.2 Strategic case study

Assessment of biomass production potential from short rotation crops (SRC) on unused agricultural land for use in biomass power plants in Croatia

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About S2Biom project

The S2Biom project - Delivery of sustainable supply of non-food biomass to support a "resource-efficient" Bioeconomy in Europe - supports the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, and roadmaps that will be informed by a "computerized and easy to use" toolset (and respective databases) with updated harmonized datasets at local, regional, national and pan European level for EU-28, Western Balkans, Moldova, Turkey and Ukraine. Further information about the project and the partners involved are available under www.s2biom.eu.

Project coordinator

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1. INTRODUCTION

Biomass is the first and the oldest source of energy used by humans. Today, it is a renewable source of energy with large exploitation potential. Thus, it could contribute to environmental protection, job creation and overall economic development of a country. Biomass consists of various products from flora and fauna and it can be divided into wood biomass (forestry and wood industry residues, short rotation crops, waste wood from other activities and a by-product wood from the agriculture), non-wood biomass (residues, by-products and waste from plant production and a biomass obtained growing oil seeds and algae) and biomass of animal origin (waste and residues from animal husbandry). There are various methods to obtain energy from biomass. Heat energy could be produced directly by combustion of biomass in order to produce steam for industrial use or domestic hot water for households or electrical energy could be produced in the steam-turbine process of small thermal power plants. Plants with a combined production of electrical and heat energy are called cogeneration plants (or combined heat and power, CHP) which are a suitable mean for exploiting the biomass. Some biomass provides oil that could be used in diesel engines. Ethanol as a fuel in the transportation sector could be produced by the fermentation process. By the process of destructive distillation methanol, acetone or charcoal can also be produced.

Croatian energy policy is focused toward increasing a share of renewable sources of energy in direct energy consumption. The highest increase is expected in usage of biomass as an energy source. These expectations are confirmed in the new action plan for renewable sources of energy from 2013. Croatia has relatively high biomass potential which comprises forestry and wood industry residues, firewood, residues from agriculture and biomass obtained from the road and infrastructure maintenance. In the next decade, it is expected to double the usage of biomass as an energy source due to incentives and development of domestic wood processing industry. Building new CHP plants will increase the share and usage of renewable sources of energy. This will lead to meeting the requirements of the Croatian energy policy **Error! Reference source not found.** and [2]. Usage of biomass as an energy source will create the need for deliberate cultivation of fast-growing wood or Short Rotation Coppice for which both poor forest areas and agricultural land are suitable.

1.1 Application of biomass from SRC as an energy source

Primary products miscanthus, poplar, willow and Reed Canary Grass (RCG) are transformed into a solid biomass in a form of briquette or chips, pellets and bales using compact technology. Solid biomass then can be used in the power and heat plants or CHP plants.

There are three types of crops which are suitable for the production of solid bio fuel:

- Annual crops – planted and harvested every year – such as grains, hemp or kenaf
- Perennial crops – once planted, growing 12 – 25 years and harvested annually – such as miscanthus or RCG
- Short rotation crops – planted once every 20 – 30 years and harvested every 2 - 8 years – such as poplar, willow, acacia or paulownias

High and constant amount of dry matter, durability and low production cost are the key features of the best energy crops. Perennial growth, low agrochemical requirements, efficient solar energy conversion and simplicity of conversion back to useful energy are guaranties that the energy efficiency of this process will be high with a minimum impact on the environment. Pruning flammable crops is better if done when they're dry. Therefore, transportation, storage and combustion are easier and heating value is higher. For manufacturing biogas, crops should be pruned when they have optimum efficiency for manufacturing the gas. It is especially useful if energy crops are suitable for use in existing power plants and combustion with currently used fuel. Hence, the investment costs are lower because only pulverizing and conveyor belt are needed. Ash content should be low, melting point of the ash should be high and combustion must be without emission of harmful elements, e.g. chlorine or heavy metals. Chips from energy crops are suitable for combustion with wood chips, peat coal and coal. Hemp, straw and RCG have higher content of chlorine and lower melting point of ash from wood biomass, which should be considered when mixing these and existing fuel. Differences in heating values are lower if the amount of dry matter is considered as shown in Table 1. Amount of water in bio fuel affects its heat value. In practice, variations in heating value can be high. Low input of fertilizers and other chemicals in the cultivation process of these crops, helps reduce negative impact on the environment and increases their energy efficiency. It is important that the crops can efficiently convert solar energy during the process of photosynthesis. During this process, trees absorb carbon dioxide, which is then embedded into the cell membrane, bole, leaves, branches and roots.

Hence, carbon dioxide accumulation in forest ecosystems has major importance, mostly in terms of greenhouse gas emissions and potential warming of the atmosphere.

Table 1. Fuel property [3]

	Unit	Willow	Hemp	RCG	Poplar	Soft wood
Moisture content at harvest	%	50	10-15	10-15	50-55	50
Production of dry matter	t_{DM}/ha/year	6-10	5-10	4-10	10-20	3-5
Ash content	%	2.9	1.5	1-8	0.5-1.9	1-2
Higher heating value	MJ/kg	19.97	18.79	19.20	19.43	20.3
Lower heating value	MJ/kg	18.62	17.48	17.28-18.72	18.10	18.97
Carbon (C)	%DM	49.8	47.3	48.6	39.7	50.6
Hydrogen (H)	%DM	6.26	6	6.1	7.7	6.24
Sulphur (S)	%DM	0.03	0.04	0.04-0.17	0.2	0.03
Nitrogen (N)	%DM	0.39	0.7	0.3-2	0.9	0.1
Chlorine (Cl)	%DM	0.03	0.01	0.01-0.09	0.04	0.01
Aluminium (Al)	g/kg_{ash}	2.2	2.1	2.8	16.7	16
Calcium (Ca)	g/kg_{ash}	243	240	66.5	189.3	238.8
Potassium (K)	g/kg_{ash}	123.3	44.7	129.5	28.6	80.7
Magnesium (Mg)	g/kg_{ash}	23.4	24	21.7	42.9	31.4
Sodium (Na)	g/kg_{ash}	2.5	3.5	7.0	3.6	4.6
Phosphorus (P)	g/kg_{ash}	36.9	49.3	32.3	17.9	12.4
Silica (Si)	g/kg_{ash}	93.3	160	218.3	178	73.9
Melting point of the ash	^{o}C	1490	1610	1400	1160	1200

Two major photosynthesis pathways are C3 and C4 pathways. Generally, C3 assimilation pathway is adapted to operate at low temperatures (15 - 20 °C), while the C4 metabolic pathway is efficient at high levels of light and in tropical climates. Tropical grass, such as sugar cane, corn, miscanthus and sweet sorghum are C4 crops. Theoretically, C4 crops can yield 55 t/ha of dry matter annually, compared to 33 t/ha of dry matter for C3 crops. However, that amount of dry matter for C4 crops can only be achieved in hot climates. Therefore, C3 crops are more suitable for use in moderate climate. Most of the short rotation crops for energy production are C3 type, e.g. willow, poplar etc. Generally, C4 crops are convenient for agricultural land, while C3 crops can be cultivated on the lower quality land. To make cultivation environmentally friendly, transport distance should be as small as possible, preferably within 40 km radius from the plant. In order to determine suitability of cultivation of energy crops in a certain area, the following factors should be considered:

- agronomic factors, such as yield, soil and climate
- the adequacy of existing machinery
- energy balance per hectare
- efficient use of all the components of crop being processed

Heating value, ash content of selected crops and ash properties such as melting point of ash and moisture content in the harvest are of crucial importance for energy production. The yield of dry matter and heating value of crops are the most important factors in determining the energy potential of solid fuels. Therefore, it should be noted that the yield of dry matter is largely dependent on the soil quality and climate conditions, while the moisture content depends on the time of the harvest. Properties for different energy crops are shown in Table 2.

In addition to the current available forest biomass, further increase can be achieved by establishing short rotation crops or by growing crops and plantations of fast growing tree species on 180,000 ha of bare forest land. Soil map and hydropedological map of the Republic of Croatia are made based on soil processing of agricultural land. These maps show the land potential for growing crops [4]. There are also opportunities for the production of renewable energy through the production of bio fuels in the uncultivated part of the areas (947,000 ha), while the part of the areas with temporarily unsuitable soils (611,324 ha) and the areas with permanently unsuitable soils (806,648 ha) could be used for the cultivation of the short rotation crops in the period of maximum 15 years [5] and [6].

Table 2. Properties of different energy crops

Crop	Production of dry matter	Lower heating value	Energy potential per ha	Moisture content	Ash content
	[t_{DM}/ha/year]	[MJ/kg_{DM}]	[GJ/ha]	%	$\%_{mass}$
Straw	2-4	17	35-70	14.5	5
Miscanthus	8-32	17.5	140-560	15	3.7
Hemp	10-18	16.8	170-300	n/a	n/a
Willow	8-15	18.5	280-315	53	2.0
Poplar	9-16	18.7	170-300	49	1.5
Reed	15-35	16.3	245-570	50	5
RCG	6-12	16.3	100-130	13	4
High grass	9-18	17	n/a	15	6
Acacia	5-10	19.5	100-200	35	n/a
Tree	3-5	18.7	74.8	50	1-1.5

2. ENERGY CROPS IN CROATIA AND THE EU

2.1 Short rotation crops - species used for production of biomass

The biomass of forest tree species can be produced by intensive cultivation of fast-growing tree species such as willow, poplar, alder, birch, acacia, etc. Short rotation crops are energy crops, mostly willow and poplar, which are used as a fuel in local heating plants for production of heat energy or in a cogeneration power plant for production of both heat and electrical energy. These crops are used as a coppice in very short cycles and they are harvested every two to five years. This results in a high density planting, from 1,000 to 30,000 plants/ha. After the harvest, new shoots occur, which will again be harvested every two to five years. Thus, after six or eight harvests the land needs to be cleared and replaced with new planting material since the vitality of young trees, as well as the production of biomass, then drops considerably. Short rotation crops are defined as intensive plantations of fast growing tree species on soils that have been abandoned, where agricultural production is not profitable or are unsuitable for growing more valuable forest species. Such plantations of fast growing trees are also known as energy crops or energy plantations. Production of biomass as a renewable and environmentally friendly energy source is the main function of these types of crops, but in addition they can be an alternative agricultural crop (on the bad quality agricultural land) and have the function of diversification of agricultural land. This also offers the possibility of environmentally advanced ways of wastewater treatment and soil (phytoremediation) and also serves to bind increasing amounts of atmospheric carbon (carbon sinks) [7], [8] and [9]. The data was provided by the research of energy crops in Croatia for willow and poplar and for the possibility of biomass production [10]. The goal of current studies was to determine the potential for the biomass production from selected clones of poplar and willow on land that is unsuitable for production of more valuable forest species. Today, in Croatia there are around 30 ha of land covered with fast-growing forest species, mainly in the Pannonian area (Figure 2.1) [11] and [12]. Clones of arborescent willow have shown the highest potential for biomass production in short rotation up to five years [13]. There are still no commercial energy crops but from the conducted research, especially on willow and poplar clones, as these are species that already grow in Croatian forests, it can be seen that it is expected that these fast-growing species should be preferred for energy use.

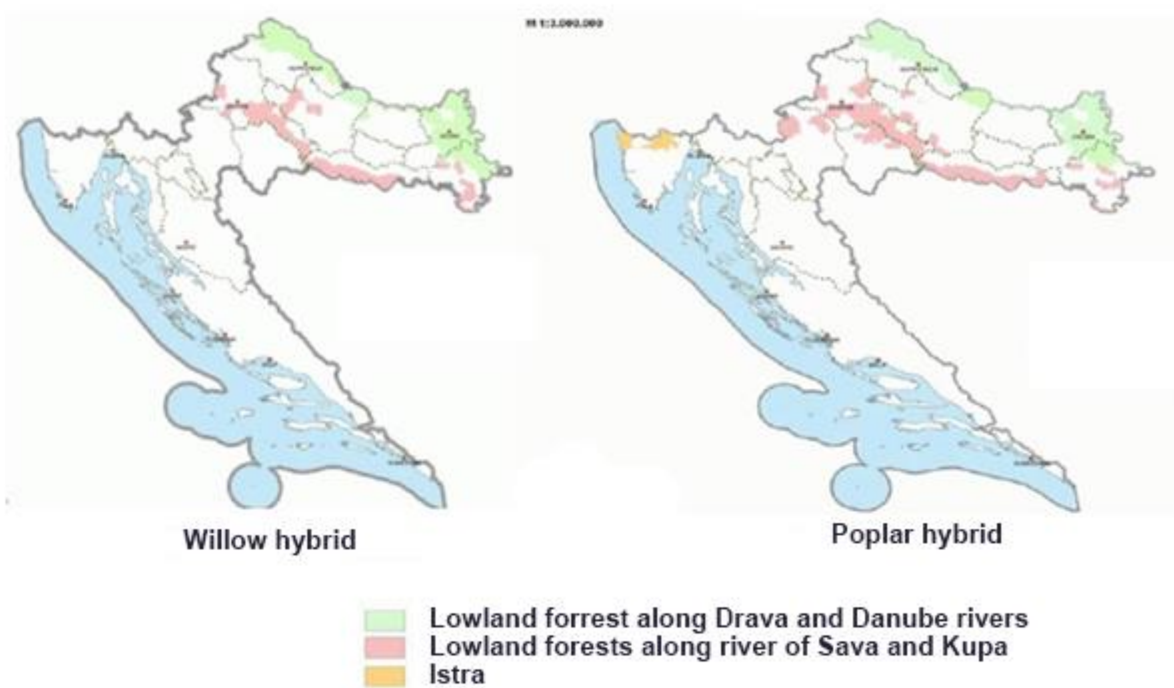

Figure 2.1 Forest areas under willow and poplar [14]

Hereinafter are presented the characteristics of major energy crops. Data related to growing and harvesting of the selected crops, transportation and storing biomass obtained from these crops along with the potential to use is shown. The focus is on the type of harvesting and soil treatment as it affects the later needed treatment of exhaust gases. This is important to take into account because it is necessary to adequately treat fuels derived from biomass to make biomass renewable and environmentally friendly energy source.

2.2 Willow

Willow includes several species of trees and shrubs, some of which are fast growing and cultivated for energy production in the so called energy forests in Sweden since the first oil crisis in the 1970s. Such plantation is shown in Figure 2.2.

Figure 2.2 Willow plantations (crops4energy.co.uk)

Willow has almost the same net heating value as wood fuel, approximately 18.5 MJ/kg_{DM}. Willow is not only a source of bioenergy, but also helps solve specific soil and environmental problems. Willow cultivation can be combined with the purification of urban and industrial water, it can help reduce the use of pesticides, it can also help avoid soil erosion, protect underground water and increase biological diversity, etc. SRC plantations act as a biological filter and remove nutrients, as well as some heavy metals when irrigated with wastewater. Such bio filtration can replace conventional tertiary treatment, while increasing SRC biomass yield due to irrigation and fertilization. The system has many advantages, such as recycling nutrients, reducing health risks, good energy balance, providing less expensive water treatment system for businesses, greater profitability due to lower fertilizer prices and increased yields. The main disadvantages are lower water treatment potential during the winter and relatively large cultivation areas. These types of irrigation systems for crops are used in Sweden, France and Ireland. Reducing the use of pesticides is another important advantage of willow plantations. Compared with the traditional grain production, about 60% less pesticides are used for the willow plantations.

Willow is mainly cultivated in southern Sweden, where about 1,250 farmers work on commercial plantations covering an area of approximately 13,500 ha. The period of establishment and harvest intervals are 3-5 years and the yield can reach about 8-10 tons of dry material per hectare per year, with significant variations depending on the region and the year. Currently around 20% of total energy consumption in Sweden is from the biomass. Biofuels from direct cultivation make a very small contribution (<1 TWh in 2008, not including crops for producing biogas), compared with those from the remains of wood industry. There is a large untapped potential and bioenergy can contribute to 220 TWh, 10% of which comes from years of cultivating biomass. To date, the willow chips for direct combustion are the most commonly used products in the market.

Willow plantations are established with seedlings in the spring. Willow usually has 2-3 meters long branches that are cut between December and March, when the buds are completely inactive. It can be planted immediately or carefully stored in cold conditions (-2 to -4 °C) while not in use. It is necessary to protect the seedlings from moisture loss during storage. Special designs and techniques for the establishment of willow plantations have been developed. Willow branches that are 2-3 m in length are cut into 15-20 cm long pieces just before planting. Twin-row design allows a gap of 0.75 m between rows and 1.5 m between the "twin lines", which results in planting density of about 13,000 seedlings per hectare. Weed control during the first year is very important. The willow root system is established in the first year during which is not as resistant as weeds. Broad spectrum herbicide, such as glyphosate, is often used to control perennial weeds before any cultivation, even two to three weeks after the cultivation has started. Mechanical weed control is an alternative. Willow plantations need a lot of water and nutrients, they usually require

3-5 mm of water per day during the growing season. Nutrient demand varies depending on the age and the stage of development of the crop. Fertilization is not recommended during the year of establishment, but 45 kg N per hectare should be applied in the second (i.e. the first harvest) year, and 100 to 150 kg N during the third and fourth year. Studies have shown that these systems have economic and environmental benefits from the use of wastewater for irrigation and sludge, together with the ash from the combustion of biofuels, as fertilizer. The studies also found that the willow can remediate soil contaminated by organic pollutants and heavy metals. Planting a mixture of different varieties or species is always recommended. The research led to the development of powerful new species of willow with increased resistance to diseases such as rust and damage from different insects. Willow harvest is shown in Figure 2.3. Willow is harvested after 3 - 5 years of cultivation, during the winter when the soil is frozen and moisture content is at the lowest level, around 50%.

Figure 2.3 Willow harvest

Willow biomass is usually harvested by directly cutting it and chopping it in the field. Chips are then transported to the district heating or cogeneration plants where they are stored and used. The same equipment used for the production of conventional wood chips can also be used for manufacturing and supplying willow chips for CHP plants. There is no big difference in the storage conditions for willow and conventional wood chips. Willow can be stored in bundles over a longer time period without a significant reduction in quality. The production process of biomass from willow is displayed in Figure 2.4.

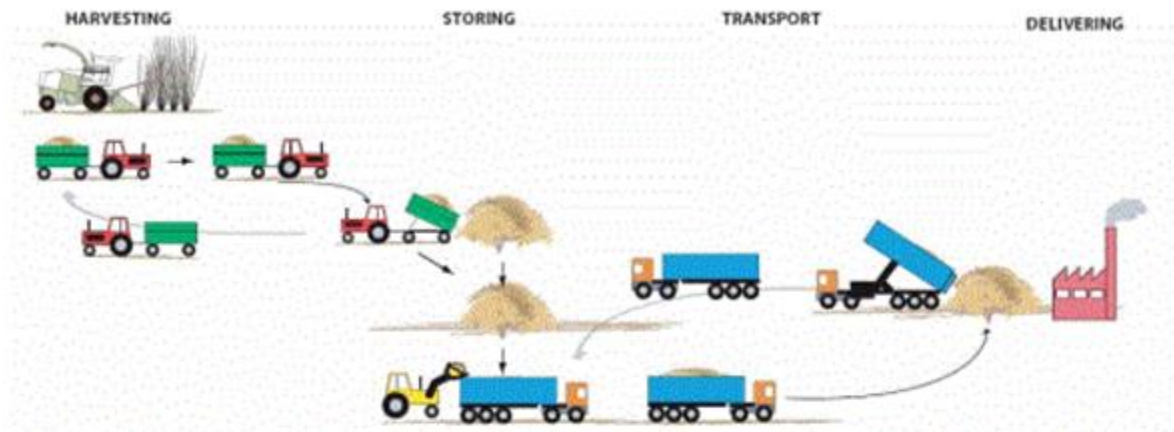

Figure 2.4 Production of biomass from willow (bisyplan.bioenarea.eu)

Willow chips are commonly used as a solid fuel for direct combustion in boilers for heating or in CHP. However, at the moment willow contributes to 20% in the fuel mixture because it contains elevated levels of the problematic elements for combustion (such as K, Cl, Na, N, Mg, etc.) compared to other wood fuels, leading to an increased risk of corrosion, slag, etc. Willow chips are used in the same way as wood chips and have a similar heating value. Studies of burning willow powder and pellets or briquettes have been conducted. It is expected that the co-incineration of willow and other types of fuel will be studied in the future.

2.3 Poplar

Poplar is a tree that belongs to the family of the *Salicacea*e, and is widely used in traditional arboriculture and forestry. It tolerates a wide range of soil conditions, but generally grows in deep fertile soils and is best suited to the Mediterranean climate, because it is very sensitive to lower temperatures and frost. Poplar plantation is shown in Figure 2.5.

Figure 2.5 Poplar plantation

Under optimal conditions of SRF (short rotation forestry) poplar plantations can reach a level of productivity of about 20 t_{DM}/ha/year. Poplar is the most important type of SRF in Italy. All existing commercial crops are based on poplar clones cultivated in the northern parts of Italy (Lombardy, Piedmont, Veneto, Friuli, Emilia Romagna) and to a lesser extent in central Italy (Marche, Umbria, Lazio and Tuscany) with a total estimated area under plantations of about 5,700 ha. The first commercial experiences with SRF date back to the beginning of 2000 in Lombardy due to the availability of funds from the rural development program and additional regional aid. At first the Swedish model (planting density, harvest every year) has been adopted and the results were encouraging, but there was a lack of knowledge by the farmers, who often used only marginal land for SRF and have not invested enough effort in maintenance and fertilization of plantations. The presence of large entities willing to invest in biomass power plants will lead to a strong potential market for wood fuel in the near future. However, the interest of farmers for the SRF has decreased in the last two years due to changes in the grain profitability. SRF is still profitable, but it is not considered competitive with traditional crops at the moment. Poplar harvest is shown in Figure 2.6.

