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BIOMASS

ASSESSMENT OF THE SUSTAINABLE POTENTIAL OF BIOMASS FROM FOREST AND AGRICULTURAL RESIDUES FOR EXPORT FROM UKRAINE TO THE EUROPEAN UNION

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Colophon

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Executive summary

The goal of this research was to determine the potential of biomass from agricultural and forest residues for export from Ukraine to the European Union. The research formed part of the BioTrade2020plus project, which aims to develop a European trade strategy for biomass for 2020.

Data was retrieved from literature and from expert interviews in Ukraine. An internship at Scientific Engineering Centre “Biomass”, a consultancy company located in Kyiv, Ukraine, formed part of the research.

A selection was made of the most promising agricultural residues. For primary agricultural residues, the focus was on residues from wheat, since these are collected in Ukraine and have a large potential. For secondary agricultural residues, the focus was on sunflower husk, which can be used for pellet production and has a large potential. Regarding forest residues, both primary and secondary residues were examined.

First the technical potential was calculated. The technical potential is 296 petajoule for wheat residues, 24.3 petajoule for sunflower husk, 22.6 petajoule for primary forest residues and 16.5 petajoule for secondary forest residues.

However, to ensure that the biomass is sustainably sourced and to prevent erosion and maintain soil organic matter, part of the technical potential should be left in the forest or on the field. The part that can be retrieve, i.e. the sustainable potential, formed 58% of the technical potential of wheat residues and 56% of the technical potential of primary forest residues. This amounts to a sustainable potential of 172 PJ for wheat residues and 16.1 PJ for primary forest residues.

Part of the biomass potential was already used domestically. To prevent distortion of markets, this domestic demand could not be used for export. For wheat residues, the domestic demand consisted mainly out of leaving the residues on the field for use as fertilizer or burning the residues on the field. The domestic demand for sunflower husk was the current production of pellets and burning of husk to produce heat. For primary forest residues, no domestic demand existed since the residues were not collected. The domestic demand for secondary forest residues consisted mainly out of burning the residues to produce heat and the production of pellets and wood chips.

The sustainable surplus, which is the biomass potential that can be exported, was equal to the sustainable potential minus the domestic demand. It amounted to between 80 and 172 petajoule for wheat residues, 16.5 petajoule for sunflower husk and 5.0 petajoule for secondary forest residues.

The cost to produce pellets out of the residues as well as transporting the pellets to three different transport hubs along the border of Ukraine were determined. The three selected transport hubs were the port of Odessa along the Black Sea, the port of Izmail along the Danube and the city of Uzhorod, which is close to the border of Poland, Slovakia and Hungary and is connected by rail to major European transport corridors. The total costs were different for each feedstock, transport hub and oblast. For wheat residues, the average costs of production and transportation were 4.6 euro per gigajoule. For sunflower husk, the average cost was somewhat lower, with 4.4 euro per gigajoule. Biomass from secondary forest residues had an average cost of 5.6 euro per gigajoule.

Preface

This research has been conducted as part of the master's programme Energy Science of Utrecht University. It was conducted in Ukraine as part of an internship at Scientific Engineering Centre "Biomass" in Kyiv and contributed to the Biotrade2020plus project.

Without the help of many people, this research would not have been possible. I want to thank my supervisor in Kyiv, Tetiana Zheliezna, for letting me work as an intern at SEC Biomass. Second, I want to thank all interviewed experts, from Kyiv to Dnipropetrovsk, who were willing to help a Dutch student learn more about this interesting field. Much of the findings would not have been made without their help. Also I want to thank Jan Peter Lesschen, for determining the sustainable straw removal rate. Furthermore, I would like to thank my supervisors in Utrecht, Martin Junginger and Lotte Visser, for their valuable feedback and advice. The quality of this report benefitted greatly from their feedback. Finally, I would like to thank my colleagues at SEC Biomass, who welcomed me in a new country and new environment. Especially I would like to thank my colleagues Olha Haidai and Oleksandra Tryboi. Their help made this research not only much easier, but above all more fun.

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Units and abbreviations:

Units:

GJ: Gigajoule

kg: Kilogram

kt: Kilotonne

m^3 Cubic metre

Mt: Megatonne

MJ: Megajoule

PJ: Petajoule

TJ: Terajoule

UAH: Ukrainian Hryvnia

Abbreviations:

EEA: European Environmental Agency

EU: European Union

FAOSTAT: Food and Agriculture Organization Corporate Statistical Database

HHV: Higher Heating Value

LHV: Lower Heating Value

NAAS: National Academy of Agrarian Sciences of Ukraine

NULES: National University of Life and Environmental Sciences of Ukraine

RPR: Residue-to-product ratio

1. Introduction

Energy produced from biomass forms an important part of the renewable energy goals set by the European Union in the Renewable Energy Directive (Pöttering & Erlandsson 2009). Biomass, defined as "the biodegradable fraction of products, waste and residues from biological origin from agriculture, forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste" (Pöttering & Erlandsson 2009), can be a sustainable source of energy and contribute to lower CO2 emissions.

In order to let a significant part of the European Union's energy production be based on biomass, the demand for biomass is expected to increase strongly in the next years (Bentsen & Felby 2012). However, this does not mean the biomass has to be produced in the European Union (EU). It might be cheaper to import biomass from other countries. To enable sustainable import of biomass to the EU, the BioTrade2020plus project aims to develop a European Bioenergy Trade Strategy for the year 2020. The project is supported by the Intelligent Energy for Europe Programme of the European Commission and wants to "ensure that imported biomass feedstock is sustainably sourced and used in an efficient way, while avoiding distortion of other markets" (BioTrade2020plus 2015).

One of the potential countries that can be a future source of biomass is Ukraine. Since Ukraine is a large agricultural producer, there is a large potential for the production of biomass from plant material. For example, it is the tenth-largest producer of wheat and sixth-largest producer of barley in the world (FAOSTAT 2013b). Furthermore sunflower and maize, which are also important sources of biomass, are produced on a large scale in Ukraine (Zheliezna n.d.). Additionally, Ukraine neighbours the EU, meaning relatively short transport distances. Finally, Ukraine and the EU have signed an Association Agreement in 2014 to promote cooperation and trade (EUAS 2015).

Biomass can be produced from various sources. Three sorts of biomass are included:
- Energy crops
- Forest residues
- Agricultural residues

Energy crops are plants that are specifically grown to be used as feedstock for the production of energy. Examples include maize, rapeseed and switch grass. Lakyda et al. (2010) have shown that energy crops have the highest theoretical potential of all possible biomass sources in Ukraine. According to Van der Hilst (2012) the Ukrainian potential could be up to 5.0 exajoules in 2030. Furthermore, it seems to be economically feasible to produce energy crops in Ukraine: even when various socio-economic and environmental issues are taken into account, the cost are "in a very attractive range of (sic) when compared to gas and oil" (Smeets & Faaij 2010: 331). However, due to time-constraints it was not possible to examine all three sorts of biomass. Since the potential and cost of energy crops were already being examined in another part of the BioTrade2020+ project, energy crops were not further examined in this research.

Forest residues include branches and other wooden residues that are left in the forest after logging (primary forest residues), as well as residues from the processing of wood such as sawdust and other sawmill by-products (secondary forest residues). In Ukraine, large forests can be found in the north and west of the country (Lakyda et al. 2010). Values for the potential of forest residues in a range between 28 and 54 petajoules (PJ) have been reported, which includes both residues from the forest and residues from the wood processing industry (Lakyda et al. (2010); Raslavičius et al. (2011); Tebodin (2013);

Geletukha et al. (2015); Gielen et al. (2015)). A detailed overview of the estimates in literature of the potential of forest residues is shown in Table 1.

Agricultural residues include primary agricultural residues, which are the leftovers after harvesting crops and secondary agricultural residues, which are the residues of the crop processing industry. A wide range of estimates of the potential of agricultural residues has been reported, ranging from 324 to 564 PJ (Lakyda et al. (2010); Raslavičius et al. (2011); Tebodin (2013); Geletukha et al. (2015); Gielen et al. (2015)). An overview is given in Table 1. Even though multiple studies have examined the production of biomass from agricultural residues in Ukraine in more detail, this potential is not fully understood. Research by Elbersen et al. (2013) has found straw from agricultural residues to be less interesting than energy crops such as switch grass or reed. The main issues regarding straw are the low quality of the biomass, due to the high potassium and chloride content and the high cost for logistics due to the low amount of straw available per hectare. On the other hand, research by Geletukha & Zheliezna (2014) which examined agricultural residues including cereal straw and residues of grain corn and sunflower, has found a large potential. This study has examined the part of the production that could be used for energy production and the authors have concluded that agricultural residues amount to one third of the total Ukrainian biomass energy potential. According to Gielen et al. (2015), the potential for biomass from agricultural residues forms even more than halve of the total Ukrainian potential. Recent research by Zheliezna (n.d.) has concluded that besides primary agricultural residues, also secondary residues (e.g. residues of breweries and the dairy industry) could prove to be interesting biomass feedstocks.

Table 1: Potential of forest and agricultural residues from literature

Study:	Type of potential:	Forest residues (PJ):	Agricultural residues (PJ):
Lakyda 2010	Theoretical	34	1169
	Technical	28	433
Tebodin 2013	Energy	55	564
Raslavicius 2011	Theoretical	N/A	628
	Technical	28.3	375
Geletukha 2015	Economical	58	357
IRENA 2015	Economical	52	368

While these studies examine the potential of biomass from agricultural and forest residues, sustainability issues are only partially taken into account. To ensure biomass imported from Ukraine is sustainably sourced as required in the BioTrade2020plus (2015) project, it is essential to take sustainability issues into account. Furthermore, current research does not quantify the local use of the residues: similar to what Berndes et al. (2003) already noted in a literature review about residues, most studies do not make "any comprehensive assessment of (...) alternative residue uses". To avoid distortion of local markets, it is necessary to understand local use of residues. Finally, there is no overview of all costs involved in exporting the biomass from Ukraine, while importing biomass is not interesting when the cost is too high. Therefore it is essential to take sustainability, current local use and costs into account to determine how much biomass from agricultural and forest residues can be exported from Ukraine.

This research builds on earlier research and examines the sustainable biomass export potential from Ukraine. Therefore, the main research question is:

What is the sustainable potential of biomass from agricultural and forest residues for export from Ukraine to the European Union?

An answer to the research question is formulated after the following sub-research questions have been answered:

1. What is the technical potential of biomass from agricultural residues in Ukraine?
2. What is the technical potential of biomass from forest residues in Ukraine?
3. What are the main sustainability constraints for primary agricultural and forest residues, and how do they limit the technical potential?
4. What is the domestic demand for biomass from agricultural and forest residues in Ukraine?
5. What is the sustainable surplus of biomass from agricultural and forest residues in Ukraine?
6. What are the costs of residues, pre-treatment and transport from Ukraine to the European Union?

Not all sub-research questions are answered for each biomass feedstock of Ukraine. A selection is made of the most promising feedstocks, as explained in the methodology section.

The research included a three-month internship at Scientific Engineering Centre “Biomass” in Kyiv. SEC Biomass provides engineering and consulting services in the field of energy production from biomass (SEC Biomass 2013).

2. Methodology

In this chapter, first the approach, methodology and structure of the research are explained. Secondly, more information is given on each of the four parts of the research. Hereafter the methods that were used to gather data are discussed. Finally the input data that was used to determine the production of crops, residue-to-product ratio and moisture content are given.

2.1. Approach and structure:

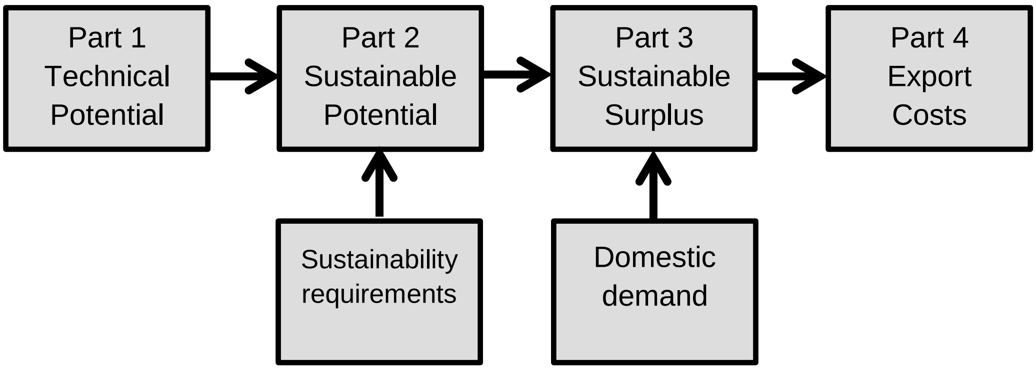
To determine the biomass potential a resource-focussed approach was used, meaning the assessment of the potential takes into account competition between different uses of the biomass and limitations to the biomass production (Batidzirai et al. 2012). Multiple methodologies are used: first of all, a statistical analysis of the biomass potential, which is a bottom-up approach to determine how much biomass is available, taking local demand into account (Batidzirai et al. 2012). In addition to this methodology, environmental constraints are taken into account. Finally the bottom up approach was combined with cost–supply analysis, which is used to evaluate the costs of the production, conversion and transportation of the biomass (Batidzirai et al. 2012).