Figure 2.6 Poplar harvest (bisyplan.bioenarea.eu)

Limiting factors for the poplar plantations are the high cost of the machinery, which led to need for bigger plantations to increase the annual number of work hours of the machinery and to reduce the unit cost, and the difficulty of the machinery with harvesting trees with more than 6 cm in diameter, which are common in plantations that are 2 - 3 years old.

Energy crops are mainly distributed by local businesses near the plant for the energy conversion or can also be used in existing systems for biomass processing (herbaceous and woody varieties). Plantations are often in the areas near power plants to reduce the costs of road transport. The maximum capacity of the truck is 90 m^3. Poplar cultivated as an energy crop is a seasonal crop in terms of production and harvesting, while a power plant is operational throughout the year. Therefore, it is necessary to store the biomass to ensure a reliable supply of wood. Long periods of storage affect the cost, quality (heating value, moisture, mould, ash) and reduction of dry matter. Storage can be in different places (near the production area, close to the plant, in between the two locations). The moisture content of fresh poplar at the time of the harvest is about 55%. As a result, external storage in heaps of loose chips can lead to fermentation and subsequent loss of dry matter up to 5% per month. To overcome this problem, researches are being actively conducted to identify the best storage solutions. Current trends are:

- Storage under the cover (only possible for a small amount of chips).
- Identification of the optimal log dimensions. Log dimensions affect the balance between evaporation and absorption capacity for moisture.
- The use of canvas (plastic mesh) or special fabric (Top Tex) that let moisture out, but are impermeable to rainwater (it tends to be a very effective solution at the moment).
- For longer storage form of logs is more convenient than chips because it reduces the biological activity and degradation associated with green woody biomass.

2.4 Energy crops in the EU

While in Croatia there are only experimental fields of willow and poplar the production of biomass from SRC as well as other energy crops has commercial use in the EU. In Scandinavian countries the SRC have been used since the oil crisis in the 1970s. Biogas is used in cogeneration plants which are popular in Germany, Austria, Italy and Denmark. It is estimated that around 600,000 ha of cultivated land is used for energy crops cultivation for biogas production. In Europe, forest types of energy crops cover around of 50,000 - 60,000 ha of land in 2007 [15] and [16], while the area for traditional energy crops, such as grains and beet covers around 2.5 million ha. In Figure 2.7 some types of energy crops in particular countries are shown.

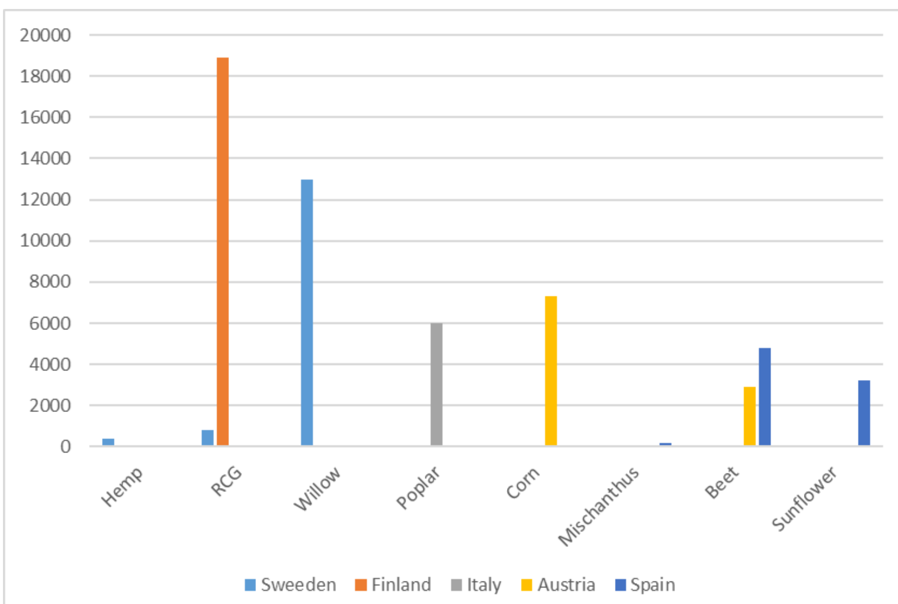

Figure 2.7 Energy crops in countries of the EU [16]

In Table 3 areas under three types of SRC are shown.

Table 3. Energy crops in EU

	Willow [ha]	Poplar [ha]	Miscanthus [ha]
AT	220-1,100	880-1,100	800
BE	60		120
DK	5,697	2,807	64
FR	2,300		2,000-3,000
DE	4,000	5,000	2,000
IE	930		2,200
IT	670	5490	50-100
LT	550		
PL	5,000-9,000	300	
SE	11,000	550	450
UK	1,500-2,300		10,000-11,000

3. METHODOLOGY FOR THE CALCULATION OF THE POTENTIAL FOR ENERGY PRODUCTION FROM BIOMASS OBTAINED FROM SRC

3.1 Unused agricultural land in Croatia

Today, agricultural land covers an area of 2,955,728 ha. Of these 1,074,159 ha are suitable, 1,074,510 ha are limited and 806,328 ha are permanently unsuitable areas for agricultural production. Potential arable land amounts to 2,150,000 ha but only about 50% is processed, about 1,092,000 ha. Today it is possible to obtain around 673,530 tons/year of biofuels from biomass in agriculture (organic waste and scrap), without jeopardizing permanent natural regeneration of organic matter in the soil [3]. Areas that are limited or unsuitable for agricultural production, are in fact suitable (and are encouraged) for the cultivation of energy crops. Areas that are suitable, but for various reasons not used for a long time, are also discussed in this paper as areas that could be used for cultivating energy crops. In the National Action Plan for renewable energy by 2020 from 2013 [2], it was stated that the remaining area of agricultural land was around 53,866.87 ha, according to the conducted public tenders. This figure could be even higher when all the land suitable for precisely this kind of use is taken into account, especially in regard to the cultivation of energy crops for which the land described as permanently inconvenient for agricultural production would also be suitable.

Until several years ago (2005), statistics on marginal land in Croatia were managed and sorted according to the Statistical Yearbook issued by the National Bureau of Statics. Such land (fallow) was sorted by counties, and it was possible to easily acquire the data on the land that has not been cultivated and is owned by the state. In Table 4 fallow areas by counties are presented. After 2005, due to the harmonization of statistical methods in the EU, data were expressed only in the total utilized agricultural area. Therefore, in the last 8 years, it was harder to obtain accurate information on unused agricultural land, marginal land and private land. Considering that later this data was not recorded in this way, in this paper areas of state land from the latest data were taken into account, such as agricultural land owned by the state, which in the meantime, weren't leased or sold through public tenders, and private fallow areas from 2004.

Table 4. Fallow area in 2004 [17]

County	Public [ha]	Private [ha]
Krapina-Zagorje	166.00	1,783.00
City of Zagreb	70.00	1,866.00
Varaždin	442.00	1,469.00
Međimurje	1,306.00	2,910.00
Kopivnica-Križevci	3,841.00	987.00
Osijek-Baranja	20,155.00	5,316.00
Vukovar-Syrmia	3,324.00	2,662.00
Virovitica-Podravina	9,908.00	5,221.00
Zagreb	7,750.00	8,890.00
Bjelovar-Bilogora	10,881.00	15,476.00
Dubrovnik-Neretva	1,976.00	3,448.00
Požega-Slavonia	10,609.00	12,875.00
Primorje-Gorski Kotar	47.00	25,541.00
Brod-Posavina	13,262.00	7,326.00
Istria	14,185.00	27,617.00
Karlovac	15.00	82,259.00
Sisak-Moslavina	10,899.00	57,412.00
Split-Dalmatia	1,171.00	39,885.00
Šibenik-Knin	618.00	18,807.00
Zadar	1,874.00	10,374.00
Lika-Senj	6,123.00	27,476.00
Total	118,622.00	359,600.00

Public fallow area is shown on the blank map of Croatia in Figure 3.1, while private fallow area is shown in Figure 3.2.

Figure 3.1 Public fallow area in Croatia

Figure 3.2 Private fallow area in Croatia

According to the agricultural census from 2003 data on unused agricultural land can be found in Table 5.

Table 5. Uncultivated agricultural land according to the agricultural census

County	Other land, of which uncultivated agricultural land,ha
Zagreb	6,972.82
Krapina-Zagorje	3,488.39
Sisak-Moslavina	14,707.12
Karlovac	13,845.16
Varaždin	2,517.19
Kopivnica-Križevci	1,178.55
Bjelovar-Bilogora	2,868.33
Primorje-Gorski Kotar	2,512.85
Lika-Senj	7,094.46
Virovitica-Podravina	1,255.85
Požega-Slavonia	2,352.72
Brod-Posavina	2,818.33
Zadar	4,109.01
Osijek-Baranja	2,376.64
Šibenik-Knin	4,498.34
Vukovar-Syrmia	1,652.02
Split-Dalmatia	6,714.37
Istria	8,707.02
Dubrovnik-Neretva	3,792.80
Međimurje	967.01
City of Zagreb	1,502.99
Total	95,931.97

Data from Table 5 is also shown on the blank map of Croatia in Figure 3.3.

Figure 3.3 Uncultivated agricultural land according to the agricultural census

Most recent data on available unused agricultural land from 2014 is shown in Table 6.

Table 6. Data on available uncultivated agricultural land from 2014

County	Uncultivated
Krapina-Zagorje	115.27
City of Zagreb	589.78
Varaždin	1,009.79
Međimurje	1,702.89
Kopivnica-Križevci	2,563.36
Osijek-Baranja	3,826.71
Vukovar-Syrmia	4,445.69
Virovitica-Podravina	7,019.16
Zagreb	7,989.94
Bjelovar-Bilogora	9,974.94
Dubrovnik-Neretva	11,179.28
Požega-Slavonia	15,391.35
Primorje-Gorski Kotar	15,811.90
Brod-Posavina	19,689.77
Istria	30,877.30
Karlovac	32,767.84
Sisak-Moslavina	33,733.16
Split-Dalmatia	38,634.64
Šibenik-Knin	57,432.02
Zadar	62,315.14
Lika-Senj	104,932.03
Unsorted land	14.85
Total	462,016.81

Data from Table 6 is shown on the blank map of Croatia in Figure 3.4.

Figure 3.4 Data on available uncultivated agricultural land from 2014

Total area of uncultivated agricultural land by counties is the sum of uncultivated agricultural owned by the state shown in Table 6 and uncultivated private agricultural land. The result is the total area of uncultivated land sorted by counties. Data is shown in Table 7.

Table 7. Total uncultivated agricultural land

County	Uncultivated (ha)
Krapina-Zagorje	1,898.27
City of Zagreb	2,455.78
Varaždin	2,478.79
Međimurje	4,612.89
Kopivnica-Križevci	3,550.36
Osijek-Baranja	9,142.71
Vukovar-Syrmia	7,107.69
Virovitica-Podravina	12,240.16
Zagreb	16,879.94
Bjelovar-Bilogora	25,450.94
Dubrovnik-Neretva	14,627.28
Požega-Slavonia	28,266.35
Primorje-Gorski Kotar	41,352.90
Brod-Posavina	27,015.77
Istria	58,494.30
Karlovac	115,026.84
Sisak-Moslavina	91,145.16
Split-Dalmatia	78,519.64
Šibenik-Knin	76,239.02
Zadar	72,689.14
Lika-Senj	132,408.03

Data from Table 7 is shown on the blank map of Croatia in Figure 3.5.

Figure 3.5 Total uncultivated agricultural land

3.2 Technical and energy potential of cultivating short rotation crops on unused agricultural land for biomass production

To determine technical and energy potential of produced biomass, areas of unused land and features of short rotation crops that are used in Europe are taken into the account. Three scenarios are being discussed, each with different area used for cultivation of short rotation crops. Cultivation of willow and poplar will be discussed due to conducted research in Croatia and favourable climate conditions. In Croatia, this species reach 12 t_{DM}/ha/year average, which is slightly lower than the maximum yield that could be expected (15 t_{DM}/ha/year) due to the different quality of land that are taken into account in this calculation. At the same time, each hectare of land available should be included, taking into account the sustainability of production through the lifetime of the plantation (15-20 years). Given that the biomass can be obtained from a specific land every 3 years and seeing how it is necessary to have a required amount of fuel every year, due to continuous operation of the plant, each hectare will be divided into three parts, each part with crops of different ages. The technical potential of short rotation crops is calculated in the following equation:

$$B_{teh(n)} = A(n) * P_y(n) * 1/3 \qquad \textbf{(1)}$$

where $A(n)$ is the area of uncultivated land in a specific county in [ha] and $P_y(n)$ is the annual yield of short rotation crops in [t_{DM}/ha/year].

Energy potential follows from the heating value of the biomass. It will be calculated, assuming that the area available is used for the cultivation of willow and poplar in the ratios that would be suitable for the conservation of biodiversity and environmental protection from diseases and pests in the area that is cultivated. Since the heating value of willow and poplar is equal, the analysis of the ratio of the area under one or another kind will not be discussed, but a lower heating value of 18.5 MJ/kg_{DM} for the willow and poplar on the dry matter basis, which is per kg_{DM} with 0% moisture, will be used. Of course, given that the moisture of biomass itself at harvest is around 50-55%. Through the further processing the biomass is mechanically processed, most often in the form of chip and stored. It will be assumed that the biomass arrives to the power plant in a form of chips with a moisture content of about 30% and heating value of 12.22 MJ/kg or 3.4 kWh/kg [18]. Taking all that into the account, energy potential $B_{ep(n)}$ for the specific county *n*, is calculated in the following equation:

$$B_{ep(n)} = B_{teh(n)} * H_{d(B)} \quad \textbf{(2)}$$

where $B_{teh(n)}$ is the technical potential for a specific county and $H_{d(B)}$ is the lower heating value of the biomass.

3.3 Scenario approach

3.3.1 Scenario 1 - 75% of the utilized land

In this scenario, 75% of available area was used for cultivating energy crops and the rest of the area remained for maintaining biodiversity and was available for cultivating food crops. In this scenario, it was assumed that one-third of the area was available for harvesting each year. In this way, according to the expression (1), the data in Table 7 was recalculated and the new available area was determined.

3.3.2 Scenario 2 - 50% of the utilized land

In this scenario, 50% of available area was used for cultivating energy crops and 50% of the area was used for cultivating food crops and for other use. Through different scenarios it could be seen how much of the available area was desirable to use for cultivation of short rotation crops.

3.3.3 Scenario 3 - 25% of the utilized land

In the last scenario, 25% of available area was used for the cultivation of short rotation crops and the rest of the area was used for food crops and for other use. This scenario proved to be the most important to distinguish between the potential of public and private uncultivated land because of their uneven distribution by counties.

3.4 Methodology for selection of macro location for the construction of power plants fueled by biomass from SRC

Location of the power plant that is fuelled by biomass produced from SRC should meet certain conditions such as [19]:

- source of biomass should be as close as possible to the power plant
- sufficient quantities of biomass must be delivered
- secured access for vehicles with existing roads
- grid connection should be simple and inexpensive
- there should be a possibility of connection to the water supply and sewerage system
- there should be a possibility to store solid fuel
- heat consumers should not be far away from the power plant to ensure lower distribution costs of heat energy

The existence of transport infrastructure is important because of the possibility of quick and low-cost delivery of biomass to reduce costs and increase economic viability. The cost of the biomass greatly depends on the distance between the power plant and the source of biomass. Price of biomass is calculated in the following equation [20]:

$$C_{B,E} = \sum_{i=1}^{n} \frac{[C_B + (T_p \times U_i)] \times K_{Bi}}{P_B} \qquad (3)$$

where:

$C_{B,E}$ the average cost of raw material at power plant location [€/t]

C_B the cost of biomass produced from SRC [€/t_{DM}]

T_P the specific cost of transporting raw materials [€/t/km]

U_i the average distance between power plant location and biomass source from area *i* [km]

K_{Bi} the total amount of biomass transported from the area *i* [tons]

P_B the total annual consumption of raw material in the power plant [tons]

In order to obtain the average distance between the location of biomass from a particular area and power plant that exploits the biomass, the centres of gravity of the areas under energy crops in particular counties were taken into account in the calculation, among which was the required optimum location for certain macro-location. Illustration of this principle is shown in Figure 3.6.

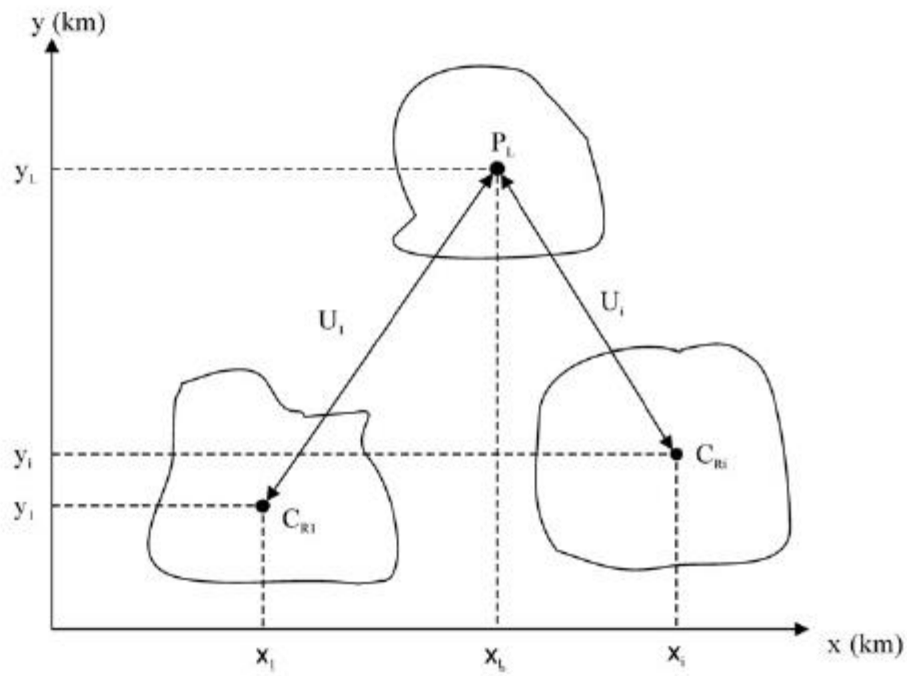

Figure 3.6 Distance between SRC farm and the power plant [20]

In order to optimize the locations of power plants, with the default parameters as the number and area of SRC farms, latitude and longitude of cities or regions where the plant would meet the needs for heat energy, maintenance and operating costs, biomass and transport costs and the cost of investment, codes that provide solutions were developed. These codes as a result give the location of the plant with the minimum cost of biomass, with a reliable supply [21]. Models that can determine the optimal location of the plant at a given macro-location, along with the knowledge of the routes of supply of biomass can be made using these codes. The model develops the network of quadrants where each quadrant represents an area of 1 km^2. Average price per ton of biomass ($C_{B,E}$) in each quadrant is calculated. The most favourable location is then selected calculating the distance from the source of the biomass, that is the centre of gravity of a county, after positioning in a particular quadrant, and sorted by distance. The biomass sources that are closer have the advantage over more distant sources until the last source of the biomass from which biomass needs to be taken is reached. For the most favourable location the exact order of sources of biomass, the amount of biomass from various sources and other data is printed. Due to the simplicity of setting the input parameters, section of the code that selects the waste biomass from wood industry can be easily modified if there is another potential source of biomass, such as agricultural land where SRC are cultivated.

3.5 Technical and economic analysis of power plants fuelled by biomass

In this paper the cogeneration plants up to 15 MW of installed capacity are discussed. Currently, the well-researched and commercially mature technology for such cogeneration plant is that one based on steam-turbine Rankine Cycle.

The combustion technologies applied in the direct combustion of biomass are divided into combustion on the grate (stationary or moving) and fluidized bed combustion. The choice of combustion technology depends on the plant size, biomass characteristics, permissible levels of emissions, the amount and scope of maintenance that the investor is willing to accept. The choice of combustion technology does not have too much influence on the specific heat consumption of the power plant. More effect on the specific heat consumption has the configuration of steam-turbine process. Modern combustion plants with combustion on the grate are most often less expensive than the plants with combustion on the fluidized bed. Fluidization of the layer increases combustion efficiency, but it also requires additional energy to power the air fan, which increases the electricity consumption of the cogeneration plant [19]. Therefore, newer and more sophisticated technologies are commonly used for larger plants (> 50 MW_e). Today, in order to increase the efficiency of smaller plants from 15 MWe methods such as raising fresh steam parameters, the reheating of the steam, regenerative feed water heating and drying of fuel with waste heat from the flue gases are used.

In the last 20 years in the field of cogeneration plants fuelled by biomass larger than 2 MW of installed capacity, mainly used technologies are [22]:

- steam boiler with a steam turbine and with the combustion on the grate

- steam boiler with a steam turbine and fluidized bed combustion
- biomass gasification in a fluidized bed with a gas turbine

The investment cost of the cogeneration plant fuelled by biomass comprises the boiler with appropriate technology, turbine and auxiliary equipment, connection to the network, staff training, system for purifying exhaust gases, fuel storage and transport systems [23]. Specific investment costs of cogeneration plant used for district heating are shown in Figure 3.7. It can be seen that the investment cost for plant up to 15 MW_e, which will be discussed in this paper, varies from 1800 €/kW_e up to 6000 €/kW_e. This range of investment cost depends on the selected combustion technology and configuration of the system.