The approach of this research is structured in four parts, which are based on the methodology developed by Mai-Moulin et al. (2014) in the BioTrade2020plus project, but adapted to the specifics and focus of this research. The four parts are:

1. Calculation of the technical biomass potential
2. Calculation of the sustainable biomass potential
3. Calculation of the sustainable biomass surplus
4. Calculation of the costs

The sustainable potential is the part of the technical potential that meets the sustainability requirements. These sustainability requirements are explained in section 2.3. of this chapter. The sustainable surplus forms a part of the sustainable potential. It is determined by subtracting the domestic demand from the sustainable potential. All residues that are used in Ukraine together form the domestic demand, as explained in more detail in section 2.4. of this chapter. An overview of all the parts as well as their relations is shown in Figure 1. All parts are discussed in more detail in the next sections.

Figure 1: Overview of parts to determine the sustainable biomass potential for export to the EU



The technical and sustainable potential as well as the sustainable surplus are estimated for each of Ukraine's 'oblasts'. Oblasts are administrative regions that can be compared to provinces. A list of all Ukrainian oblasts can be found in Appendix B.

2.2. Technical potential

In the first part of this research an estimation was made of the technical biomass potential, which is defined as: “the fraction of the potential that is available under current and future technological possibilities, and taking into account spatial restrictions due to competition with other land uses” (Mai-Moulin et al. 2014: 24). The methodology to determine the available amount in kilotonnes of the residues is explained first for agricultural residues and hereafter for forest residues. Finally, the method to determine the energy value of the residues is explained.

Due to time-constraint not all primary agricultural residues could be examined. Therefore a selection was made of five residues. Of the crops that produce useable residues, the five crops with the highest amount produced in Ukraine were selected.The amount of agricultural residues was determined for these five crops for each oblast by multiplying the amount of production by the residue-to-product-ratio (RPR). This ratio shows the amount of residue per amount of product produced. Many values for the RPR can be found in literature. Both Koopmans & Koppejan (1997) and Scarlat et al. (2010) created an overview. These overviews reveal that there is a considerable difference in figures between various studies. Furthermore, these figures are not specific to Ukraine. Therefore, RPRs specifically determined for Ukraine were used. The RPRs give an estimation of the total amount (in kilotonnes) of residues that can be harvested, so the stubble and roots are not included in the amount of residues. Furthermore, the RPR does not specify any moisture content but is the amount of residue left on the field after harvest.

The technical potential of secondary agricultural residues for Ukraine was derived from literature. However, no data was available on the amount of secondary agriculture residues per oblast. Furthermore, there is a very wide range of different types of secondary agricultural residues. For example, Lakyda et al. (2010) and Gielen et al. (2015) only consider sugar beet bagasse, rice husks and sunflower husks for Ukraine while according to Zheliezna (n.d.) also breweries, distilleries and the dairy industry could be sources of secondary agricultural residues. Because of the aforementioned reasons, the focus was on the most important source of secondary agricultural residue that can be used for the production of solid biomass. The secondary agricultural residue with the largest amount available in Ukraine is sugar beet residue, which is generated during the production of sugar from sugar beet. However, sugar beet residues are mostly used already (mainly as fodder for cattle) and can only be viably transported over a large distance after producing biogas (Zheliezna n.d.), which was outside of the scope of this research. Because of these reasons, the focus was on the secondary agricultural residue with the second largest amount available in Ukraine, which is sunflower husk. The residues are generated during the production of oil from sunflower seeds. The technical potential of sunflower husk was determined for each oblast by multiplying the production of sunflower based on data from the State Statistics Service of Ukraine (Vlasenko 2014) by the amount of husk per sunflower seed (based on estimates by interviewed experts). So it was assumed that sunflower is processed in the same oblasts as it is produced.

Both primary and secondary forest residues were estimated based on data on the availability of forest biomass per oblast from Lakyda et al. (2010). Lakyda et al. (2013) estimated how this total amount of forest biomass was divided between three categories: primary forest residues, secondary forest residues and stemwood. The latter is not a residue, but the wood from the stem of the three. Stemwood is not used as biomass but harvested for other purposes. By multiplying the amount of forest biomass per oblast from Lakyda et al. (2010) with the percentage of primary forest residues from Lakyda et al. (2013), the amount of primary forest residues was determined. It was assumed this division was similar for all oblasts, so this calculation was made for each oblast. A similar calculation was made for secondary forest residues.

The agricultural production statistics in Ukraine were given in kilotonnes. Also, since the RPR was based on the weight of crops and residues, the amount of agricultural residues was also determined in kilotonne. However, since the residues are used for the production of energy, it is more relevant to know the energy value of this amount of residues. Therefore the heating value (also known as calorific value) of the various biomass feedstocks was determined. Two issues needed to be taken into account:

The first issue is the distinction between the Higher Heating Value (HHV) and Lower Heating Value (LHV). The difference between the two values is the condensation heat of the water created during combustion of the fuel (Blok 2007). In case of the HHV it is assumes this heat can be used by condensing the flue gasses, and therefore this heat is included in the heating value. In case of the LHV, this heat is excluded from the heating value. Since it is not certain that all boilers in which the biomass might be used are able to utilise this heat by cooling the flue gasses, the LHV was used in this research. Thereby it followed the approach used by the European Environmental Agency (EEA 2007b) and the Biomass Energy Europe project (as used by Lakyda et al. (2010) and described in the Methods Handbook of Vis & Berg (2010)).

Secondly, the heating value is influenced by the moisture content. The higher the moisture content, the lower the heating value, because not only does the moisture provides no energy, it takes energy to heat the moisture in the feedstock. To calculate the heating value of the biomass, it is therefore essential to know the moisture content of the residues. The values used in this research were determined specifically for Ukraine and are given in section 2.8.

Multiple authors have made an estimation of the heating value of feedstocks. An overview of the values can be found in literature reviews by Nordin (1994) and McKendry (2002). There are various ways the heating values can be determined: by experiment (e.g. Mani et al. (2004)) or by calculation based on the composition of the main elements in the biomass feedstocks (e.g. Sheng & Azevedo (2005)). Research by Annamalai et al. (1987) showed that the values which results from these two different methods do not differ much. However, since equipment was unavailable and the elementary composition unknown another method was used in this research.

Since there is some variation between different estimations, an average was created of the figures provided in studies mentioned to have the most reliable figure. However, most studies gave the HHV, while only some studies provided the LHV. Furthermore, the studies used different moisture contents to determine the figures. To compare these figures on an equal basis and to have enough values to determine a reliable average of the LHV, the HHVs given in literature were reconfigured to LHVs. However, since this requires not only the moisture content but also the hydrogen fraction (Blok 2007), this was only possible in two cases for primary agricultural residues

Therefore the LHV used for primary agricultural residues was based on the average of four studies: the LHV provided in the two Ukrainian studies by Zheliezna (n.d.) and Golub (n.d.)[1] and the HHV given in the literature review by Nordin (1994) and the IEA Bioenergy's database (IEA Bioenergy Task 32 n.d.). The HHVs given these studies were first reconfigured to LHVs using the following formula based on Blok (2007: 30).

$$LHV_{wb} = HHV_{dry} * (1 - w) - h * E_{W,evap} * m_{H2O} * (1 - w) - E_{w,evap} * w$$

[1] Instead of providing LHVs Golub (n.d.) provides formulas to calculate the LHV. Using these formulas, the LHVs were calculated based on the moisture content given in Table 7.

Where:

$LHV_{wb} = Lower\ Heating\ Value\ on\ a\ wet\ basis$
$HHV_{dry} = Higher\ Heating\ Value\ on\ a\ dry\ basis$
$w = moisture\ content, fraction\ of\ water\ in\ the\ biomass\ on\ a\ wet\ basis$
$h = fraction\ of\ hydrogen\ in\ the\ oven\ dry\ fuel$
$E_{W,evap} = energy\ required\ for\ evaporation\ of\ water\ (2.26\ MJ/kg)$
$m_{H2O} = the\ mass\ of\ water\ created\ per\ unit\ mass\ of\ hydrogen\ (8.9\ kg/kg)$

The calculation of the LHV based on the HHV and the abovementioned formula is shown in Appendix A.

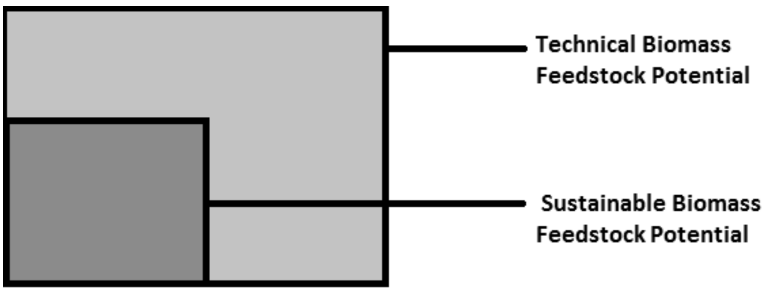
For the secondary agricultural residue sunflower husk, a similar approach was used to determine the heating value. However, of the aforementioned sources only IEA Bioenergy Task 32 (n.d.) gave an estimation of the HHV. Therefore values from Demirbaş (2002), Haykiri-Acma & Yaman (2009) and SEC Biomass were also used to determine an average. Since most of the sources gave an HHV, the aforementioned formula of Blok (2007) was used to determine the LHV. See Appendix A for the calculation of the LHV.

Since the technical potential of primary and secondary forest residues given in Lakyda et al. (2010) was not only given in megatonnes, but also in petajoules, there was no need to make an estimation of the LHV. Instead the LHV used by Lakyda et al. (2010) (as described in Vis & Berg (2010)) was used.

2.3. Sustainable potential

The technical biomass potential does not represent the final biomass potential. Part of the technical potential does not meet the sustainability requirements and therefore does not form a part of the sustainable potential, as shown in Figure 2. Only the sustainable potential is considered for export to the EU. Therefore the goal of part 2.3 is to make an assessment of the sustainable biomass potential.

Figure 2: Technical and sustainable biomass potential



However, the sustainable potential has not been determined for all feedstocks. Due to time-constraints, it was not possible to determine for each individual feedstock the part of the technical potential that cannot be used due to the sustainability requirements and the domestic demand. Instead, a selection was made of the feedstocks with the highest potential that could be harvested. Only those feedstocks were taken into account in the remainder of the research. More information on the selection can be found in the results section.

The most important sustainability criterion is that the removal of residues for production of biomass does note degrade the quality of the land. For primary residues, this degradation includes multiple factors. The first is erosion: leaving residues on the field prevents soil erosion, which includes both erosion by wind and by rainfall. Therefore Nelson et al. (2004) stated that the quantity of residues that can be removed is limited because there is a “maximum rate of soil erosion that will not lead to prolonged soil deterioration and/or loss of productivity”. The research of the authors showed the amount of wheat and maize residues that can be removed is limited by this constraint.

Besides erosion, a second factor is the organic matter content of the soil. The growth of crops extracts organic matter, including organic carbon and nutrients, from the soil. Normally, this organic matter is partially returned to the soil by de degradation of the residues that are left in the field. When the residues are removed, the soil organic carbon matter decreases, which hampers future production. Research by Wilhelm et al. (2007) showed for multiple fields (different in slope, tillage and crop rotation) that the amount of agricultural residues that needs to be retained on the field to prevent the organic carbon content to decrease is larger than the amount needed to prevent wind and rain erosion. In other words, the need to maintain soil organic carbon forms a greater constraint to the sustainable potential of residues than both wind and rain erosion.

To determine the sustainable potential of primary agricultural residues, the sustainable removal rate was defined. This is the percentage of the technical potential that can be taken of the field while ensuring the sustainability criteria are met.

$$Sustainable\ potential\ =\ technical\ potential\ \times\ sustainable\ removal\ rate$$

The sustainable removal rate is equal to 1 minus the percentage that should remain on the field to ensure the soil organic carbon content does not decrease (further):

$$Sustainable\ removal\ rate\ =\ 1 - percentage\ of\ the\ technical\ potential\ that\ should\ remain\ on\ the\ field$$

Estimates in literature about the percentage of residues that should be left in the field to prevent depletion of organic matter of the soil and erosion vary widely. For example, Ericsson & Nilsson (2006) assume 75% of the residues should remain on the field to ensure long-term productivity. Hoogwijk et al. (2003) examined the approaches used for assessing biomass potential and came to the same conclusion: based on the results of existing studies, the authors state that “about 25% of the total available agricultural residues can be recovered”. On the other hand, some researchers believe all residues should remain on the field. For example, Lal (2008) argues that residues must never be removed from croplands because leaving residues does not only prevent soil erosion, but it also contributes positively to water conservation and soil biodiversity. Also, residues return valuable nutrient to the soil, which amounts to more than 80 per cent of global fertilizer consumption (Lal 2009).