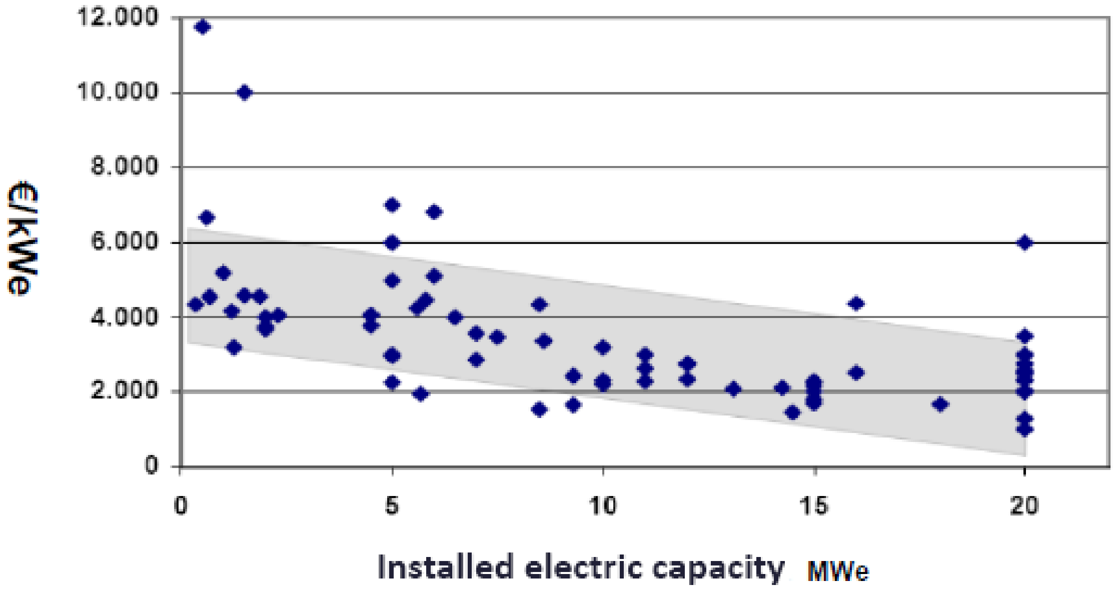

Figure 3.7 Specific investment cost of cogeneration plant for district heating

Below, for each macro-location size of the plant in accordance with technically and economically available biomass and heat energy needs will be chosen. The operating cost of the plant in the range of installed power of interest for this paper is between 2 and 3% of the total investment [19].

To determine if the project is economically feasible, there are different methods that can be divided into [32]:

- Payback period method
  - simple payback period method
- Discounted cash-flow after taxation method
  - net present value method
  - internal rate of return method

Internal rate of return (IRR) method will be used in this paper to analyse the feasibility of the project cogeneration power plant fuelled by biomass. The IRR method is a method that takes into account the time value of money and the size of the cash flow. Internal rate of return is the discount rate that equates the present value of expected costs with the present value of expected revenues. If it is greater than the applicable discount rate, the investment is profitable, if it is less, the investment is not profitable in the parameters that are given. The profit of the plant, of which the investment is returned, is derived from the difference between revenues and expenditures.

Profits of cogeneration plant fuelled by biomass comprise [19] and [23]:

- income from the sale of electric energy
- income from the sale of heat energy

Expenses comprise:

- investment costs in mechanical and electrical equipment
- investment costs in design, permits, etc.
- construction work costs
- costs of taxes and other
- maintenance and operating costs

Attention should be given to the operation and maintenance costs since they include the cost of fuel. The price of fuel, in this case biomass produced from SRC, consists of the cost of biomass itself and of the cost of transport to the power plant.

Price of the biomass C_B, which refers to the biomass harvested at the site of the SRC farm, is calculated as:

$$C_B = T_S + T_Z + T_{O\&M} \quad \textbf{(4)}$$

where:

T_S the cost of seedlings of the selected type [€/ha]

T_Z the cost of land and its treatment [€/ha]

$T_{O\&M}$ the maintenance cost of SRC farm and harvest of biomass [€/ha]

Biomass obtained from energy crops is transported and stored in the same way as other types of forest biomass, so the storage and transport costs will be the same as for chip forest biomass and forestry residues.

In Europe, areas of land under SRC are already in operation in several locations. The costs of establishing and maintaining the SCR farm and price of obtaining biomass is shown in Table 8. Northern countries have a slightly higher price, mainly due to lower productivity (8-10 t_{DM}/ha/year).

Table 8. Establishment and maintenance costs of SRC farms in Europe [24]

Country	Crop species	Establishment cost €/ha	Maintenance cost €/ha/y	Sale price €/t_{DM}
Sweden - Nynas Gard	Willow	1222	330	65
Sweden - Puckgarden	Willow	1110	265	52
Latvia	Willow	1450	-	-
Latvia - SALIXENERGI	Willow	1630	480	-
France - Bretagne	Willow	2545	355	-
Germany - Gottingen	Poplar	2750	250	65

Italy - Rinnova	Poplar	2320	875	55
Croatia - estimation	Willow	3916	196	43.47

In Eastern Europe, some studies have shown that the cost of establishing SRC plantations is between 1500 and 2500 €/ha [4]. Previous research has pointed that the current cost of establishing a hectare of energy crops in Croatia is about 3916 €/ha, with the maintenance costs of 2350 €/ha throughout the life of the plantation of willow (12 years). That gives a total of 6266€/ha. The average production of biomass was 12 t_{DM}/ha/year, which is 144 t_{DM}/ha in the lifetime of the plantation. The price of this biomass, amounts to 43.47 €/t at the middle exchange rate against the euro of 7.66 HRK = 1 € [5].

In the structure of total costs the depreciation takes a special place as an accounting cost. This cost can be defined as a mean of calculating the investment through the lifetime of the power plant and it does not affect the income of the plant, but the amount of the tax which needs to be paid. This cost lowers the accounting income of the power plant in the particular accounting period, the higher the depreciation the lower the income tax that needs to be paid. For the write-off of fixed assets and construction work a linear method using the average annual depreciation rates is used [25]. The average annual depreciation rate for each asset that is depreciated is shown in Table 9.

Table 9. Depreciation rates [20] and [23]

Asset	Accounting life (years)	The average annual depreciation rate (%)
Buildings and operation	20	5
Equipment and devices	15	6.67
Intangible assets	5	20

The main income of the cogeneration plant will be the price of electricity produced by the plant submitted to the electric network. From the October 31st 2013 the new tariff system for electricity production from renewable energy sources and cogeneration is in place, according to which the incentive price (C) for the power plant fuelled by biomass with an installed capacity more than 5 MW, is calculated from the following expression:

$$Ck = C\ x\ k \tag{5}$$

where k is the correction factor for the incentive price. It is estimated around 0.9 for the plants with total annual efficiency <45%, is equal to 1 for the plant with an efficiency between 45% and 50% (inclusive), and for the plants with a total annual efficiency of >50% it is 1.2. Incentive price (C) of biomass power plants under the new tariff system is expressed as a reference price of electricity (RC), which is equal to the price of applicable tariff for active energy per single daily tariff for electricity supply within the universal service, tariff model Blue. Currently, that price is 0.78 HRK/kWh$_e$. It is important to note that the reference price of electricity is determined for each accounting period of payment of incentives so that this amount is variable. As expected, however, that electricity prices will not drop and therefore neither will the incentive fee, but it is realistic to expect that this amount could increase over the years. In this paper, the equal incentive price over 14 years, which is the duration of the contract guaranteed purchase prices, will be assumed. This will be later discussed in the section on sensitivity analysis. Also, the plant will be calculated with the total efficiency of >50% in order to achieve a correction factor of 1.2. Guaranteed incentive prices then amount to:

$$Ck = 0.78\ x\ 1.2 = 0.936\,\frac{HRK}{kWhe} \tag{6}$$

With exchange rate of 7.66 HRK = 1 € this price amounts to 0.12219 (€/kWh$_e$) [21], [26]. To ensure this incentive tariff, it is necessary that the plant achieves production according to the next expression:

$$0.5 \leq \frac{P_{el} + P_{th}}{P_{fuel}} \tag{7}$$

where P_{el} [kWh] is the produced electrical energy, P_{th} [kWh] is the produced heat energy and P_{fuel} [kWh] is the energy of fuel burned.

Heat energy prices in Croatia for district heating systems (DHS) are determined with the tariffs of company HEP Heating Ltd., for larger cities. Price of heat energy without distribution for households and industry in major cities, where DHS exists are shown in Table 10. For the purpose of calculating the income of power plants from the heat energy sale, the average price specified in Table 10 will be taken. With the middle exchange rate against the euro of 7.66 HRK = 1 € this price amounts to 0.0247 (€/kWh$_t$) for households, 0.0368 (€/kWh$_t$) for industry while the average price between these two tariffs is 0.0307 (€/kWh$_t$).

Table 10. Heat energy price for DHS in Croatia [27]

City	Households [kn/kWh]	Industry [kn/kWh]
Osijek	0.1492	0.2891
Zagreb	0.1525	0.305
Sisak	0.1089	0.2058
Samobor	0.2605	0.2952
Velika Gorica	0.276	0.3128
Average	0.18942	0.28158

4. CASE STUDY CROATIA

4.1 Technical and energy potential of biomass produced from SRC

So far discussed, biomass was expressed based on dry matter mass [t_{DM}/ha/year]. Biomass that will be stored at the location of the power plant and then used in the power plant, will be in the form of a chips with 30% moisture content. This is converted into dry biomass with 30% moisture content on a dry basis given that 12 t_{DM}/ha/year is equal to 15.6 t/ha/year of the biomass after it is stored with a heating value of 12.22 MJ/kg [28], [29]. The technical potential for all the scenarios defined is shown in Figure 4.1.

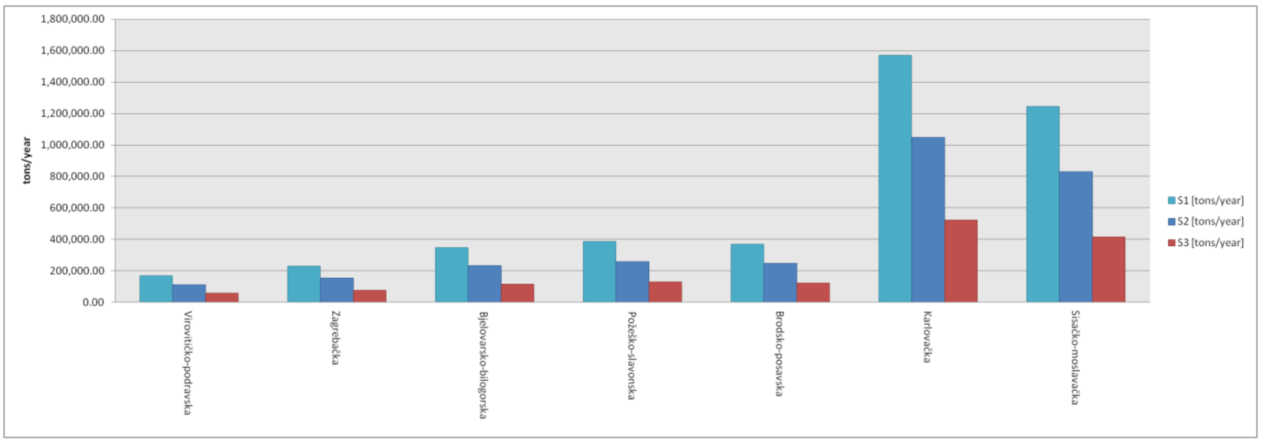

Figure 4.1 Technical potential of biomass by counties and scenarios

The technical potential of private and land owned by the state can be observed separately as shown in Table 4. The technical potential of biomass is expressed in [tons/year]. The technical potential of biomass from the land owned by the state is shown in Figure 4.2 while the technical potential of biomass from the private land is shown in Figure 4.3. Due to a significant difference in the available land area in counties only the counties with high technical potential are shown in these figures. Below in tabular form, technical potential for all counties is shown.

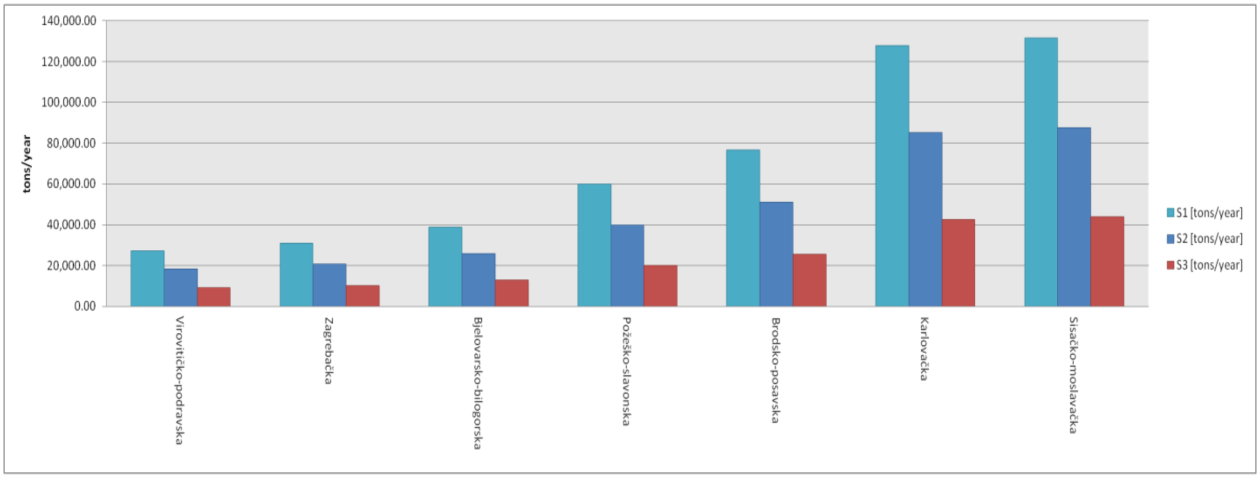

Figure 4.2 Technical potential of biomass from the land owned by the state

It can be noted that in the continental part of Croatia there is a relatively small area of unused private land compared to the land area owned by the state. In the Karlovac county and Sisak-Moslavina county there is still a lot of unused land, both private and that owned by the state. As mentioned above, this biomass will be converted into wood chips with 30% moisture content.

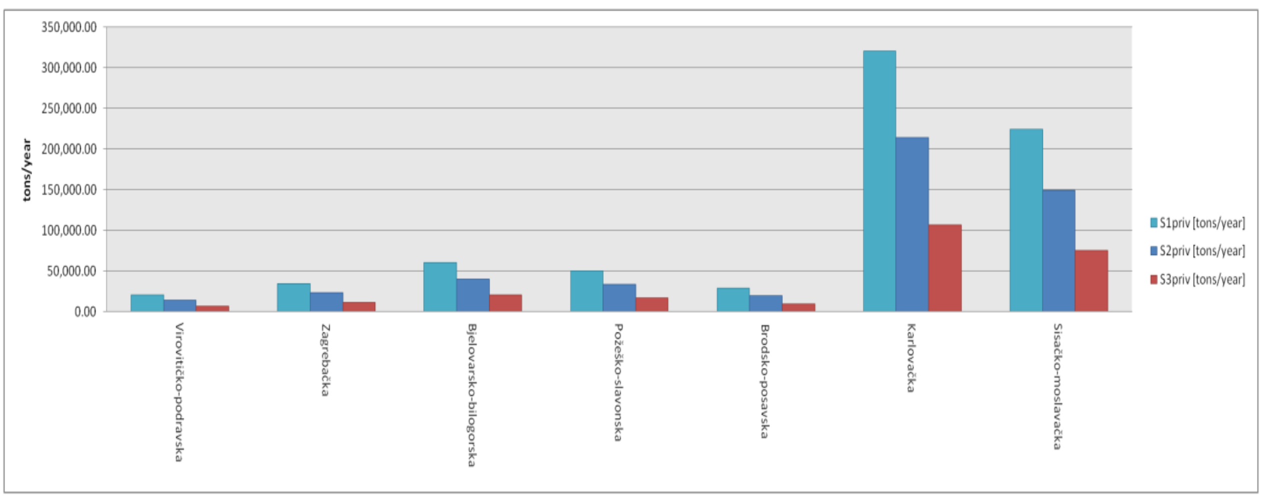

Figure 4.3 Technical potential of biomass from the private land

The technical potential of that biomass is shown in Figure 4.4. The technical potential on that figure is expressed in [m^3/year] and for the land owned by the state.

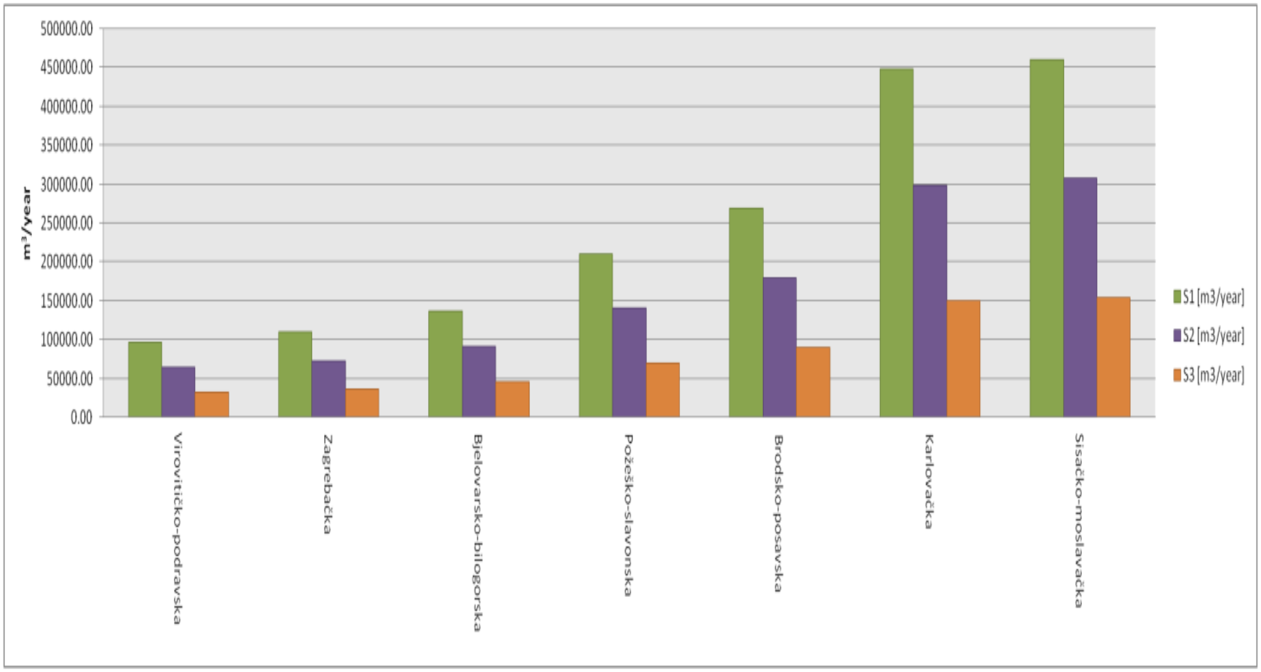

Figure 4.4 Technical potential of biomass in a form of wood chips

For the private land the technical potential is shown in Figure 4.5.

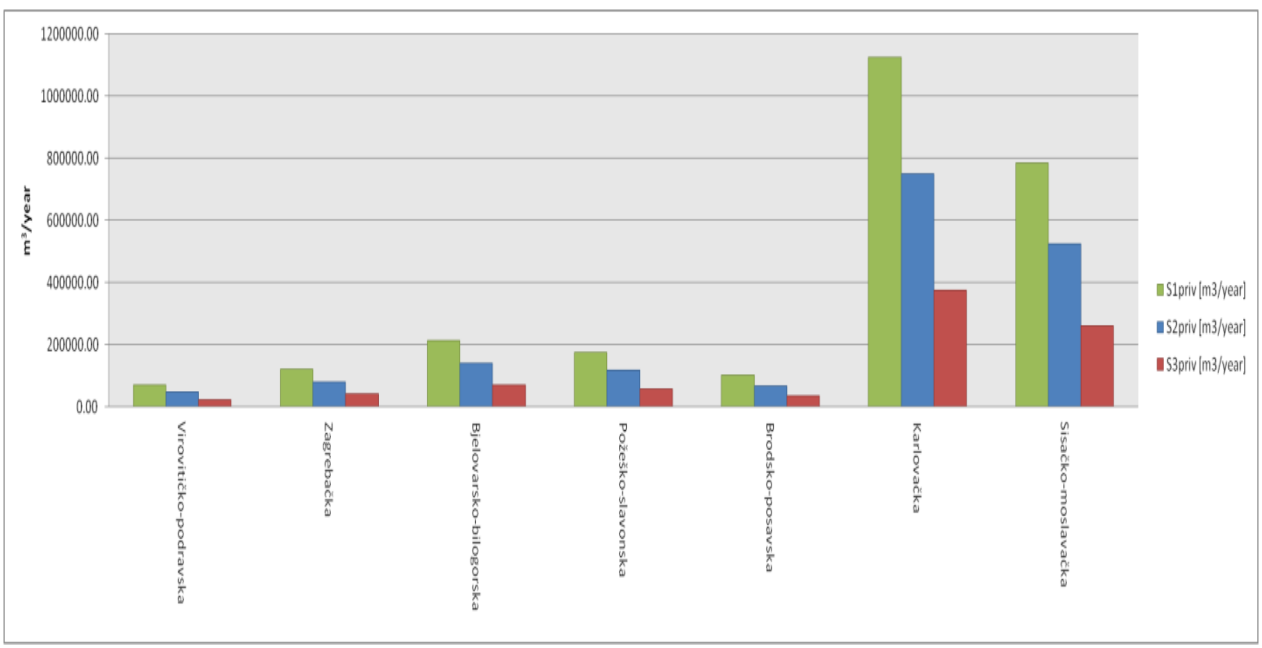

Figure 4.5 Technical potential of biomass in a form of wood chips

The technical potential, according to the counties, scenarios and ownership of the land is shown in Table 11.