However, Wilhelm et al. (2004) conducted a literature review and concluded that “results from studies reported in the literature do not provide consistent conclusions on the impact of residue removal on soil characteristics and crop yield”. According to the authors, the conflicting conclusion of different studies were caused by “factors such as existing SOC levels, climate and weather, soil characteristics, and crop management practices” and “difficulties in accurately measuring changes, especially in the short term, in SOC level”. When Muth et al. (2012) tried to determine the sustainable agricultural residue removal potential for three field (all in Iowa in the United States) the authors found three different rates, ranging from 21% to 83%. This confirmed the conclusion by Wilhelm et al. (2004) that the removal rate can vary strongly and is highly dependent on location. Furthermore, Muth et al. (2012) found that their sub-field analysis gave different results than the official approach using the National Conservation Practice Standards. The authors concluded that “current conservation management planning approach using representative soil, representative slope, and field average yield may lead to unsustainable residue removal decisions or may understate the residue removal potential of a field” (Muth et al. 2012: 980).

The literature review of Wilhelm et al. (2004) shows that the results of various studies are highly dependent on local circumstances and cannot easily be used in different situations. Therefore the results from Ericsson & Nilsson (2006), Hoogwijk et al. (2003) or other studies that are not specific to Ukraine, cannot be used in this research. Research by Muth et al. (2012) showed that even fields within the same region can have strong differences and added that even knowing the soil, slope, and yield of a field is not enough.

So even results from studies on some Ukrainian regions or fields cannot give an exact figure for this research. Nor would an extrapolation based on an detailed analysis of some fields give a reliable figure. Therefore a different approach was used. For each oblast, the sustainable straw removal rate was determined by Jan Peter Lesschen using the Miterra-Europe and RothC model. Data on the soil organic carbon was used as input, taken from the European Soil Database. The soil organic carbon balance was determined for the situation in which all straw was removed from the field as well as the situation in which no straw was removed. Based on the outcomes, it was determined how much percent of the straw could be removed from the field to have a soil organic carbon balance of zero. In the case in which there was a negative soil organic carbon balance even when no straw was removed, the sustainable straw removal rate would be zero.

The sustainable potential of primary forest residues was determined using a different method. The European Environmental Agency (EEA) set a maximum extraction rate of the theoretical potential to determine what can be harvested, taking into account (EEA 2007a):

- Conservation and protection of biodiversity
- Sustaining site productivity/site fertility
- Soil protection/soil erosion
- Water protection
- Forest management and fire protection measures
- Nitrogen deposition and fertilisation

The rate takes also into account that “not all residue biomass is technically extractable”, that “ecologically sensitive or inaccessible micro-habitats are excluded” (EEA 2007: 10) and includes foliage, which is not used for biomass. Since these issues are normally already taken into account in the technical potential, this rate uses the theoretical potential instead. Since Lakyda et al. (2010) also determined the theoretical potential, this rate was used to determine the sustainable potential in Ukraine.

The level of residue removal varies according to the suitability of the forest (EEA 2007a). The EEA set the maximum extraction potential at 60%[2] of the total theoretical biomass potential for the highly suitable sites and lower for less suitable sites, as shown in Table 2.

[2] The maximum rate is 60% of “total above ground residue biomass” (EEA 2007: 10), i.e. including foliage. It corresponds to 75% of stem and branches. The theoretical potential of Lakyda et al. (2010) also assumed total biomass, not only stem and branches.

Table 2: Extraction rates of primary forest residues

Categories of sustainability:	Extraction rate (%):
High	60
Moderate	40
Marginal	12
Unsuitable	0

To determine the category of sustainability, the EEA (2007a) uses various criteria, including slope, height, soil type, soil compaction and base saturation. The main criteria are soil type and base saturation. The soil type of the forest in Ukraine was determined by comparing maps on forest and soil type in the computer program ArcGIS. Based on this information a first categorisation of sustainability was made. Regarding base saturation, the EEA notes that in the EU almost 20% of areas with a high suitability were reclassified as moderately suitable due to their low base saturation. It was assumed this would be similar in Ukraine and 20% of the forest that were classified as highly suitable were reclassified as moderately suitable.

For both secondary forest and secondary agricultural residues, there are no sustainability criteria. All residues, which are created at production facilities, can be used without negatively impacting the environment. Therefore no sustainable potential was determined for secondary residues. Instead the sustainable potential is equal to the technical potential.

2.4. Sustainable surplus

Biomass from agricultural and forest residues is not only interesting for use in the EU, but is also used in Ukraine, e.g. for energy production or food for cattle. To avoid distortion of markets in Ukraine and since only the amount that is not used in Ukraine can be exported, it was estimated how much biomass is not yet used domestically. This is done by subtracting the size of the domestic demand for biomass from the earlier calculated sustainable biomass potential. The result is the sustainable biomass surplus.

$$Sustainable\ surplus = sustainable\ potential - domestic\ demand$$

The domestic demand includes the use of biomass for energy production such as domestic heating. Other possible ways in which biomass is used in Ukraine were identified from literature and from interviewing experts. The next step was to estimate how much of the biomass is used for each possible purpose. Data for these estimation was retrieved by interviewing experts. Together, these estimations formed a range of the domestic demand. It was assumed the domestic demand (as a percentage of the technical potential) is similar for all oblasts. When a negative sustainable surplus was determined for an oblast, the sustainable surplus was assumed to be zero.

It should be noted the sustainable surplus of primary agricultural residues is the available amount of straw as collected from the field. In practise, this straw cannot be used for pellet production without further treatment, due to two reasons. First of all, the collected straw is not pure: often rubbish is found in the bales. Besides non-organic content, part of the straw can be rotten. Kuznetsova (2012) assumes the rubbish content of straw is 10%. Secondly, the moisture content of straw is too high. The moisture content is 20%, while the moisture content should be lower than 12% (Kuznetsova 2010). This cleaning and drying might affect the surplus available.

However, the RPRs used in this research determine pure residues, meaning there is no need to reduce the surplus by taking rubbish into account in the calculations. To determine the part that was rotten and possible other losses, experts were asked to estimate how much of the collected residues is lost. The sustainable surplus was reduced by the percentage estimated. Furthermore, reducing the moisture content significantly affects the amount of surplus in kilotonne, because water is removed. But since the moisture has no energy value, the energy potential does not change. Therefore the surplus was not determined in kilotonne but only in petajoule.

2.5. Biomass cost

First, the method to determine the total cost is explained. Hereafter the methods to determine the pre-treatment and transport costs are discussed in more detail.

2.5.1. Total costs

The sustainable surplus indicates a theoretical potential for export but does not reveal anything about the practical possibilities for export to the EU. Whether or not biomass can be exported to the EU depends on the cost. Therefore a cost–supply analysis was done to evaluate the cost of the biomass.

The cost of residues includes both the price of acquiring the residues as well as the extra cost incurred for collecting the residues. Other important costs are the cost of pre-treatment and logistics. The latter involves both the cost of transporting the residues to the pre-treatment facility as well as the cost of transporting the product out of Ukraine. The total costs of biomass can be determined by using the following equation:

$$C_{tot} = C_r + C_{pt} + C_t$$

Where:

C_{tot} total cost of biomass.
C_r cost of residue.
C_{pt} cost of pre-treatment
C_t cost of domestic transport

Estimations of the various costs were based on literature and the expert interviews. Most of the times, costs in literature are displayed in euro's. However, in the last few years the value of the Ukrainian Hryvnia (UAH) compared to the value of the euro has decreased by 60% (XE 2015). Estimations in euro's from earlier years therefore overestimate the costs. Therefore the value was recalculated to UAH, using the specific exchange rate mentioned by author/study. In case no exchange rate was given, the exchange rate of the 1st of July of the year in which the study was conducted was used, using the values given by XE (2015).

It must be noted that the prices in UAH have also not been constant in recent year due to the inflation in Ukraine. But due to the unstable exchange rate the change in prices in UAH was smaller than the change in prices in euro, making the UAH a better measure for comparison. Prices in UAH were corrected for inflation, using an exchange rate of 4.3% for 2013 and 14.7% for 2014 (World Bank 2015). Final values in the report are shown in euro's, assuming an exchange rate of 23 UAH per euro, which was the exchange rate of the 1st of July 2015 (XE 2015).

2.5.2. Pre-treatment

Biomass has several negative characteristics, such as a low energy content per kilogram and a low energy density, as well as that it is hydrophilic (meaning it absorbs water) and heterogeneous (meaning the material has a wide range of sizes and shapes) (Batidzirai 2013). The low energy content and the related low energy density mean high transportation cost per amount of energy. The heterogeneity means the energy content is variable, which makes biomass an unreliable fuel. To overcome the negative characteristics, pre-treatment is required before transportation in most cases. In this process, the moisture content and hydrophilicity of the biomass are decreased while the energy density and uniformity are increased .

Various pre-treatment methods are available, including pyrolysis, torrefaction, producing biogas and pelletizing. However, not all are commercially viable. While torrefaction and pyrolysis (which make use of heat to create either a solid biofuel or bio-oil out of biomass) could be promising pre-treatment technologies in the future, both are not ready for widespread commercial application (Marshall 2013; Carbo et al. 2014). Therefore these two technologies were not taken into account in this research.

Another possible option might be to produce biogas out of agricultural residues. However, the biogas market in Ukraine is not well developed: only four biomass plants are active, which all need manure instead of agricultural residues as input and use the biogas directly at the production site to produce heat and electricity (Geletukha et al. 2013). Even if a significant amount of biogas could be produced, it still needs to be transported. While the extensive gas network connecting Ukraine to the European Union might be considered to form an attractive export method, biogas cannot be injected in this gas network. First of all, biogas is a gas mixture that on average consist for only 55% out of methane, meaning upgrading facilities are required to produce biomethane (FNR 2013). Secondly, injection of biomethane into the gas network is not happening in Ukraine and also not possible due to legislation (Geletukha et al. 2014). Due to these barriers, the production of biogas out of agricultural residues is not a realistic option for export at the moment and was not taken into account in this research.

The focus was on a proven pre-treatment technology: pelletisation. For biomass, this is the “standard method for the production of high density, solid energy carriers from biomass” (Safar 2014) and “currently the most important pre-treatment approach for solid biomass” (Batidzirai 2013: 8). Biomass is pressed together to form small cylindrical-shaped particles. While straw usually has a density of around 80 kilogram (kg) per cubic metre (m^3) and straw bales of around 250 kg/m^3, during pelletisation the density is increased to 650 kg/m^3 (Jamblinne et al. 2013). The diameter of the pellet is between 6 and 25 millimetre, while the length can be between 10 to 50 millimetre (Alakangas 2010). The size and standard form of pellets make it not only easier to transport and store biomass, but also easier to use in a power plant.

To create pellets out of the agricultural residues, various steps need to be taken. An overview is shown in Table 3.

Table 3: Steps of pelletisation

Step:	Description:
Filtration	Removing unwanted materials
Drying	Decreasing moisture content by heating
Reducing size	Creating small particles
Pelletizing	Increasing density by pressure
Cooling	Reducing temperature, which was increased by the pressure
Packing together	Storing in a bag to protect pellets form moisture and pollutants

An estimation was made of the cost of creating pellets out of the residues by pelletisation. Data was retrieved from literature, interviewed experts, and experts from SEC Biomass. It was assumed that the cost of pre-treatment in a new pellet plants is similar to the current cost of producing pellets. This means it was assumed that investment cost are included in the price of pellets and that new pellet plant will not produce cheaper than current ones. This estimation of the pre-treatment cost included the cost for collection and transport of the residues from the field or production location to the pellet factory.

2.5.3. Logistics

Logistic costs form an important part of the total costs of export: Ojala et al. (2010) showed logistic costs formed 12.8 percent of total trade value for exports in Ukraine. The cost of exporting pellets to the EU depends on where in the EU the pellets will be used. Since this can be variable and was unknown, a different approach was used. This research only included the cost of getting the pellets to the border of Ukraine. Therefore transport hubs along the border of Ukraine were selected based on the available transportation options for export to the EU and the cost to transport the biomass from the pellet factory to these hubs was determined.