Table 11. Technical potential of biomass

Scenario						
County:	S1private [tons/year]	S1state [tons/year]	S2private [tons/year]	S2state [tons/year]	S3private [tons/year]	S3state [tons/year]
Krapina-Zagorje	6,953.70	449.55	4,635.80	299.70	2,317.90	149.85
Varaždin	5,729.10	3,938.18	3,819.40	2,625.45	1,909.70	1,312.73
Međimurje	11,349.00	6,641.27	7,566.00	4,427.51	3,783.00	2,213.76
Kopivnica-Križevci	3,849.30	9,997.10	2,566.20	6,664.74	1,283.10	3,332.37
Osijek-Baranja	20,732.40	14,924.17	13,821.60	9,949.45	6,910.80	4,974.72
Vukovar-Syrmia	10,381.80	17,338.19	6,921.20	11,558.79	3,460.60	5,779.40
Virovitica-Podravina	20,361.90	27,374.72	13,574.60	18,249.82	6,787.30	9,124.91
Zagreb	34,671.00	31,160.77	23,114.00	20,773.84	11,557.00	10,386.92
Bjelovar-Bilogora	60,356.40	38,902.27	40,237.60	25,934.84	20,118.80	12,967.42
Požega-Slavonia	50,212.50	60,026.27	33,475.00	40,017.51	16,737.50	20,008.76
Brod-Posavina	28,571.40	76,790.10	19,047.60	51,193.40	9,523.80	25,596.70
Karlovac	320,810.10	127,794.58	213,873.40	85,196.38	106,936.70	42,598.19
Sisak-Moslavina	223,906.80	131,559.32	149,271.20	87,706.22	74,635.60	43,853.11

The overall technical potential, according to the ownership and scenarios is shown in Figure 4.6.

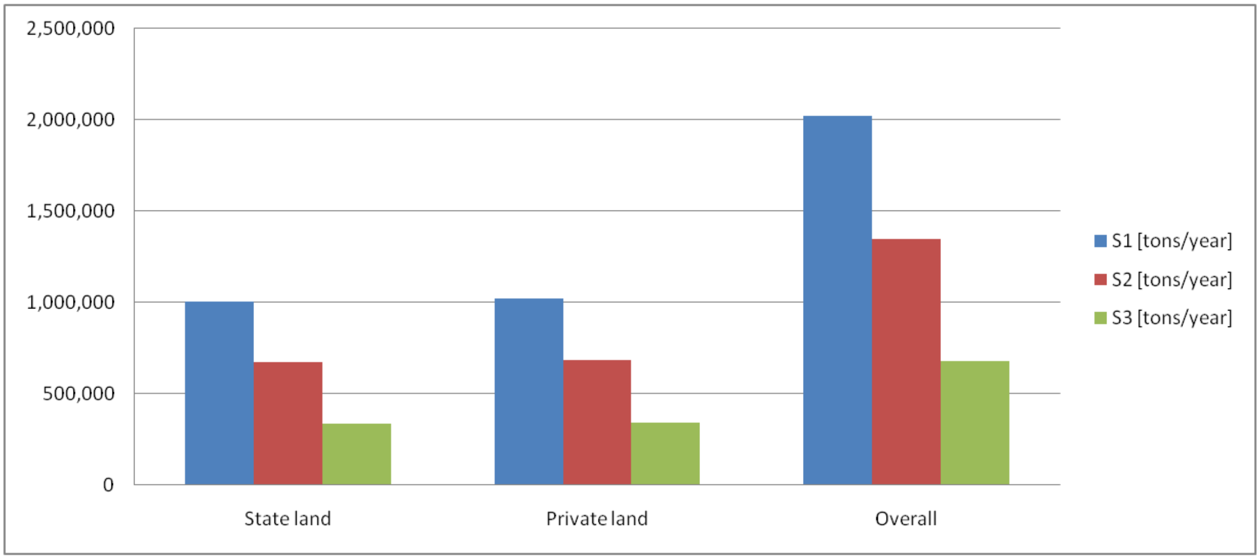

Figure 4.6 Overall technical potential

Conversion from the technical potential to energy potential is done by using the expression (2). The energy potential is shown in Figure 4.7.

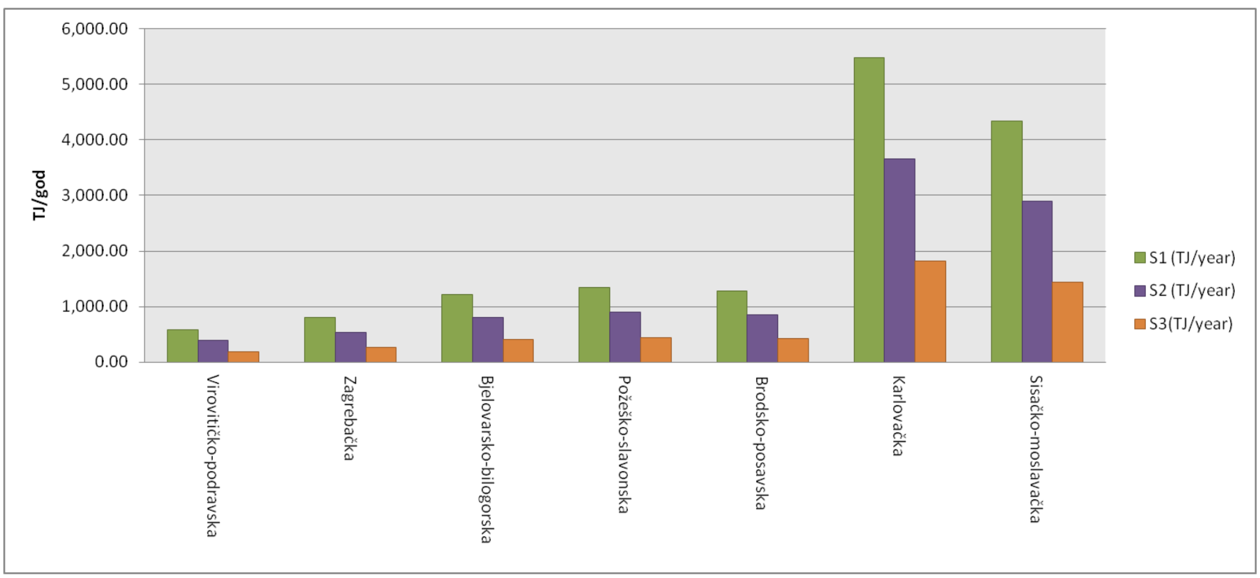

Figure 4.7 Energy potential according to the counties and scenarios

Tabular representation of the energy potential, according to the counties and scenarios is shown in Table 12.

Table 12. Overall energy potential

Scenario:	S1 (TJ/year)	S2 (TJ/year)	S3(TJ/year)
Krapina-Zagorje	90.47	60.31	30.16
Varaždin	118.13	78.76	39.38
Međimurje	219.84	146.56	73.28
Kopivnica-Križevci	169.20	112.80	56.40
Osijek-Baranja	435.72	290.48	145.24
Vukovar-Syrmia	338.74	225.83	112.91
Virovitica-Podravina	583.34	388.89	194.45
Zagreb	804.46	536.31	268.15
Bjelovar-Bilogora	1,212.94	808.63	404.31
Požega-Slavonia	1,347.12	898.08	449.04
Brod-Posavina	1,287.52	858.35	429.17
Karlovac	5,481.95	3,654.63	1,827.32
Sisak-Moslavina	4,343.80	2,895.86	1,447.93
Total	24,703.63	16,469.08	8,234.54

From the perspective of energy planning, the adoption of measures and strategies for sustainable energy development and for linking the energy sector and rural sector it is interesting to discuss the energy potential according to ownership of the land. The energy potential of biomass from SRC on the land owned by the state is shown in Figure 4.8.

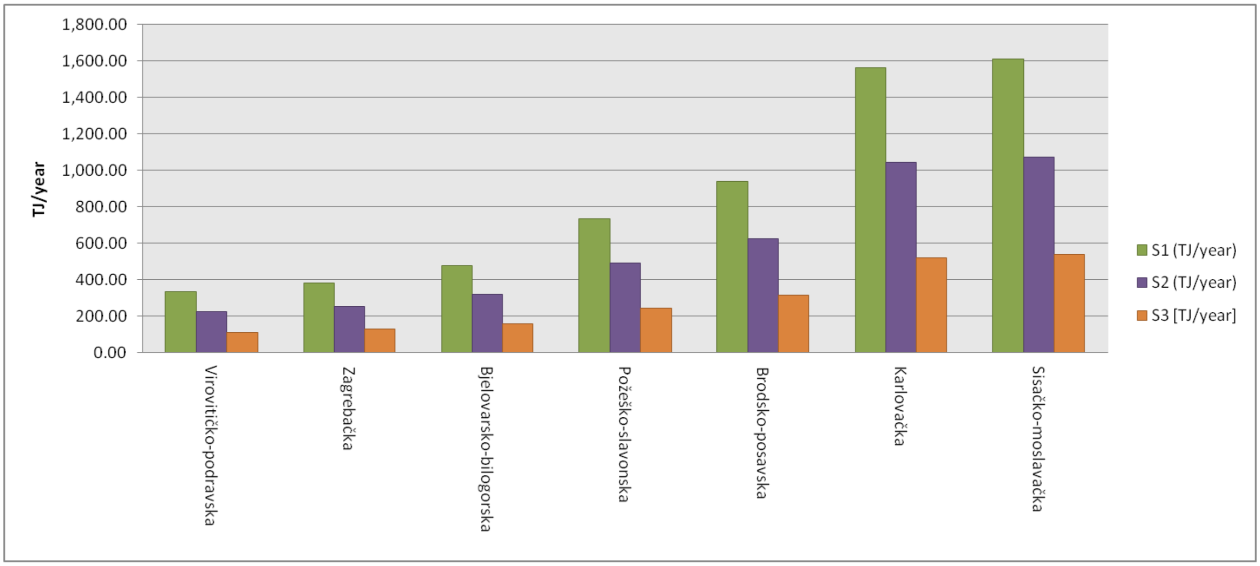

Figure 4.8 Energy potential from the land owned by the state

The energy potential of biomass from SRC from the private land is shown in Figure 4.9. Again the significant difference can be noted for the Karlovac county and Sisak-Moslavina county regarding other counties. As well as for the technical potential, counties with higher energy potential are shown in these figures while below in tabular form the energy potential for other counties is shown.

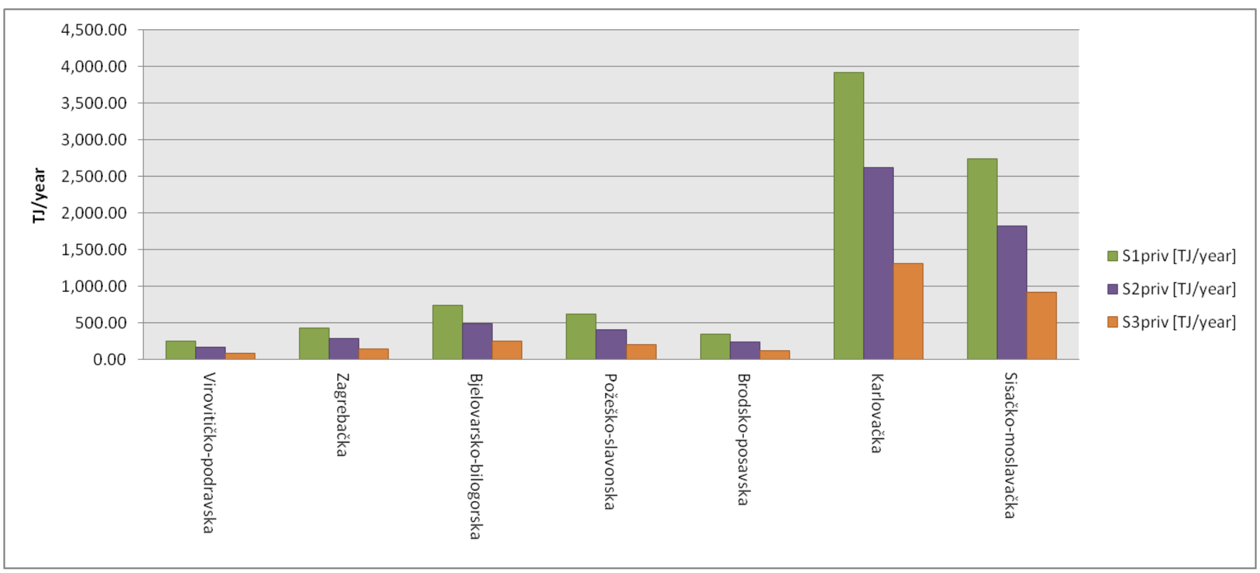

Figure 4.9 Energy potential from the private land

The energy potential on the private land and the land owned by the state, according to the counties and scenarios is shown in Table 13.

Table 13. Energy potential according to the counties, ownership and scenarios

County:	Scenario					
	S1private [TJ/year]	S1state [TJ/year]	S2private [TJ/year]	S2state [TJ/year]	S3private [TJ/year]	S3state [TJ/year]
Krapina-Zagorje	84.97	5.49	56.65	3.66	28.32	1.83
Varaždin	70.01	48.12	46.67	32.08	23.34	16.04
Međimurje	138.68	81.16	92.46	54.10	46.23	27.05
Kopivnica-Križevci	47.04	122.16	31.36	81.44	15.68	40.72
Osijek-Baranja	253.35	182.37	168.90	121.58	84.45	60.79
Vukovar-Syrmia	126.87	211.87	84.58	141.25	42.29	70.62
Virovitica-Podravina	248.82	334.52	165.88	223.01	82.94	111.51
Zagreb	423.68	380.78	282.45	253.86	141.23	126.93
Bjelovar-Bilogora	737.56	475.39	491.70	316.92	245.85	158.46
Požega-Slavonia	613.60	733.52	409.06	489.01	204.53	244.51
Brod-Posavina	349.14	938.38	232.76	625.58	116.38	312.79
Karlovac	3,920.30	1,561.65	2,613.53	1,041.10	1,306.77	520.55
Sisak-Moslavina	2,736.14	1,607.65	1,824.09	1,071.77	912.05	535.88

The overall energy potential according to the ownership and scenarios is shown in Figure 4.10.

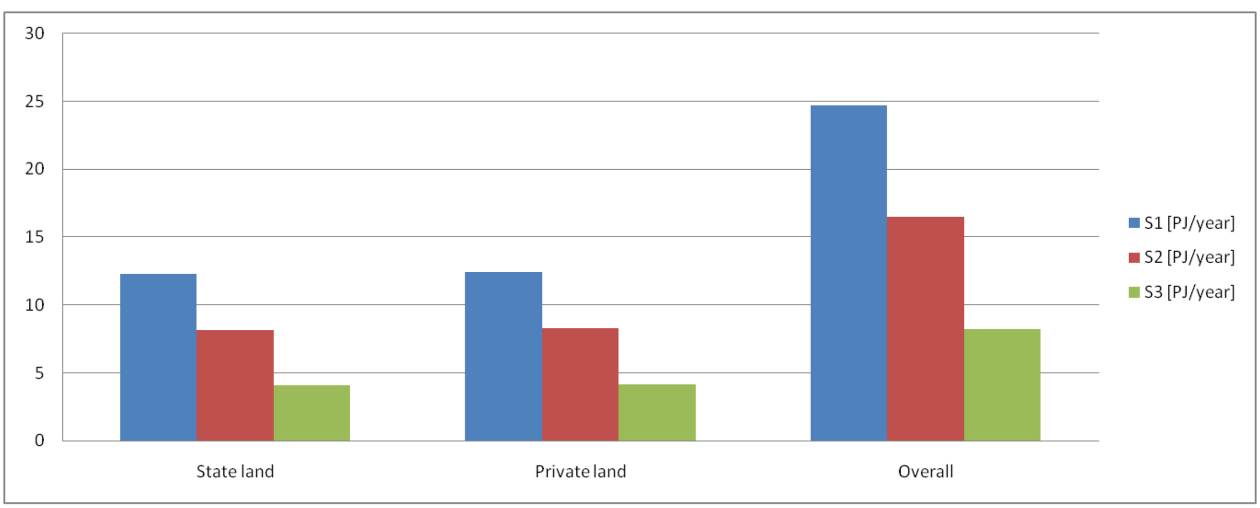

Figure 4.10 Overall energy potential

4.2 Economic analysis

In this chapter discussed scenarios will be analysed. Depending on the heat demand in the selected macro-location and available quantities of biomass for each location, the size of the power plant is obtained and for that power plant costs and revenues are shown. Cash flow and the IRR are shown. If the IRR is greater than the discount rate the project is considered as profitable otherwise the project is considered as unprofitable. Furthermore, the change of significant parameters such as the cost of the biomass from SRC, the cost of the transport to the power plant and electricity prices as these factors affect power plants revenues and IRR of investment.

According to section 3.4 the next macro-location were chosen:

- Macro location 1 - VelikaGorica
- Macro location 2 - Sisak
- Macro location 3 - Koprivnica
- Macro location 4 - Slavonski Brod
- Macro location 5 - Osijek

These macro locations are shown in Figure 4.11.

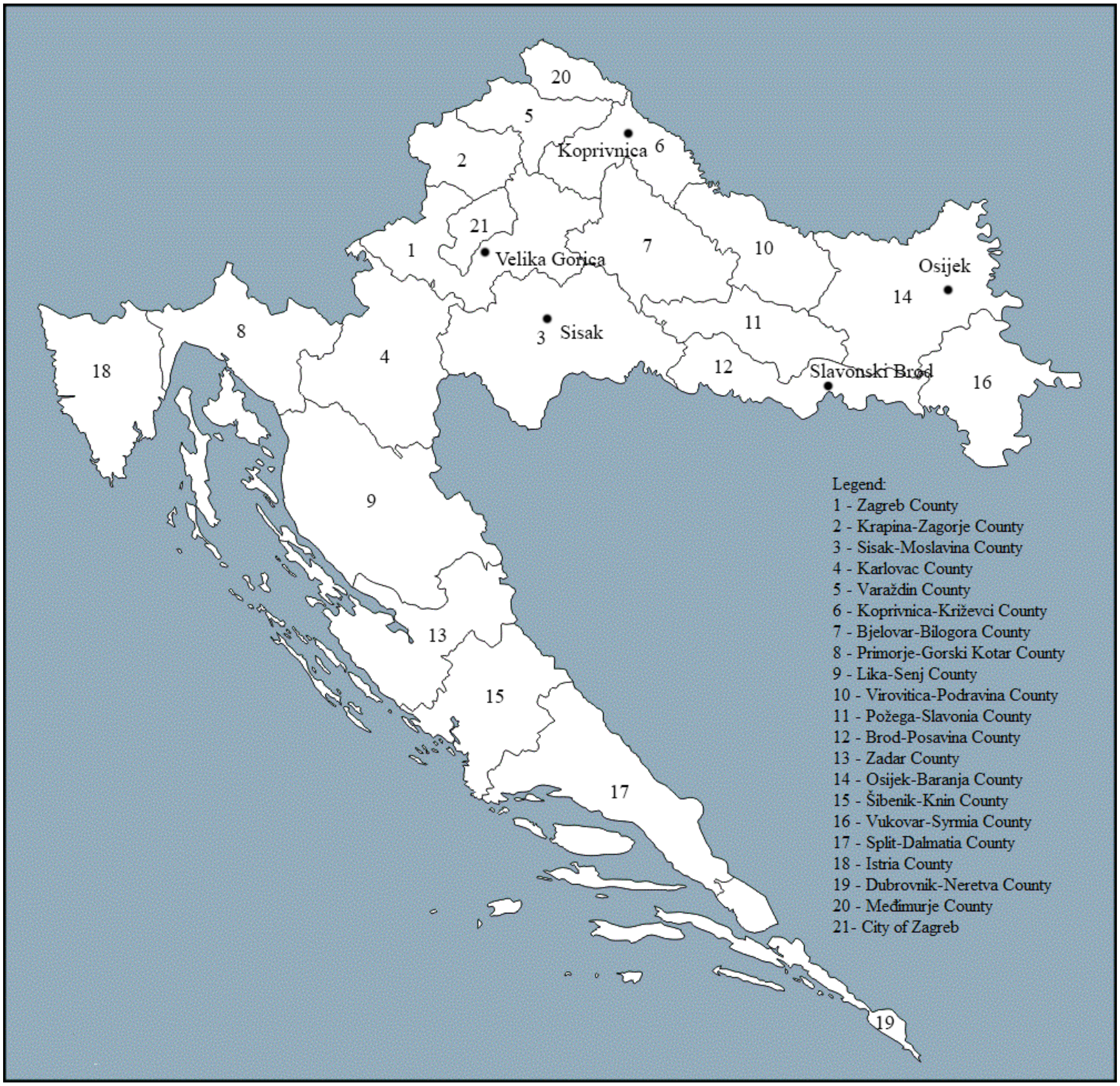

Figure 4.11 Selected macro locations

For these locations the cost-benefit analysis was done using the IRR method and the sensitivity analysis was carried out. Price of the biomass on the threshold of the power plant was obtained from the expression (3) using the model in Matlab [21] and [25] in accordance with the methodology. Biomass price for the chosen macro location is shown in Table 14.