The selection of the transport hubs was based on the best way to export pellets from Ukraine to the EU. The most-suitable way of export from Ukraine to the EU depends on the final destination of the biomass. For example, to Spain transport by river is less viable than transport by sea ship, since there are no good river connections between Ukraine and Spain, while for Hungary it is the other way around. Since the selection of a final destination in the EU does not form part of this research, multiple possibilities transportation methods were considered. However, while transport by truck within Ukraine was considered, export to the EU by truck was not taken into account because the European Biomass Industry Association concluded that for distances longer than 300 kilometre, transport by truck is not economically viable due to the high transportation cost in comparison to the low production cost (EUBIA 2009) and only a small part of the EU is within 300 kilometre distance of Ukraine. Three ways of export remained: train, shipping by sea and shipping by river. For each of these three options, the best transportation hub on the border of Ukraine was selected.

The next step was to determine the best way to transport the pellets from the pellet factory to these three transportation hubs. Two ways of transport were considered: train and truck. Transport by inland waterway was not considered because even thought it might be possible in some situations (i.e. when the pellet factory and transport hub are located on the same river), transport by inland waterway is almost never used in Ukraine. Data from the Ministry of Economic Development and Trade of Ukraine (n.d.) showed freight transport by water was only around one-twentieth of transport by rail in 2007. Since inland waterway transport forms only around halve of the water transport (the other halve being sea transport) the share is very low. Furthermore, transport by inland waterway decreased by almost 70% since 2007 (Statista 2015). So transport by inland waterway is not used a lot in Ukraine, implying it is not a viable option. Therefore it was not taken into account. A choice between either transport by truck or by train was made based on estimations of the lowest cost. For transport by train, this included the cost of bringing the biomass to the train station.

After the endpoints and the way of transportation were determined, the cost of transportation was calculated. This was done by multiplying the estimation of the interviewed experts of the cost per kilometre by the distance. The distance between the oblasts and the transport hub was determined by using the tortuosity approach. The actual travel distance between two point can be determined by with multiplying the shortest distance between two points with the tortuosity factor, which is “the ratio of actual travel distance via the roads to the shortest straight line distance” (Sultana & Kumar 2014: 290). The shortest distance between the transportation hub and the oblasts was determined by Lotte Visser using the computer program ArcMap. The central location in the oblast was chosen of the location of the pellet factory, since many oblasts had no pellet factory and it was not possible to predict where, if a pellet factory would be build, this would be. Sultana & Kumar (2014) determined the tortuosity factor to be between 1.28 and 1.42 for the province Alberta area in Canada. Yagi & Nakata (2011) measured both distances in Japan and calculated a factor between 1.2 and 1.7. To determine the tortuosity factor for Ukraine, the distances measured in ArcMap were compared to actual travel distances in Ukraine by using Google Maps. For this several oblasts were used as measuring point: the northern oblast Kiev, the eastern oblast Luhansk, the southern oblasts Sevastopol and the western oblast Lviv. This comparison yielded tortuosity factors between 1.21 (Kiev) and 1.51 (Luhansk), with an average of 1.32. Based on this analysis, a tortuosity factor of 1.32 was used in this research. The estimation of the cost of transport were checked by interviewing experts from pellet factories.

2.6. Trends

An analysis was made of the trends that might influence the future potential of biomass from forest and agricultural residues in Ukraine, based on the information gathered in literature and interviews. It was discussed how these trend influence the future potential.

2.7. Methods for gathering of data

The main method which was used to retrieve the necessary data was expert interviews. The interviews were semi-structured: while a list of questions was prepared in advance, the interviewee was given much room to deviate from the planned structure. The interviews took place at various location. Most of the times the interviews were at the office of the interviewee. While some interviews were conducted in English, the majority of the interviewed experts did not speak English. Therefore a translator was used. Most of the times a colleague from SEC Biomass, familiar with the subject, acted as translator during the interview, but sometimes the interviewee brought a translator along. Due to the fact that a large part of the interview was conducted in Russian or Ukrainian, no recordings were made. Instead, notes were made during the interview.

The interviewees formed part of a large pool of people that were contacted. The pool of possible interviewees totalled more than 70 organisations, including research institutes, universities, agricultural companies and pellet producers. Relevant organisation were found in literature, for example the overview of pellet producers by Tebodin (2013). Some organisations were found via search engine Google.

These potential interviewees were contacted via e-mail. When no reaction was received, a reminder was send, both in Russian as well as English. When also this reminder did not lead to a response, the organisation was called. Unfortunately, not all could be reached by phone, because not all calls were answered and at multiple organisations no English was spoken. In additions, extra interviews were arranged by SEC Biomass.

An overview of the organisations at which the interviewees worked is given in Table 4.

Table 4: Interviewed experts

Interview:	Organisation:	Type:
A	Department of agronomy, National Academy of Agrarian Sciences of Ukraine (NAAS)	Research institute / university
B	Ukrainian Pellet Union	Industry association
C	National University of Life and Environmental Sciences of Ukraine	Research institute / university
D	Farm / Kischenzi Agriculture	Residue producer
E	Project 'Local Alternative Energy Solutions in Myrhorod'	Research institute / university
F	Bronto	Pellet machinery producer
G	Department of agriculture, irrigation and mechanization, NAAS	Research institute / university
H	Farm	Research institute / university
I	Dnipropetrovsk State Agrarian University	Research institute / university
J	Farm, sunflower oil-producer	Residue producer
K	Almaz-M	Pellet producer
L	Vin-Pellet	Pellet producer

The second method was a literature study. Multiple scientific articles and reports were gathered, summarized and used. This was mainly done by using the search engine Google Scholar, but also reports were retrieved via SEC Biomass and the supervisors of this research.

2.8. Data input

Data on the top crops produced in Ukraine was taken from the Corporate Statistical Database of the Food and Agriculture Organization of the United Nations (FAOSTAT). In order of amount produced, these are maize, wheat, potato, sunflower, sugar beet, barley, soybeans and rapeseed (FAOSTAT 2013a). But since the harvest of potato and sugar beet does not produce any significant amount of agricultural residues, these feedstocks were not included. Also, soy was excluded because no data on the production of soy per oblast was available. Furthermore, the production of soy is only around one-third of the production of barley (FAOSTAT 2013a), making it a less important feedstock. Because of the aforementioned reasons, this research focused on the following five feedstocks: maize, wheat, barley, sunflower and rapeseed. Data on the production of these feedstocks was retrieved from literature: the State Statistics Service of Ukraine published production figures for each oblast for 2013 (Vlasenko 2014). Data from 2013 was used because it was the most recent official data available and the most detailed data available. The production is shown in table 5.