Table 14. Biomass price for the chosen macro locations

Location	15 MW_e + 30 MW_t				
	S1	S2	S3		
	Biomass price (€/t)				
			State	Private	Total
VelikaGorica	43.52	43.56	46.42	46.36	45.83
Sisak	43.82	43.82	43.87	43.82	43.82
Koprivnica	45.88	46.70	49.01	48.37	47.12
SlavonskiBrod	44.05	44.05	45.45	47.53	44.78
Osijek	45.00	45.98	49.44	49.78	47.78

It can be noted that the biomass price is lower for the locations that are close to the Karlovac county and Sisak-Moslavina county since there is a lot of unused land so the obtained biomass is sufficient to cover the needs of much greater power plants than the ones discussed. Also, for the scenarios 1 and 2 the analysis gives similar prices of biomass for private land and state ownership. The Scenario 3 is considered as a critical case which will be discussed. In this scenario the case with the highest biomass price is discussed. For every other case the profit of the project is greater due to the lower biomass price.

Graphical representation of the used model is shown in Figure 4.12. It is a map with the size of 19x19 where each field has an area of 1 km^2 for a selected macro-location. The power plant is marked with the black square while the centre of the city is marked with the white square.

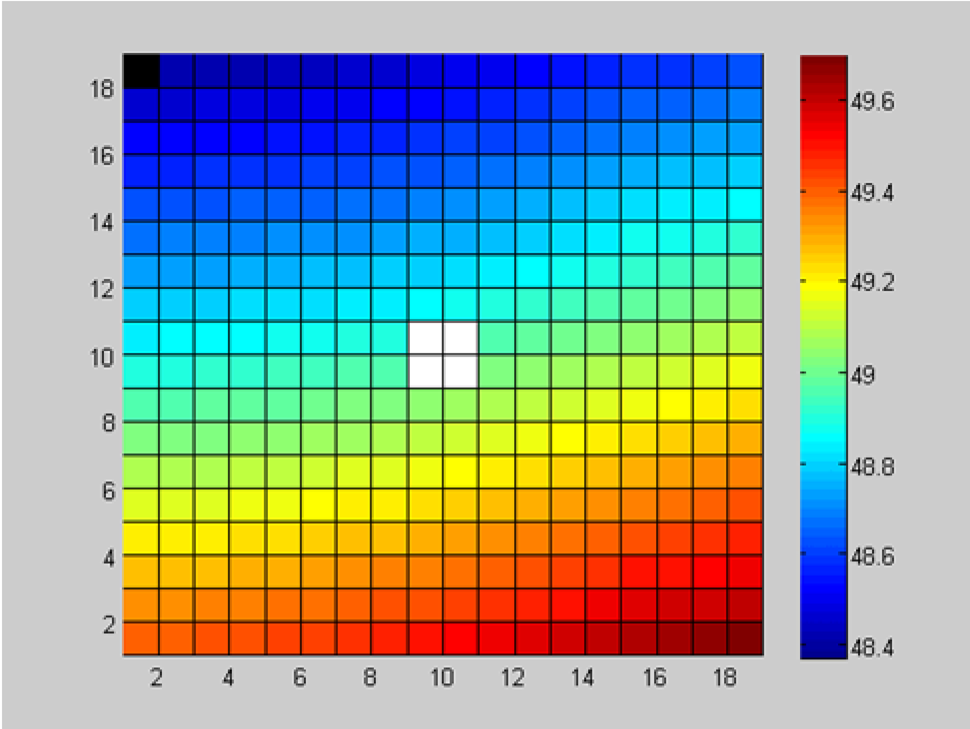

Figure 4.12 Location of the power plant regarding the biomass price

General parameters, that are same for power plants at all selected locations, are shown in Table 15.

Table 15. Investment costs

Investments	Amount
Specific investment cost [€/kW$_e$]	2500
Installed capacity of the generator [MW]	15
The overall efficiency of the plant	0,6
The share of loan in the investment [%]	100
Loan repayment time [year]	14
The interest rate of loan [%]	7
Discount rate [%]	12

The absolute values of investment costs are also the same and are shown in Table 16.

Table 16. Absolute values of investment costs

Construction costs	Amount
The overall investment cost	37,500,000.00 €
Construction works	3,750,000.00 €
Mechanical equipment and devices	33,375,000.00 €
Intangible costs	375,000.00 €

Maintenance and operating costs are also the same for all power plants. Maintenance costs are shown in Table 17.

Table 17. Maintenance and operating costs

Variable cost	Of the total investment [%]	Amount
The cost of operation and maintenance	3	1,125,000.00 €

Depreciation costs of all components are the same for all locations and are shown in Table 18.

Table 18. Depreciation

Component	Accounting lifetime	Depreciation rate [%]	Annual depreciation
Construction works	20	5	187,500.00 €
Mechanical equipment and devices	15	6.66667	2,225,000.00 €
The project, permits, etc...	5	20	75,000.00 €

Loan details are shown in Table 19.

Table 19. Loan rate

Loan amount	37,500,000.00 €
Interest	7.00%
Repayment	14
Loan rate	4,287,935.20 €

Power plants generate revenues from the sale of electricity and heat energy. The prices at which electrical and heat energy are sold amount, as mentioned in the previous section, 0.12219 (€/kWh), or for heat 0.0307 (€/kWhthermal). The annual sales revenue is shown in Table 20.

Table 20. Revenues

Revenue from sales of electrical energy [€]	Revenues from sales of heat energy [€]
14,662,800.00 €	4,789,200.00 €

As mentioned above for the assessment of investment profitability the IRR method will be used. If the IRR is greater or equal to the discount rate the project is considered profitable and if the IRR is lower than the discount rate the project is unprofitable.

Below are analysed, for each macro-location, the optimal location of the plant, the annual cost of fuel, according to the scenarios, and IRR for each of the scenarios, according to categories of land ownership. Then for each location sensitivity analysis is carried out, to determine how changes in significant parameters affect the IRR for each case. Also, the critical scenario, the Scenario 3, will be discussed.

4.3 Macro location 1 - Velika Gorica

In Figure 4.13 the power plant location and city location are shown. The power plant is marked with a black square and the city is marked with a white square.

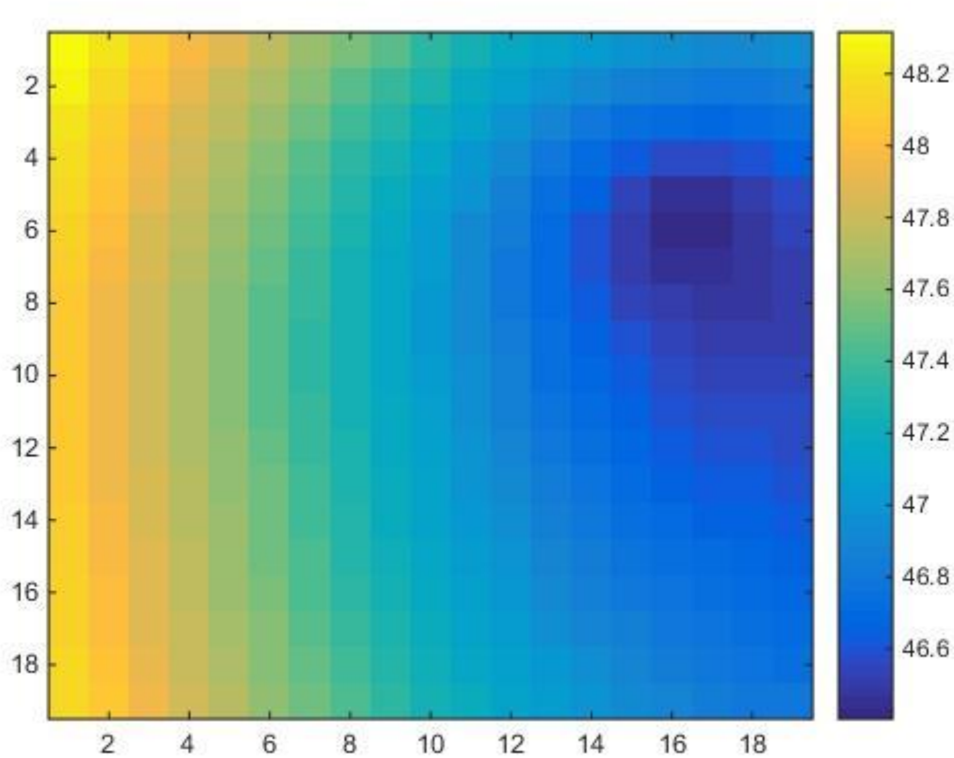

Figure 4.13 Velika Gorica - power plant location

With the calculated fuel price, which is 46.42 [€/ton], the annual fuel cost is shown in Table 21. This cost is constant over the duration of the contract. Changes in the fuel price and electricity price are affecting IRR, which will be analysed later.

Table 21. Velika Gorica - Annual fuel cost

Annual fuel cost	
State ownership	Private ownership
7,205,476.24 €	7,196,162.82 €

The IRR with above mentioned expenses and revenues is shown in Table 22. As it can be seen the slightly lower IRR is for the state ownership.

Table 22. Velika Gorica - IRR

Category of ownership	IRR
State	11.39%
Private	11.41%
Overall	11.65%

4.4 Sensitivity analysis

Important factors that could affect the viability of the project during its work lifetime in this case are the price of biomass from SRC, specific investment cost, the selling price of electricity and the price of transport. Changes of these factors will be discussed for the state ownership of the land.

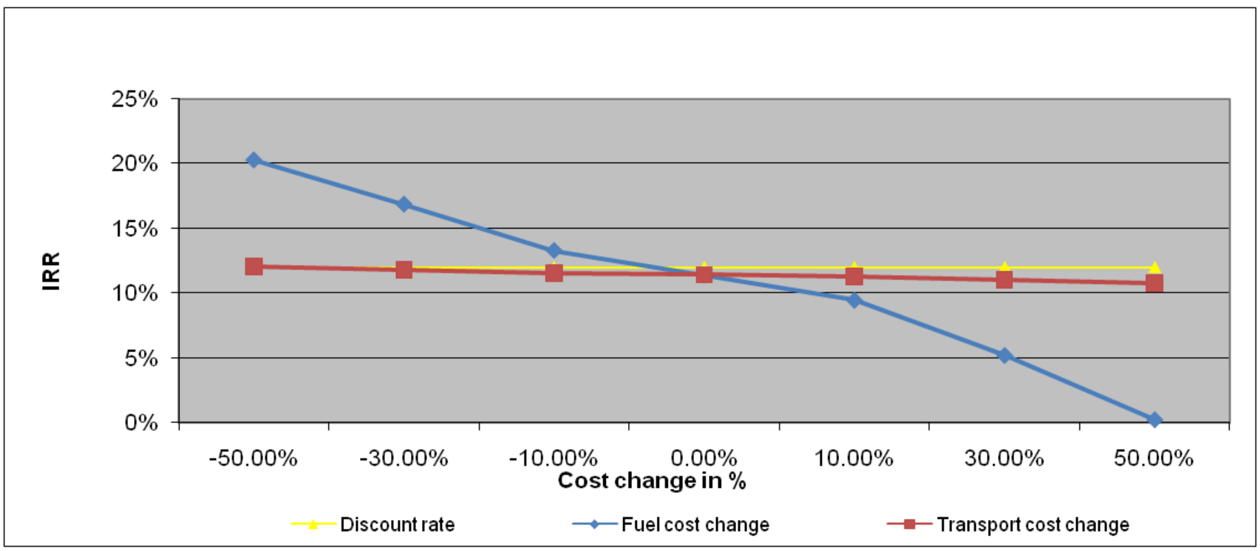

Figure 4.14 Velika Gorica - IRR dependence on the fuel and transport cost

IRR dependence on fuel and transport cost is shown in Figure 4.14. It can be noted that the highest impact on IRR has the fuel price. Next, in Figure 4.15 IRR dependence on the investment cost and the purchase price of electricity is shown.

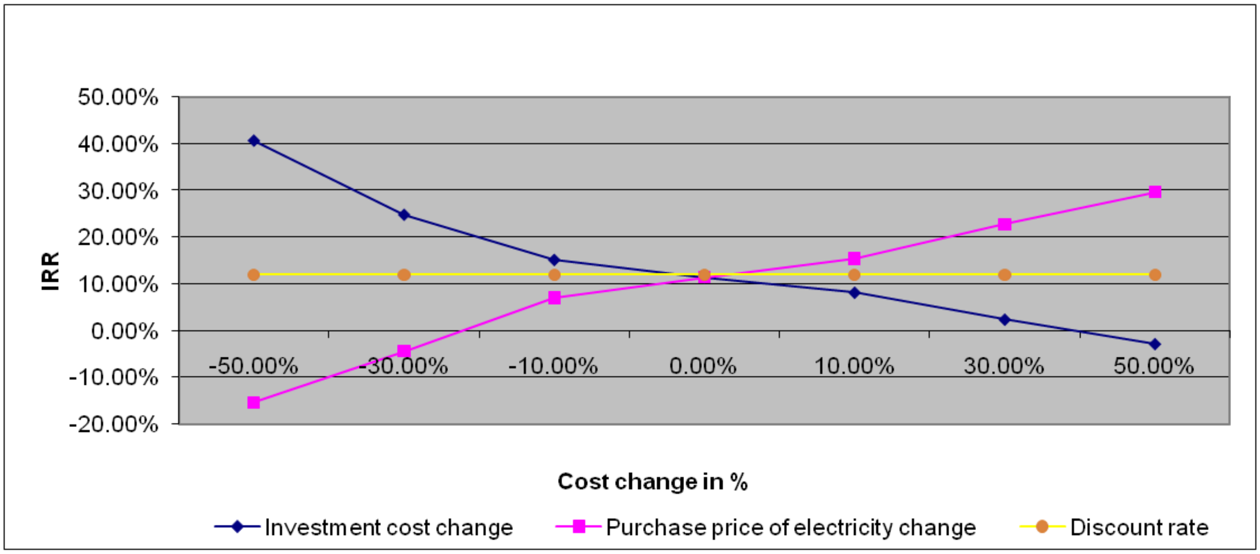

Figure 4.15 Velika Gorica - IRR dependence on the investment cost and the purchase price of electricity

As it can be seen, these factors have a larger impact on the IRR value to the previously mentioned. If the investment cost is 10% lower or the purchase price of the electricity is 10% higher the project would be profitable. Also, 10% lower fuel price would also make this project profitable.

4.5 Macro location 2 - Sisak

For the second selected location, power plant location and city location are shown in Figure 4.16. As for the previous location, the power plant is marked with a black square and the city is marked with a white square.

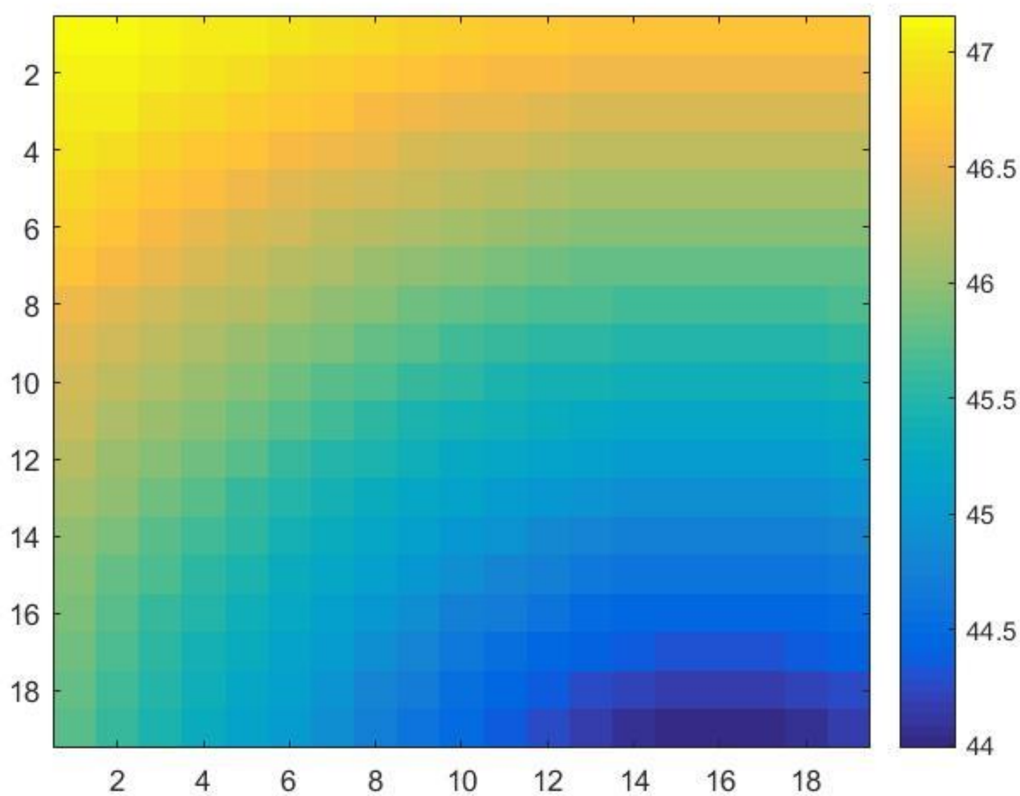

Figure 4.16 Sisak - power plant location

The fuel price for this location is 43.87 [€/ton]. With this fuel price the annual fuel cost is given in Table 23.

Table 23. Sisak - Annual fuel cost

Annual fuel cost	
State ownership	Private ownership
6,809,656.24 €	6,801,895.06 €

Then the IRR can be calculated and it is shown in Table 24. It can be noted that this project in the case of currently discussed scenario, which is the Scenario 3, is already profitable with the discount rate of 12%. Again, slightly lower IRR is for the state ownership.

Table 24. Sisak - IRR

Category of ownership	IRR
State	12.50%
Private	12.52%
Overall	12.52%

4.6 Sensitivity analysis

Important factors that could affect the viability of the project during its work lifetime in this case are the price of biomass from SRC, specific investment cost, the selling price of electricity and the price of transport. Changes of these factors will be discussed for the state ownership of the land.

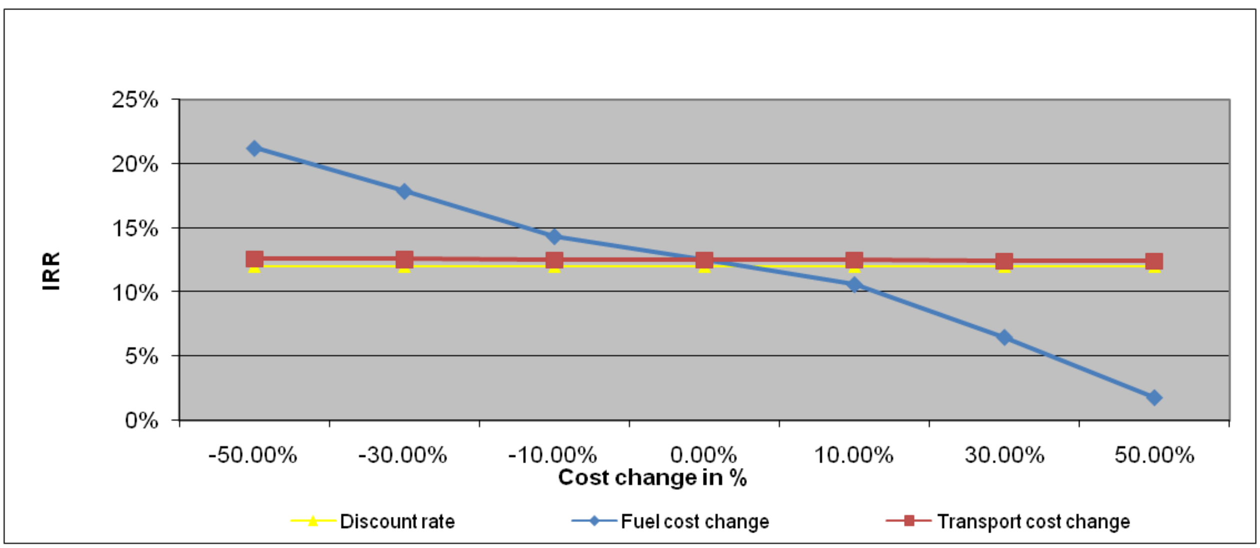

Figure 4.17 Sisak - IRR dependence on the fuel and transport cost

IRR dependence on the fuel and transport cost is shown in Figure 4.17. As for the previous location, larger impact on the IRR has the fuel price. In Figure 4.18 IRR dependence on the investment cost and the purchase price of electricity is shown. In this case, these factors have a larger impact on the IRR. If the purchase price of the electricity is 10% lower or the investment cost is 10% higher this project would be considered unprofitable.

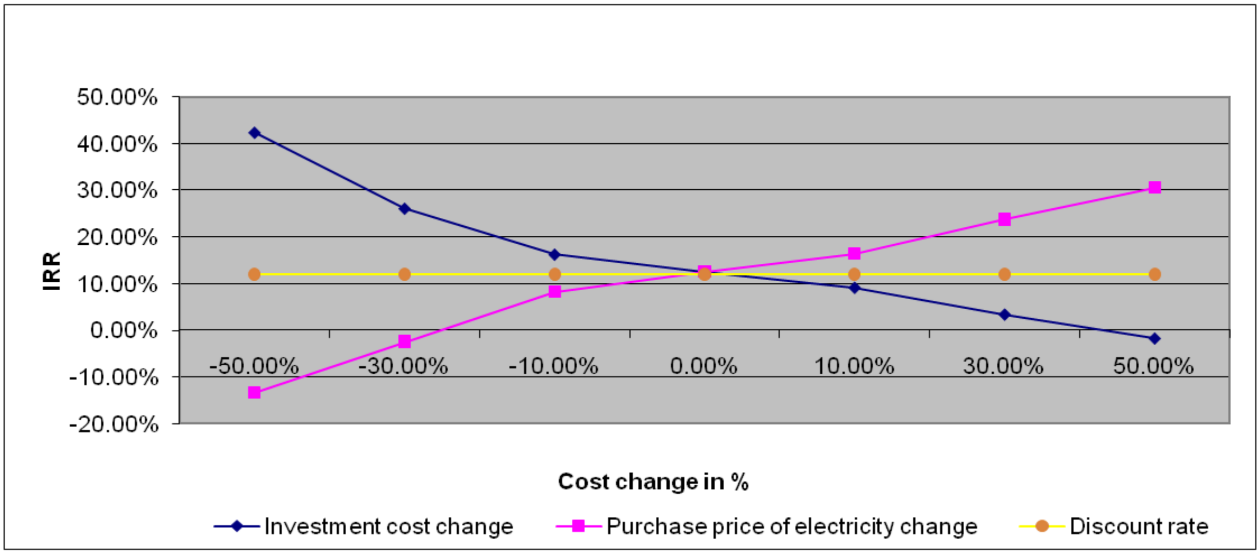

Figure 4.18 Sisak - IRR dependence on the investment cost and the purchase price of electricity

4.7 Macro location 3 - Koprivnica

Power plant and city location are shown in Figure 4.19.

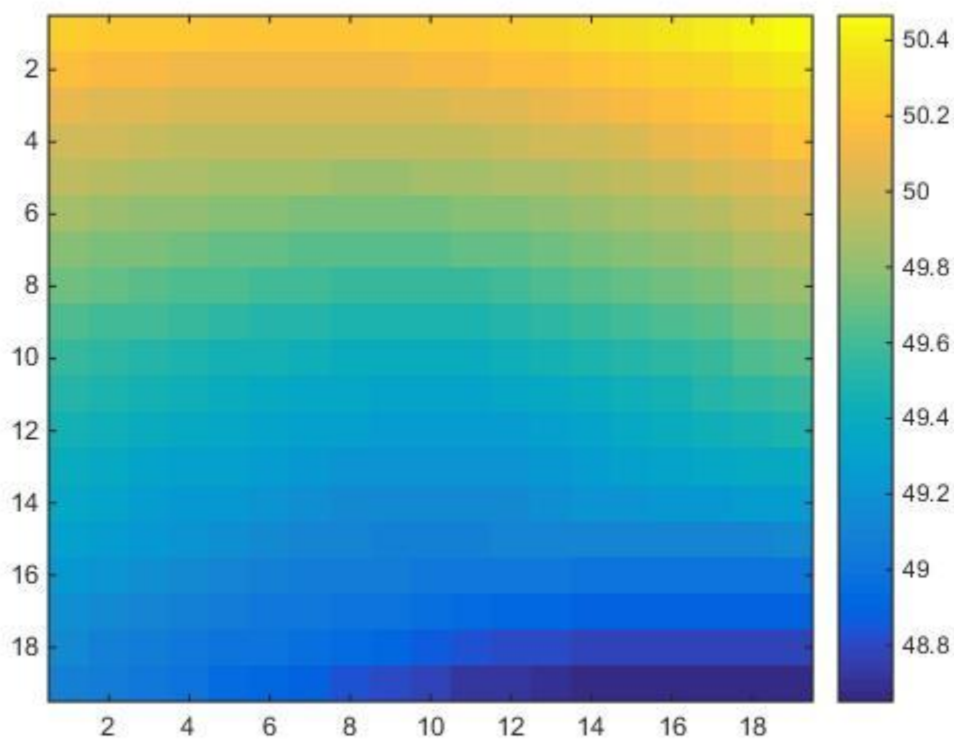

Figure 4.19 Koprivnica - power plant location

The fuel price for this location is 49.01 [€/ton] and the annual fuel cost is shown in Table 25.

Table 25. Koprivnica - Annual fuel cost

Annual fuel cost	
State ownership	Private ownership
7,607,505.18 €	7,508,162.12 €

Next the IRR is calculated and it is shown in Table 26. It can be seen that for this location the project is not profitable (discount rate is 12%) due to a higher fuel cost. The sensitivity analysis will show when the project would become profitable.

Table 26. Koprivnica - IRR

Category of ownership	IRR
State	10.23%
Private	10.52%
Overall	11.08%

4.8 Sensitivity analysis

First, the IRR dependence on the fuel and transport price is shown in Figure 4.20.

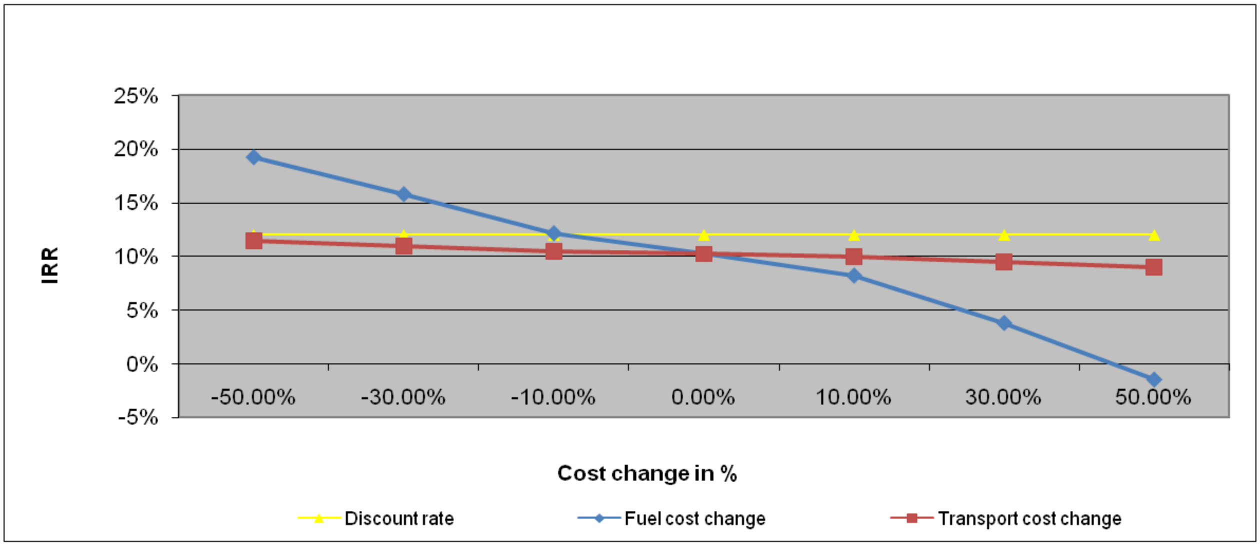

Figure 4.20 Koprivnica - IRR dependence on the fuel and transport cost

As it can be seen from the above figure, a 10% lower fuel price would make this project profitable. Also, for this location the IRR sensitivity was discussed for the state ownership. Next, in Figure 4.21 the IRR dependence on the investment cost and the purchase price of electricity is shown. It can be seen that a 10% lower investment cost and a 10% higher purchase price of the electricity would make this project profitable. Transport cost has a little influence on the IRR and a 50% lower transport cost would make this project on the verge of profitability.

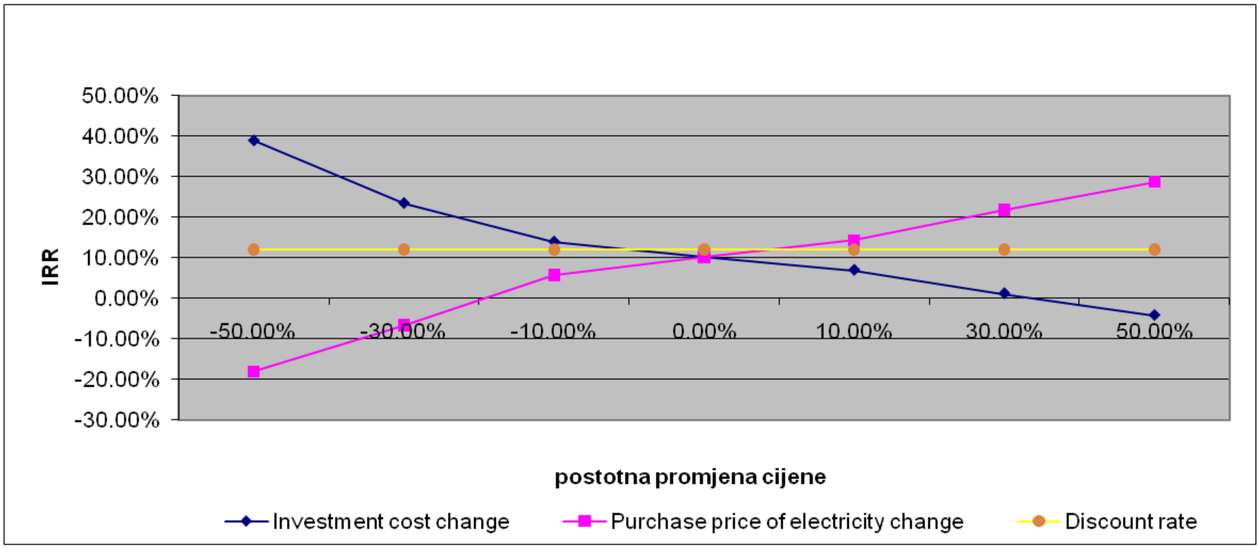

Figure 4.21 Koprivnica - IRR dependence on the investment cost and the purchase price of electricity

4.9 Macro location 4 – Slavonski Brod

Power plant and city location for Slavonski Brod are shown in Figure 4.22.

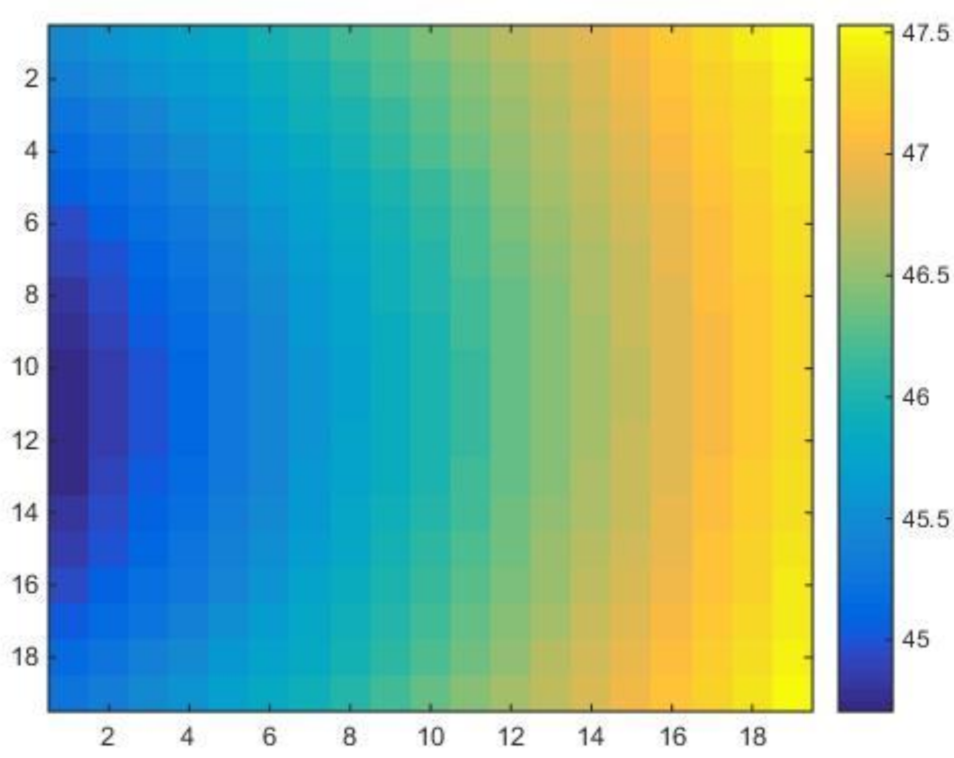

Figure 4.22 Slavonski Brod - power plant location

For this macro location the fuel price from the state land is 45.45 [€/ton] while the price of the biomass from the private land is 47.53 [€/ton]. In previous macro locations the fuel price was lower on the private land. With this the annual fuel cost is shown in Table 27.

Table 27. Slavonski Brod - Annual fuel cost

Annual fuel cost	
State ownership	Private ownership
7,054,909.41 €	7,377,774.35 €

IRR is then calculated and shown in Table 28.

Table 28. Slavonski Brod - IRR

Category of ownership	IRR
State	11.81%
Private	10.89%
Overall	12.10%

It can be seen that if the project is combined with the state and private land it would be considered profitable.

4.10 Sensitivity analysis

As before the dependence of the IRR on the fuel price, transport cost, investment cost and purchase price of the electricity will be analysed. The difference from the previous cases is that the critical case is for the private ownership unlike the other cases where the sensitivity analysis was done for the state ownership. The IRR dependence on the fuel and transport cost is shown in Figure 4.23.

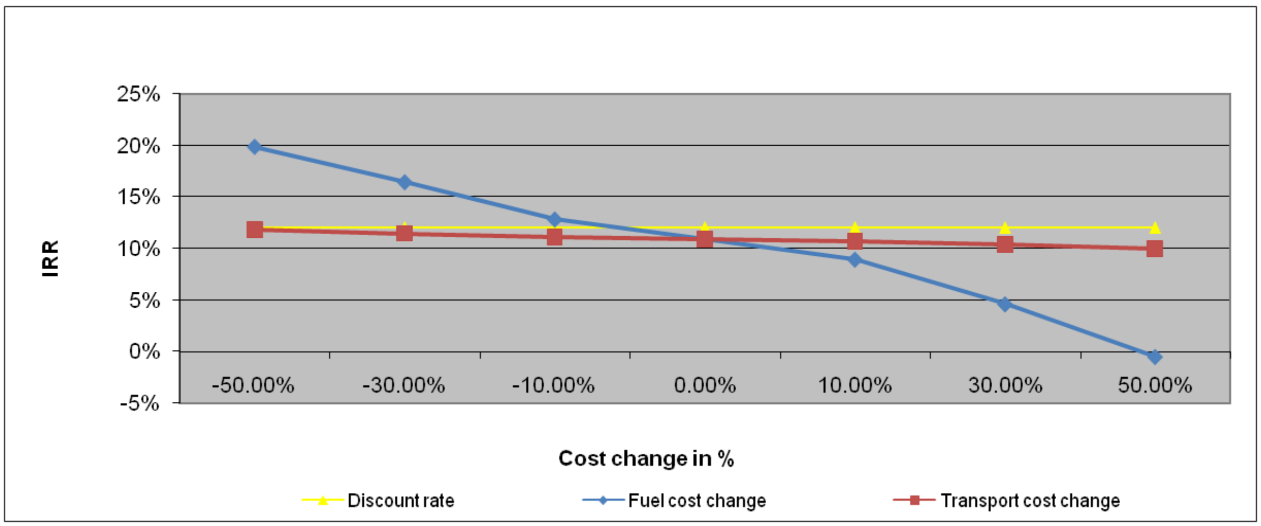

Figure 4.23 Slavonski Brod - IRR dependence on the fuel and transport cost

Next, in Figure 4.24 the IRR dependence on the investment cost and the purchase price of electricity is shown.

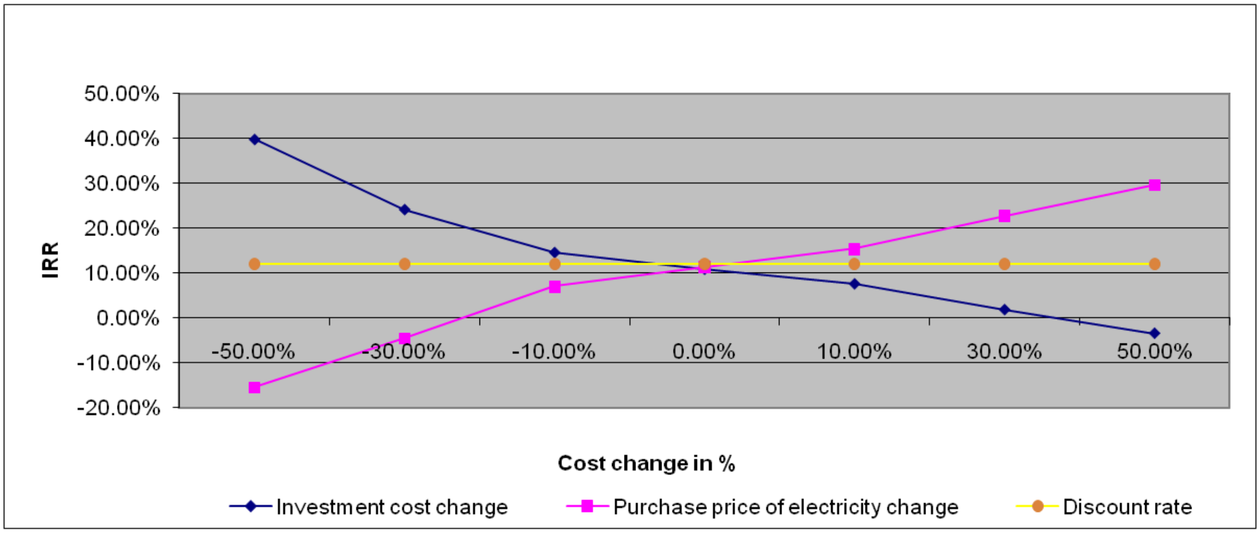

Figure 4.24 Slavonski Brod - IRR dependence on the investment cost and the purchase price of electricity

From this it can be seen that a 10% lower fuel price would make this project profitable, while a 50% lower transport cost would only make this project on the verge of profitability. As before a higher impact on the IRR have the investment cost and purchase price of the electricity. A 10% lower investment cost or a 10% higher purchase price of the electricity would make this project profitable.

4.11 Macro location 5 - Osijek

The last selected location is Osijek. Power plant location and city centre are shown in Figure 4.25.

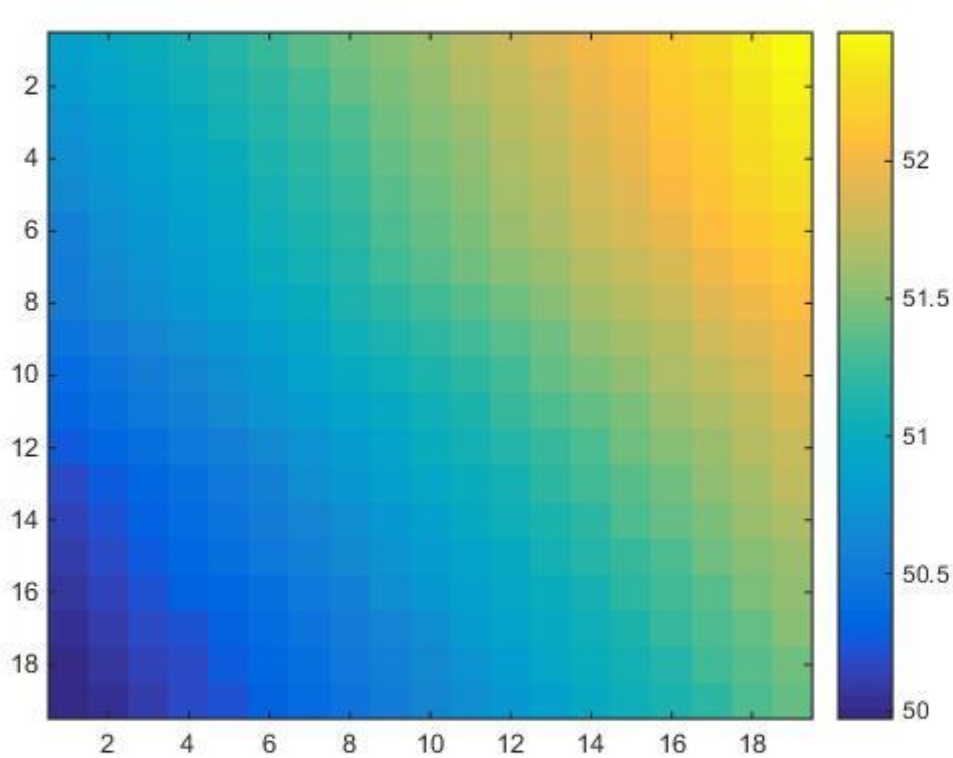

Figure 4.25 Osijek - power plant location

For this macro location the fuel price from the state land is 49.44 [€/ton] while the fuel price from the private land is 49.78 [€/ton]. With this the annual fuel cost is shown in Table 29.

Table 29. Osijek - Annual fuel cost

Annual fuel cost	
State	Private
7,674,251.29 €	7,727,027.29 €

The IRR is then calculated and shown in Table 30.

Table 30. Osijek - IRR

Category of ownership	IRR
State	10.03%
Private	9.88%
Overall	10.78%

4.12 Sensitivity analysis

As for the macro location 4 the critical case is for the private ownership and thus it will be analysed. The IRR dependence on the fuel and transport price is shown in Figure 4.26.

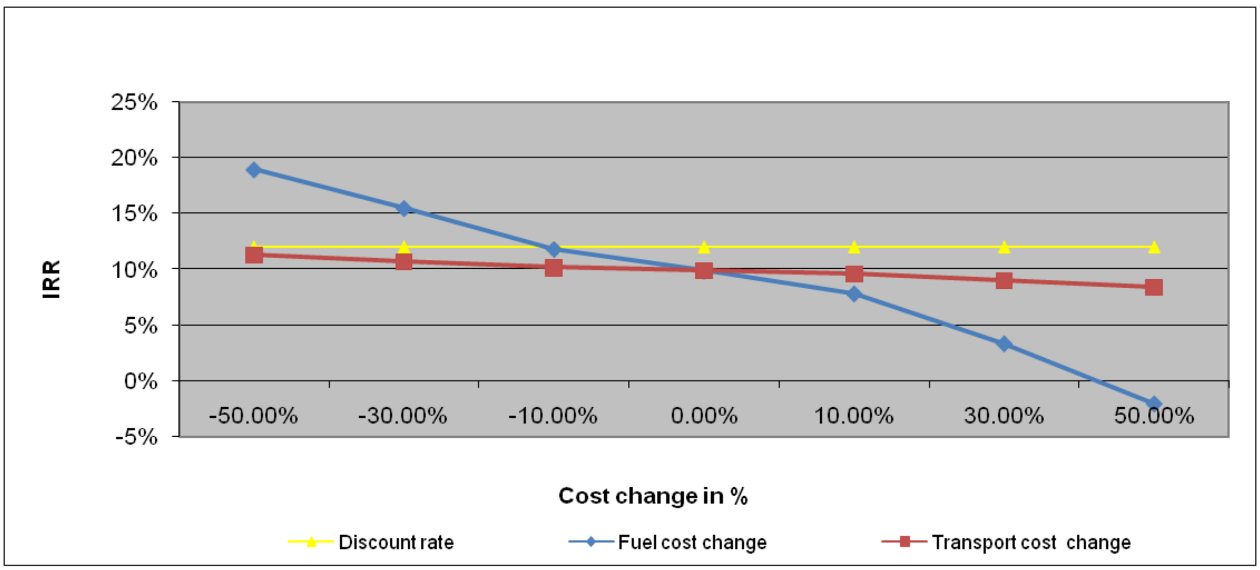

Figure 4.26 Osijek - IRR dependence on the fuel and transport cost

It can be noted that the project is profitable if the fuel price is lower at least 20%, while the 50% lower transport cost would still make this project unprofitable. Next, the IRR dependence on the investment cost and the purchase price of electricity is shown in Figure 4.27. There it can be noted that a 10% lower investment cost and a 10% higher purchase price of the electricity would make this project on the verge of profitability.

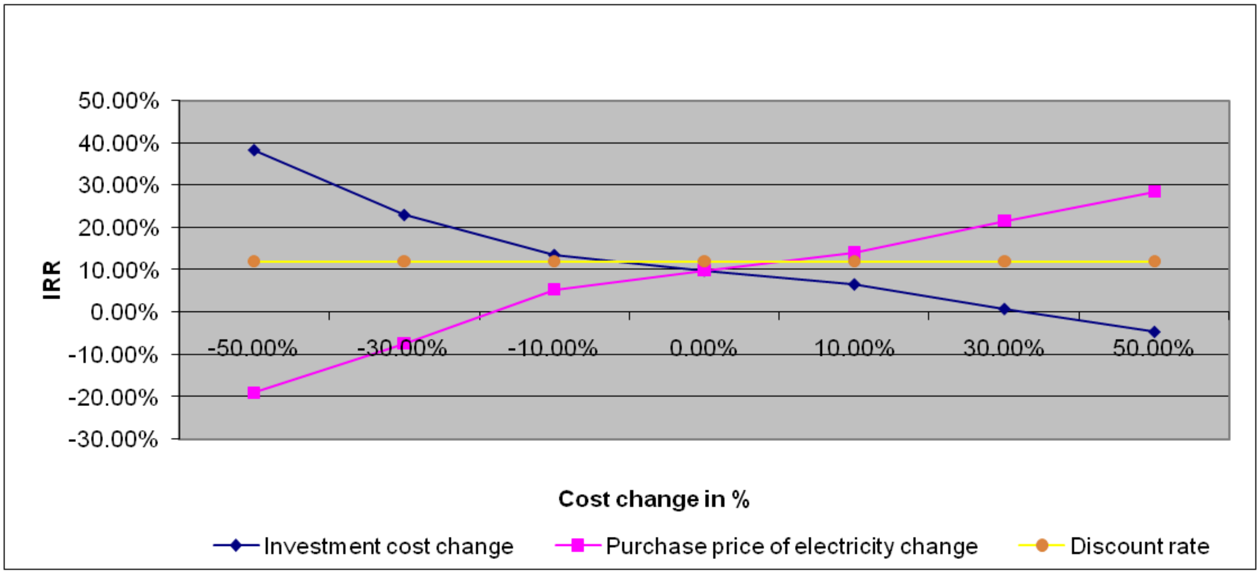

Figure 4.27 Osijek - IRR dependence on the investment cost and the purchase price of electricity

5. CONCLUSION

The goal of this study was to assess the potential for energy production from biomass produced from SRC in Croatia. As a part of the EU, Croatia strives to increase the share of renewables in overall energy production by using and developing technologies for exploiting various renewable energy sources such as the Sun, wind or biomass. Cultivating energy crops has multiple advantages such as: good biomass yield, increasing biodiversity, temporary animal habitat, regeneration of contaminated soil and filtration of wastewater which was discussed in previous chapters. At the same time, Croatia has large areas of agricultural land that are not being cultivated at the moment, which is considered as an unused potential. Also, the current economic situation in Croatia is not very good hence every option that could help create jobs and improve the economic situation should be considered.

Recent data show that there is a large energy potential of unused agricultural land. The energy potential was determined based on the category of ownership for different counties in Croatia. With a developed model, the price of biomass from SRC and the location of the power plant were determined. Methodology to determine energy and technical potential for energy production from biomass from SRC was discussed in Chapter 3. Next, the case study for Croatia was done with 5 selected macro locations. Power plants up to 15 MW of installed capacity were taken into account. The IRR method was chosen to represent the technical and economic analysis of the selected locations for power plants as it was shown in Figure 5.1. This figure represented the IRR for the Scenario 3 which was considered as the critical scenario because only 25% of the unused land was used for the cultivation of SRC for biomass production. Projects with IRR higher than 12% were considered profitable. It could be noted that only macro location Sisak was profitable with default parameters such as the investment cost, heat energy price, electricity price, etc. For each macro location the sensitivity analysis was done discussing how the change of important factors like the electricity price, transport cost, investment cost and fuel price could change the IRR. Generally, for all macro locations increase of the purchase price of electricity or decrease of the investment cost or fuel price only by 10% would make almost all the projects profitable. Transport cost had a very low influence on the IRR and it was shown that only 50% lower transport cost for some locations could help make projects profitable.

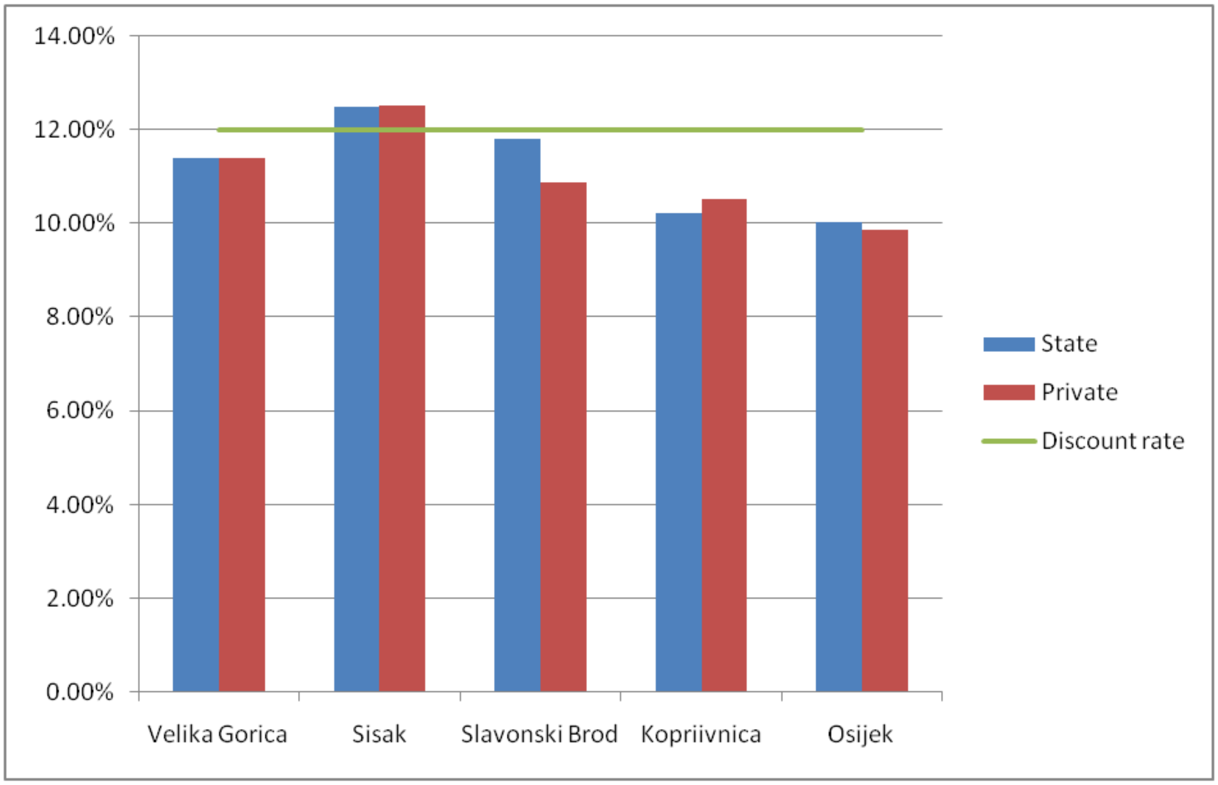

Figure 5.1 IRR for the selected macro locations

To be sure that SRC will be used for biomass production to generate electricity or heat energy more research should be conducted within the framework of local energy planning. Also, it is of great importance to arrange a legal framework, which would define what SRC in Croatia are and on what land it could be cultivated and what would be stimulated in the next 15 - 20 years.

Solving these administrative issues would open the doors for the development of the market for a new type of fuel currently still unknown in Croatia and which has the potential to increase the employment, improve the economic situation and help preserve the environment with the help of a new green energy.

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ANNEX

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Economic feasibility of CHP facilities fueled by biomass from unused agriculture land: Case of Croatia

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A B S T R A C T

In this paper, the energy potential of biomass from growing short rotation coppice on unused agricultural land in the Republic of Croatia is used to investigate the feasibility of Combined Heat and Power (CHP) facilities fueled by such biomass. Large areas of agricultural land that remain unused for food crops, represent significant potential for growing biomass that could be used for energy. This biomass could be used to supply power plants of up to 15 MW_e in accordance with heat demands of the chosen locations. The methodology for regional energy potential assessment was elaborated in previous work and is now used to investigate the conditions in which such energy facilities could be feasible. The overall potential of biomass from short rotation coppice cultivated on unused agricultural land in the scenarios with 30% of the area is up to 10 PJ/year. The added value of fruit trees pruning biomass represents an incentive for the development of fruit production on such agricultural land. Sensitivity analysis was conducted for several parameters: cost of biomass, investment costs in CHP systems and combined change in biomass and technology cost.

1. Introduction

In the European Union's (EU) struggle to achieve the energy package goals in 2020, in particular increasing the share of the EU energy consumption produced from renewable resources to 20%, biomass has a very significant position with 68% share of total gross inland consumption of renewable energy in 2011 and 8.4% of total final energy consumption in Europe in 2011. At the same time biomass is almost exclusive renewable fuel for heat with 95.5% share [1]. In Croatia, besides being widely used for domestic heating in rural areas, biomass is a dominant renewable resource in the most recent National Renewable Energy Action Plan, with a planned contribution of 26 PJ and 85 MW of capacity in 2020 [2]. These ambitious goals rest on biomass due to its socio-economic potential in Croatia, which is higher compared to the other renewable resources because of Croatia's forest and land potential. Croatia has problems with unemployment, similarly to some other countries in the EU, and at the same time large areas of unused agricultural land, both in public and private sectors. Extensive research has been conducted so far on the marginal land use for growing crops for biomass and biofuels [3]. Today, overall agricultural land in Croatia amounts to 2,955,728 ha. Out of that, 1,074,159 ha is considered suitable, 1,074,510 ha is considered to be of limited suitability and 806,328 ha is listed as unsuitable for agricultural production [4]. In order to fulfil its goals regarding renewable energy sources integration, while making a change and progress in other mentioned fields, Croatia might resort to Short Rotation Coppice (SRC), a form of cellulose biomass that has already been developed for energy use in some other countries of the EU. Previous research in this field in EU countries focused on annual yields [5] and most favorable species [6], and impact on soil [7] and biodiversity [8]. These energy crops are eligible for cultivation on a wide range of soils that are of limited suitability or unsuitable for agricultural production. Initial studies have already been carried out in the field of choosing the optimal clones of willow and poplar. These species are common in Croatia and thus most relevant candidates for use on larger scale, as shown for white willow [9], with respect to the issue of marginal land [10] and to the way appropriate clones of willow are chosen [11]. Moreover, initial research has been carried out to frame the overall potential of marginal land on the whole territory of Croatia [12]. Although there are some experimental fields of willow being

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studied, there is no commercial SRC farm currently in Croatia. Recent study discussed the uptake of the SRC by the farmers in Europe [13], which demonstrated that the potential profitability of SRC is not yet recognized, while the study of economics of SRC in continental Europe gives the roadmap toward the increase in feasibility compared to other types of crops [14].

The usage of SRC, as well as other energy crops started in Scandinavian countries right after the oil crisis in the 1970s. Production chains with energy crops are well developed in Sweden, Finland, the UK and Denmark and are making progress in countries of Central and South Europe. Recent data on areas under various energy crops is given in Table 1.

Important part of energy transition toward systems based on renewable energy sources is district heating with combined heat and power (CHP) plants using biomass as the energy source. Because of their importance, a lot of research has been conducted recently to investigate the application of these types of solutions. In [15] results for three variants of combined heat and power (CHP) biomass plants were calculated. Kilkis [16] developed a model for the net-zero exergy district development for a city in Sweden, which among other units includes a CHP plant with district heating and cooling system. Krajačić et al. [17] provided an overview of potential feed-in tariffs for different energy storage technologies. Wang et al. [18] published a paper dealing with multi-objective optimization of a combined cooling, heating and power system driven by solar energy. Raine et al. [19] optimized combined heat and power production for buildings using heat storage. Mikulandrić et al. [20] examined the possibilities of a hybrid District Heating (DH) systems in small towns, with advantages in lower cost when the system is powered by renewable energy. Recently, the study of biomass CHP and DH applications in the urban areas being competitive with natural gas was conducted in Pantaleo et al. [21], with detailed sensitivity analysis conducted in a separate paper [22]. In Rudra et al. [23], the research goes further to propose more complex novel polygeneration systems based on biomass utilization, which increases the efficiency of resource utilization, minimizes the impact on the environment due to distributed generation and, through flexible operation, supports the integration of renewable energy [23]. Research in the use of biomass for CHP systems is well connected to the overall goal to achieve energy systems with 100% energy produced from the renewable sources. In the recent research regarding the possibility of 100% renewable energy system in the whole SEE, biomass is viewed more conservatively than before, with the energy potential of 726 PJ/year for the entire region. The use of SRC could increase this potential further [24].

In this paper, the research builds upon the current state-of-the-art scientific work by showing how unused agriculture land in Croatia could be used to cultivate SRC, which later could be used as fuel in the CHP plants. This is considered firstly for a novel system that combines cooling, heating and power and is supplied by storage. Further elaboration is conducted regarding feasibility of such system and the sensitivity analysis of the most important factors.

2. Metodology

Short rotation coppice species are perennial species which have a lifetime of 15–20 years, depending on the species, and are usually harvested every 2–8 years. In order to have continuous output of biomass for energy plants each hectare of agricultural land deemed to be at the disposal is divided into three fields, with the assumption that in every rotation only one field would be harvested, so that one hectare supplies biomass continuously during the lifetime of the species [25]. Therefore, the technical potential of the respective county or region is calculated in Eq. (1):

Table 1
Cellulosic energy crops in EU in 2011 [1].

	Willow (ha)	Poplar (ha)	Miscanthus (ha)
AT	220–1100	880–1100	800
BE	60		120
DK	5697	2807	64
FR	2300		2000–3000
DE	4000	5000	2000
IE	930		2200
IT	670	5490	50–100
LT	550		
PL	5000–9000	300	
SE	11,000	550	450
UK	1500–2300		10,000–11,000

$$\sum_{i=1}^{n} B_{teh}(i) = \sum_{i=1}^{n} \left(A(i) * P_y(i) * k + A_f(i) * P_f(i)\right) \quad (1)$$

where $B_{teh}(i)$ is the technical potential of the county (i) (t), $A(i)$ is the area of unused agricultural land at the disposal (ha), $P_y(i)$ is the yearly production of biomass from the species used on the area A in (t/year) and k is the factor of rotation which determines the pace of harvesting. For every species or clones, factor k can be arbitrated according to the location in question. Furthermore, $A_f(i)$ is the area of the county (i) under fruit trees (ha) and $P_f(i)$ is the yearly production of biomass from pruning of the fruit trees (t/year).

The energy potential of the respective county or region is calculated with the assumption that the obtained biomass is stored after harvesting and finally reaches the gate of energy plant with moisture value of 30% and lower heating value of 3.5 kW h/kg respectively [26]. The energy potential is calculated in Eq. (2):

$$B_{ep(i)} = B_{teh(i,SRC)} * Hd_{SRC} + B_{teh(i,fruit)} * Hd_{fruit} \quad (2)$$

where $B_{ep(i)}$ is the energy potential (GJ/year) of the county (i) and Hd_{SRC} is the lower heating value of the biomass from SRC at the gate of energy plant (GJ/t), while $B_{teh(i,fruit)}$ is the technical potential of biomass from fruit trees pruning (t/year), $B_{teh(i,SRC)}$ is the technical potential of biomass from SRC (t/year) and Hd_{fruit} is the average lower heating value of biomass from fruit trees pruning (GJ/t).

For the calculation of the price of biomass at the gate of power plant, the method from [27] was used in Eq. (3). The price of biomass as a function of the SRC farm distance from the power plant is calculated:

$$C_{B,E} = \sum_{i=1}^{n} \frac{[C_B + (T_p \times U_i)] \times K_{Bi}}{P_B} \quad (3)$$

where $C_{B,E}$ is the price of biomass at the gate of power plant (€/t), C_B is the price of biomass harvested from the SRC farm (€/t), T_p is the specific cost of transport (€/t/km), U_i is the average distance between the farm and power plant (km), K_{Bi} is the amount of biomass from the location (i) (t), P_B is the total yearly amount of biomass used by the power plant (t).

For the purpose of gaining a better insight into regional differences in potential, which is crucial for economic viable choice of location for both SRC farms and biomass power plants, the scenario approach has been adopted. Various percentages of unused agricultural areas have been taken into account and the difference between public and private agricultural land has been considered in order to benefit the future research of different operational and maintenance costs of SRC farms. The farms can be run by hired workforce and mechanisation compared to private landowners that can use their own, slightly modified mechanisation and labor, which might lower the costs significantly.

The cost of the biomass harvested from the SRC farm is calculated according to Eq. (4) [12,25]:

$$C_B = T_S + T_Z + T_{O\&M} \tag{4}$$

where T_S is the cost of seeding material (€/ha), T_Z is the cost of land cultivation and $T_{O\&M}$ is the cost of labor and harvesting in the life cycle of species. Typical costs in Europe are shown in Table 2. The selling price is expressed in Euro per ton of dry matter (DM).

In each scenario, a combination of SRC, predominantly willow and fruit cultures, will be considered for the production of biomass. For the calculation of biomass costs at the respective power plants' gate and the Net Present Value (NPV) for each location, a code programmed in MATLAB has been used. It is an original code from [25], altered in order to take into account unused agricultural land instead of forests and forest residue. The model develops a network of quadrants with each quadrant representing an area of 1 km^2. The model calculates the average price per tonne of biomass ($C_{B,E}$) in each quadrant, and selects the most appropriate site. The code firstly positions in a particular quadrant and then calculates the amount of biomass resources which are sorted according to the distance. Biomass being closer has an advantage over the more distant biomass until it reaches the last source of biomass to be taken. For the most favorable location it lists the correct order of the sources, which it takes the biomass from with the amount of biomass taken from each source. Due to the simple assignment of input data, a piece of code that selects the waste biomass from wood processing industry can be easily modified if there is another potential source of biomass, such as agricultural land planted with SRC. All locations are given in the form of geographical coordinates: latitude and longitude. Distances between specific coordinates of the model are calculated using the Haversine formula, which takes the Earth as a sphere, ignoring the effects of the ellipse.

The Haversine formula has been first used in the beginning of the 19th century. The formula calculates the distances between the two points on a sphere using the spherical triangles. Thus, simplifying the Earth's shape as a sphere instead of an ellipsoid, the Haversine formula can be used. Due to the relatively short distances between different areas in the model, this simplification doesn't influence the result significantly since the mistake never goes beyond 0.5% [28].

3. Case study Croatia

Macro-locations for power plants have been chosen according to local heat demands obtained from the Sustainable Energy Action Plans (SEAP) of the cities considered. In each location that was considered, heat demand was taken from the SEAP and used as a base for calculation of the required CHP installed capacity, which was 15 MW$_e$ and 30 MW$_t$ for each location being investigated.

Since there are no commercial SRC farms in Croatia so far, the price of biomass from such a farm was calculated including the establishment of the farm, yearly expenses for workforce and mechanisation and yearly production of biomass from the hectare of area, taking into consideration various soil quality and suitability. Investment, operation and maintenance costs were estimated to be 6267 €/ha for the whole life cycle of 12 years of willow cultivation, achieving 12 t$_{DM}$/ha/year or 144 t$_{DM}$/ha in the life cycle of the SRC farm. Therefore, C_B of biomass from such a farm was estimated to be 43.47 €/t [12]. In the case of willow, a 3-year rotation has been selected for the calculation. Using state owned land (through land concession or other instruments) is beneficial from the point of view of ownership, which is often a great barrier for any area intensive project in Croatia, since private land is often shared by multiple owners. On the other hand, at locations where

Table 2
Typical costs for SRC farms [12,30].

Location	Species	Cultivation costs (€/ha)	Operation costs (€/ha/y)	Selling price (€/t$_{DM}$)
Sweden – Nynas Gard	Willow	1222	330	65
Sweden – Puckgarden	Willow	1110	265	52
Latvia	Willow	1450	n/a	n/a
Latvia – Salixenergi	Willow	1630	480	n/a
France– Bretagne	Willow	2545	355	n/a
Germany – Goettingen	Poplar	2750	250	65
Italy – Rinnova	Poplar	2320	875	55
Croatia	Willow	3916	196	43.47

private land could be utilized without a very costly and time consuming process of dealing with ownership problems, the costs of land and mechanisation could be lower, presenting the investors with the opportunity to reach the scenarios presented in sensitivity analysis, making the SRC production feasible.

In order to make comparison, as well as to preserve biodiversity and encourage production in the region, biomass from fruit trees pruning was also taken into account in the scenarios. The amount of biomass from fruit trees was calculated according to [29]. Table 3 reports on how much biomass could be obtained by pruning of plantations of respective fruit cultures. The combustion of other types of biomass with biomass from SRC is considered desirable at this stage in the practice of Central European countries [30].

The separate issue is the statistical coverage of unused agricultural land. It has been followed through yearbooks of the National Bureau of Statistics until the year 2005, when due to the adjustment to the European standards in statistics, unused land was no longer published as a dataset. In the year 2009, a new Agency for Agricultural Land was founded and started to review data on state-owned agricultural land.

Their newest findings were used here to calculate available agricultural land in each county. For private unused agricultural land, data from the Statistical Yearbook 2004 of the National Bureau of Statistics was used. Although the difference of 10 years in datasets could cause some inaccuracies, assumptions in the scenarios were conservative enough to make sure that the calculated technical potential could be actually achieved [31]. In Table 4 the data on unused agricultural land is provided [32].

Private land stands for exclusively private-owned land, while the state-owned land is in the ownership of local self-government or the companies such as the Croatian Forests, owned directly by the country of Croatia. The difference is significant due to the state of the land, concerning the ownership by private citizens, which usually makes the land on the same location more fragmented and causes significant practical difficulties for anyone trying to put the land into use.

For the case study of Croatia, scenarios were devised as follows:

SCENARIO 1 – 30% of unused agricultural land was used to cultivate willow SRC. The scenario was divided according to the ownership to show the difference in local potential when:

(1a) 30% of state-owned land was used
(1b) 30% of private land was used
(1c) 30% of aggregated state-owned and private land was used

SCENARIO 2 – 20% of unused agricultural land was used to cultivate willow SRC. The scenario was divided according to the ownership to show the difference in local potential when:

(2a) 20% of state-owned land was used
(2b) 20% of private land was used
(2c) 20% of aggregated state-owned and private land was used

Table 3
Biomass from fruit trees pruning [29].

	Total biomass (kg/ha)
Fruit trees	
Apple	5571.43
Pear	5833.33
Peach and nectarine	2921.21
Apricot	1619.58
Cherry (sweet and sour)	1783.07
Plum	2053.15
Fig	1281.12
Dry fruit trees	
Walnut	538.04
Hazelnut	1848.48
Almond	1625.17
Grape	
Total	4258.37
Olive	
Total	2522.22

Table 4
Unused agricultural land divided according to ownership [25,32].

County	Public (ha)	Private (ha)
Krapina-Zagorje	115.27	1783
Varazdin	1009.79	1469
Medjimurje	1702.89	2910
Koprivnica-Križevci	2563.36	987
Osijek-Baranja	3826.71	5316
Vukovar-Srijem	4445.69	2662
Virovitica-Podravina	7019.16	5221
Zagreb	7989.94	8890
Bjelovar-Bilogora	9974.94	15,476
Požega-Slavonia	15,391.35	12,875
Brod-Posavina	19,689.77	7326
Karlovac	32,767.84	82,259
Sisak-Moslavina	33,733.16	57,412

SCENARIO 3 – 10% of unused agricultural land was used to cultivate willow SRC. The scenario was divided according to the ownership to show the difference in local potential when:

(3a) 10% of state-owned land was used
(3b) 10% of private land was used
(3c) 10% of aggregated state-owned and private land was used

SCENARIO 4 – 20% of unused agricultural land was used to combine cultivation of willow SRC with the increase in production of the most widespread fruit sorts in Croatia (apple, pear, peach, cherry, plum, walnut and hazelnut) according to the data from [33]. The scenario was divided according to the ownership to show the difference in local potential when:

(4a) 20% of aggregated state-owned and private land was used, divided to achieve a 100% increase in areas under most widespread fruit sorts and to use the rest of the area for SRC cultivation.
(4b) Same as in 4a, but with a goal to achieve a 50% increase in areas under fruit sorts.
(4c) Same as in 4b, but with a goal to achieve a 25% increase in areas under fruit sorts.

District heating systems powered by the acquired biomass ran on novel Combined Heat and Power (CHP) plant, in order to meet as much energy demand as possible. For this case study, data from Table 4 was calculated as the base data of the CHP plant. The District Heating System (DHS) includes heating grid and heat storage to allow the plant to extend its availability during months with lower heat demand and to enable peak shaving.

Recently, following the European Commission's recommendation, a new form of subsidizing the investment in renewable energy sources has been implemented in Croatia. Instead of feed-in tariffs used before, a feed-in premium has been approved to be the main scheme for subsidizing renewables [34]. It is expected that a tender will be called for filling in the quotas set for specific technology in which the offer with the lowest feed-in premium will be chosen. However, as the procedure is only in the starting phase, the range of offers that will be offered is still unclear. Thus, the best approximation can be found in Dominković et al. [35]. The calculated feed-in premium should be around 0.085 €/kW h of electricity supplied to the grid in order that subsidy level remains in the same range as it was the case with feed-in tariffs. For this case study, the level of subsidy is given in Table 5.

In Fig. 1, the simulated behavior of the CHP plant on the market is given. The blue[1] line is the income from the market, according to the Nordpool market prices from 2014, and the red line is the income including the Feed-in Premium.

Since the new Act is not yet in force and no ordinances have been declared to describe how the feed-in premium will be implemented, the sensitivity analysis is conducted under the Act that is still in force and uses a feed-in tariff, calculated on the basis of the average, "blue" tariff from [36].

4. Results

In this section, the results of the methodology applied in the case study of Croatia are presented. Also, the sensitivity analysis is performed at the end of the chapter to discuss the circumstances in which the exploitation of this potential for fuel in CHP could be feasible.

Technical potential and energy potential of biomass from SRC for the scenarios 1a, 1b, 2a, 2b, 3a and 3b for six most promising counties are shown in Fig. 2.

There is a noticeable potential in the Karlovac and Sisak-Moslavina counties due to the large areas of unused agricultural land in those counties. This can be seen in even greater disparity in Fig. 3, which shows the results of technical and energy potential of biomass from SRC for the scenarios 1c, 2c and 3c.

In the scenarios 4a, 4b and 4c shown in Fig. 4, technical and energy potential are lower due to the inclusion of the biomass from fruit trees pruning. However, the advantages of that are larger employment and the reduction of country's fruit import dependence.

Technical and energy potential for all the scenarios for the Continental Croatia (counties from Table 4), is given in Table 6. Counties of the Mediterranean Croatia were not included in this paper because of specific differences in climate and soil, which would influence the choice of SRC culture that should be cultivated. Moreover, the scarcity of agricultural land in those counties might contribute to seeing SRC as a competition with food crops. For the economic feasibility of such power plant and its DHS, the method of the Net Present Value (NPV) was used. Negative results for each of the macro-locations are presented in Fig. 5, which shows nets of 19 × 19 km of each macro-location for the scenario 1c. The values presented in Fig. 5 show that this value chain, connecting SRC and CHP with seasonal storage would not be feasible with the given parameters.

Using the code in Matlab from [35], the techno-economic analysis was conducted for macro-locations in Croatia. Results

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

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Table 5
Base data for the calculation of the CHP plant [37–39].

	Amount	Unit
Power plant availability	0.9	
Biomass price at the SRC field	43.47	€/ton
Lower calorific value (30% moisture)	3,500	kW h/ton
η power plant total	0.87	
η_{el}	0.29	
HTP ratio	2.00	
η storage	0.8	
Storage temperature	90	°C
Power plant specific investment cost	3600	€/kW$_e$
Absorber investment cost	400	€/kW
District system piping cost	5820	€/dwelling
Dwellings connected to DHS	8700	
Storage investment cost	56	€/m^3
Plant's own electricity consumption	6%	
Discount rate	7%	
Feed-in-tariff	0.122	€/kW h$_e$
COP	0.7	
Design temperature for heating	21	°C
Design temperature for cooling	26	°C
Fixed power plant O&M cost	29	€/kW per annum
Variable power plant O&M cost	0.0039	€/kW h
District heating O&M cost	75	€/dwelling per annum
Storage O&M cost	0.39	€/m^3 per annum
Heating energy revenue	0.0198	€/kW h
Project lifetime	14	Years

are supplied in a view of the cost of biomass at CHP plant's location – which was optimized according to this cost.

In order to supply complete information, the cost of biomass for each scenario and location is presented in Table 7. Locations in the vicinity of the Karlovac and Sisak-Moslavina counties have lower prices of biomass from SRC.

Other factors that are challenging for the implementation of SRC biomass based DHS are the size of the heating (cooling) network and the cost of SRC biomass. The cost of the biomass could be influenced in particular by encouraging private landowners to adopt SRC cultivation and use their own mechanization and workforce. In Fig. 6 the result of sensitivity analysis is presented.

The sensitivity analysis was performed for the case of Osijek macro-location because of the least amount of available land for the SRC cultivation in the surrounding counties. Furthermore, this location already has a DHS grid, which is the first criteria that would need to be fulfilled at this point, if the use of SRC is to be feasible.

The factors discussed in the analysis are investment cost, the price of biomass following investment cost changes and the price of biomass without the change of the investment cost.

Therefore, when discussing the lower price of biomass standalone, it refers to only taking into account the lower price of biomass without change of the investment cost or other conditions. When discussing the reduced investment cost, the price of biomass

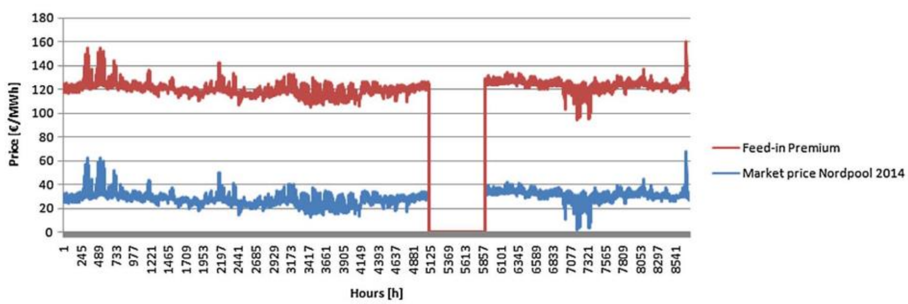

Fig. 1. Model of feed-in premium in market conditions for the CHP plant [35].

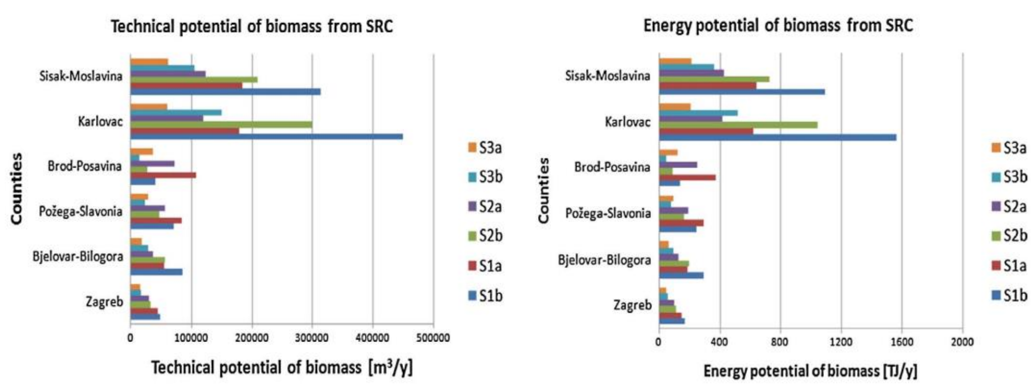

Fig. 2. Technical and energy potential of biomass from SRC in "a" and "b" scenarios.

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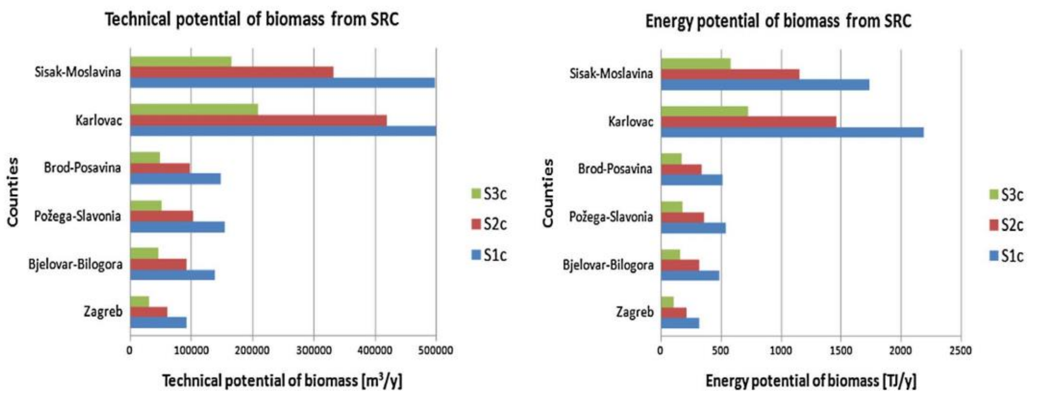

Fig. 3. Technical and energy potential of biomass from SRC in aggregate land scenarios.

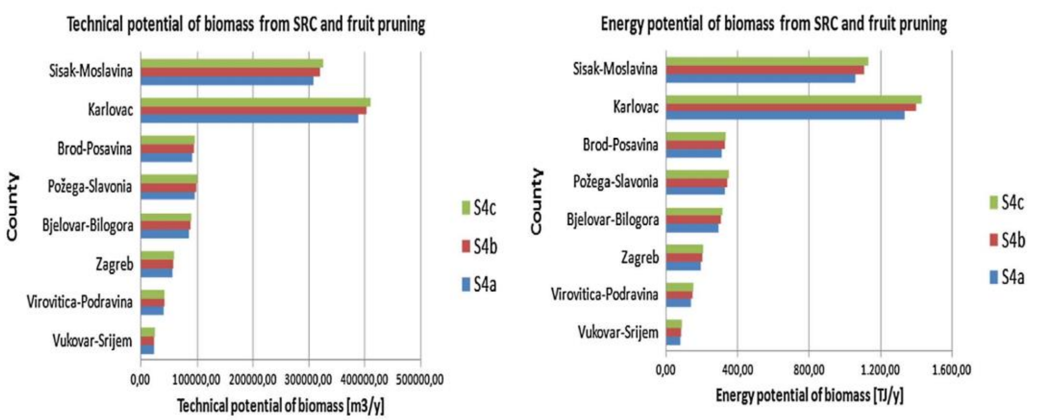

Fig. 4. Technical and energy potential of biomass from SRC and fruit trees pruning.

remains constant, while the combined approach takes into account both effects: investment cost reduction and reduction in the price of biomass at the same time.

It can be seen that only the simultaneous reductions of the investment cost and the price of biomass made the system economically feasible. Large difference toward feasibility is expected and can be reached in reality through incentives or by choosing simpler systems like the already working DH systems with the fuel shift to SRC. Price of the SRC and fruit biomass can be lower if the rate of privately owned land is increased, and the price of fruit pruning biomass decreased. The biomass price can be further lowered by using one's own labor force in a combination with entrepreneurs who own their machinery.

Table 6
Technical and energy potential for aggregated for continental Croatia.

Croatia	Technical potential (m^3/y)	Energy potential (TJ/y)
$S1_a$	1,404,094	4902
$S1_b$	1,426,108	4979
$S1_c$	2,830,202	9881
$S2_a$	936,062	3268
$S2_b$	950,738	3319
$S2_c$	1,886,801	6588
$S3_a$	468,031	1634
$S3_b$	475,369	1659
$S3_c$	943,400	3293
$S4_a$	1,169,257	4176
$S4_b$	1,212,193	4329
$S4_c$	1,233,661	4356

5. Conclusion

Cultivating SRC for biomass has already been commercially established value chain in some of the EU countries, especially in Sweden, Denmark, Germany, the UK, Poland and Italy. In the EU, research continues on the influence of SRC on soil, SRC yield and the best practices to exploit SRC for biomass as a valuable contribution to common energy and environmental goals in 2020 and beyond. In Croatia, SRC can be seen as a new fuel, which fosters the integration of factors such as large areas of unused agricultural land, high unemployment and renewable sources inclusion goals. Analysis of regional potential shows that even conservative assumptions on the area that could be cultivated with SRC could lead to the substantial contribution to meeting local energy demands in a more sustainable way and creating new job opportunities at the same time. At the moment, the most innovative

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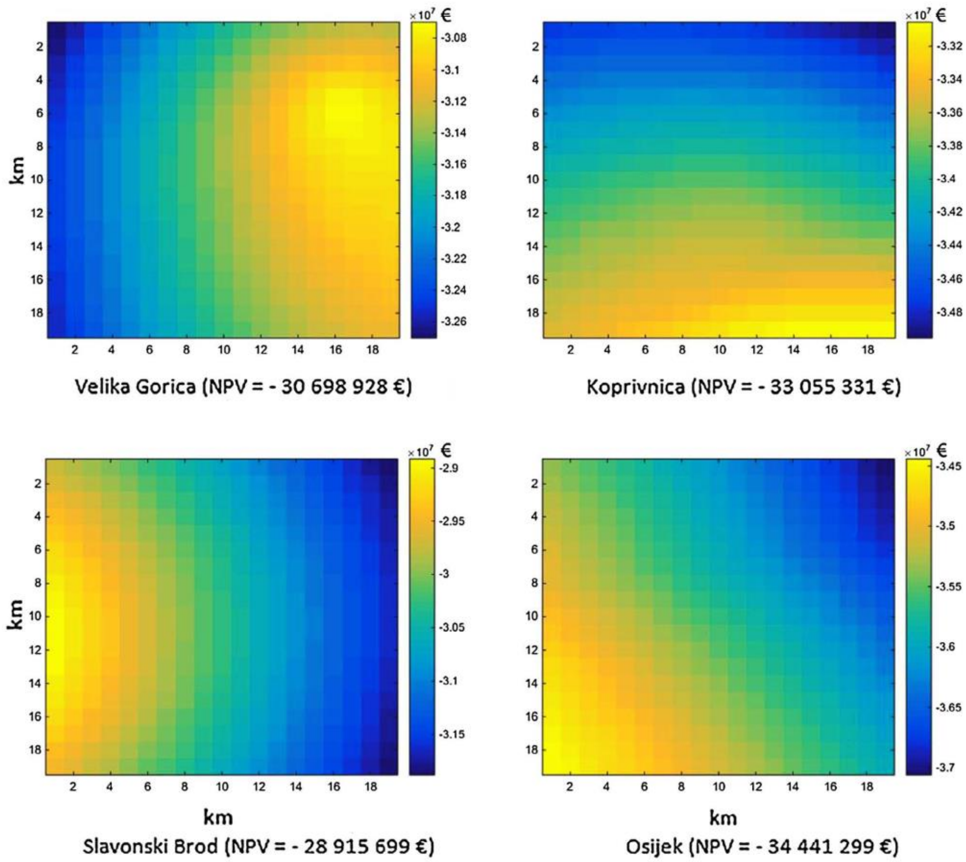

Fig. 5. NPV of optimal locations at each macro-location for the scenario S1c.

Table 7
Cost of biomass at plant location from all scenarios.

Location	Velika Gorica	Koprivnica	Slavonski Brod	Osijek
Scenario	Cost $C_{B,E}$ (€/t)			
S1a	47.7	51.1	45.9	51.9
S1b	47.6	50.2	48.7	52.3
S1c	46.4	48.7	44.7	50.0
S2a	48.2	52.6	47.7	52.9
S2b	48.0	51.8	51.2	55.0
S2c	47.4	49.7	46.2	51.2
S3a	50.7	55.2	53.3	58.9
S3b	49.3	53.8	55.7	61.2
S3c	48.0	52.2	49.2	53.4
S4a	47.5	49.9	46.4	51.5
S4b	47.4	49.8	46.3	51.3
S4c	47.4	49.7	46.3	51.3

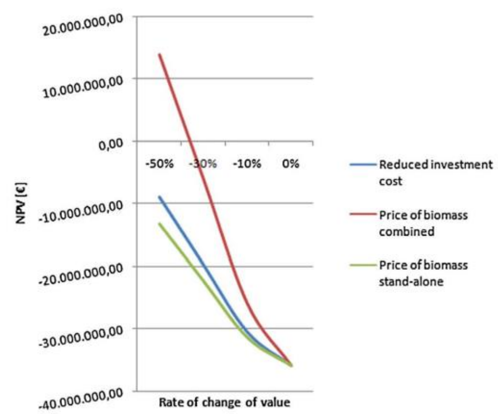

Fig. 6. Sensitivity analysis in relation to investment cost and price of biomass.

approaches with the combined heating and cooling plants with seasonal storage are not the economically feasible way of exploiting biomass from SRC, but some more conventional CHP solutions would be feasible to implement.

Further research should be conducted on more precise determination of the unused agricultural areas which could be used for the SRC cultivation. This could lead to the creation of local value chains which would include SRC and other biomass sources to meet local demand in a sustainable way through DHS. Other important reductions of cost could be achieved by the use of private landowners' own machinery and workforce, which could make the SRC biomass more competitive and interesting for further investigation.

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