Table 5: Agricultural production in Ukraine in 2013 per feedstock

Crop:	Production (kt)
Barley	7562
Maize (for grain)	30950
Rapeseed	2352
Sunflower	11051
Wheat	22279

The National Academy of Agrarian Sciences published RPRs for various crops (NAAS 2012). These values were used in research before (e.g. Dubrovin (2013) and Geletukha & Zheliezna (2014)) and were confirmed by an expert from SEC Biomass to be the best available RPRs. An overview of the ratios used is given in Table 6

Table 6: Residue-to-product-ratios

Crop:	RPR:
Barley	0.8
Maize	1.3
Rapeseed	1.8
Sunflower	1.9
Wheat	1.0

In this research the most recent estimations of the moisture content of residues of crops in Ukraine by SEC Biomass (Geletukha & Zheliezna 2014; Zheliezna n.d.) was used. The values are shown in Table 7 and show the moisture content of the residues after harvesting, so before drying

Table 7: Moisture content of primary agricultural

Feedstock:	Moisture content (%):
Barley	20
Maize	50
Rapeseed	20
Sunflower	60
Wheat	20

3. Results:

This chapter is structured in five parts. In the first part, the technical potential of the residues is determined. Hereafter, the sustainable potential of primary residues is determined. In the third part, the domestic demand and sustainable surplus of wheat, sunflower husk and secondary forest residues are estimated. In the next part, the costs of making pellets out of the residues as well as transporting the pellets to the border of Ukraine are estimated. In the final part, trends are discussed that influence the future potential.

3.1. Technical potential

In this section the technical potential of primary agricultural residues is discussed. Hereafter, the technical potential of secondary agricultural residues is determined. Finally, the technical potential of forest residues is described.

3.1.1. Technical potential of primary agricultural residues

The technical potential of the primary agricultural residues, calculated by multiplying the production figures with the RPRs (see the methodology section) is shown in Table 9 for each feedstock in kilotonne. First, the LHVs of barley, maize, rapeseed, sunflower and wheat from Zheliezna (n.d.), Golub (n.d.), Nordin (1994) and IEA Bioenergy Task 32 (n.d.) as well as the calculated average of these studies are shown in Table 8. The calculation of the LHV from Nordin (1994) and IEA Bioenergy Task 32 (n.d.) based on the HHV is shown in Appendix A.

Table 8: Lower heating values of primary agricultural residues

Feedstock:	**LHV** (Zheliezna n.d.)	**LHV** (Golub n.d.)	**LHV** (Nordin 1994)	**LHV** (IEA Bioenergy Task 32 n.d.)	**Average (GJ/tonne):**
Barley	14.5	13.0	13.5	13.5	13.6
Maize	8	7.4	N/A	7.3	7.6
Rapeseed	14.5	13.5	13.2	16.0	14.3
Sunflower	6	N/A	N/A	5.5	5.7
Wheat	14.5	12.5	13.7	12.4	13.3

Using the average LHV, the technical potential per feedstock was calculated in petajoule, as shown in Table 9.

Table 9: Technical potential per feedstock

Feedstock:	**Technical potential (kt):**	**Technical potential (PJ):**
Barley	6049	82
Maize	40234	305
Rapeseed	4233	61
Sunflower	20996	121
Wheat	22279	296

The figures show maize, sunflower and wheat residues have the largest technical potential. The technical potential was not only calculated for Ukraine, but also for each oblast. Results are shown in Appendix B and reveal that for maize residues, the most important oblasts are Poltava, Vinnytsya and Cherkasy, which together have more than 30% of the total maize residues in Ukraine. The oblasts with the highest amount of sunflower residues are

Kirovohrad, Dnipropetrovsk and Kharkiv. Each of these oblasts produces more than 10% of the total sunflower residues. For wheat residues, the oblast with the highest amount available are again Kharkiv and Dnipropetrovsk, but also Odesa. Together these oblasts produce almost a quarter of the total Ukrainian wheat residues.

As explained in the methodology, not all feedstocks were examined, but only the ones with the highest potential. While the technical potential of maize, sunflower and wheat residues in Ukraine is the highest of the five examined feedstocks, this does not mean that all of this potential is available in Ukraine. According to Gielen et al. (2015: 22): “collecting it for use is a challenge. Most agricultural enterprises are not able to gather, bundle and adequately store straw”. This is especially true for straw from maize and sunflower.

When maize is harvested, either the ears can be collected (with or without husk) or the harvesting machine also threshes the ear and collects only the kernels. The residues (stalks and leaves) are either:

- Comminuted and collected in a truck.
- Comminuted and spread over the field
- Not comminuted but dropped on the field, where the residues can be collected by baling.

In Ukraine, the threshing of ears takes usually place in the field, while the residues are comminuted and spread over the field (Geletukha & Zheliezna 2014). Since residues are comminuted no baling can take place and the residues are not collected. Therefore also no balers for maize stalk are available in Ukraine.

When sunflower is harvested the residues consist out of stalks and heads. Similar to the residues of maize, sunflower residues can either be:

- Shredded and collected in a trailer
- Shredded and spread over the field
- Non-shredded and dropped on the field, where the residues can be collected.

In the latter case, which is wat happens in Ukraine, ricks (heaps of straw in a line) are made of residues. Also, the stalks that remained in the ground are cut and shredded by disc plows and made into ricks (Geletukha & Zheliezna 2014). These ricks of residues could be baled and collected after drying in the field. However, an interviewed expert (C) explained these residues are not baled and collected. Also Geletukha & Zheliezna (2014: 18) state that “in Ukraine there are no examples of the use of sunflower stubble residues for energy production”.

Since maize and sunflower residues are not collected, these residues cannot be used for pellet production at the moment. Also, there is no domestic demand for these residues at the moment. Therefore it was not possible to calculate the surplus, so primary residues of maize and sunflower were not included in the remainder of this chapter.

According to Geletukha & Zheliezna (2014) the residues of wheat (straw) are processed in four ways in Ukraine :

- Streaming: shredded and collected in trailers
- Spreading: shredded and spread over the field
- Stacking: stacks are made of residues and dropped on the field
- Swathing: residues are spread in lines over the field and collected by baling

According to Geletukha & Zheliezna (2014), streaming is the most used technology in Ukraine, but also baling is becoming more popular. So contrary to maize and sunflower residues, wheat residues are collected on large scale in Ukraine.

Since the technical potential of wheat residues was more than three times larger than the potential of barley residues and more than four times larger than the potential of rape residues, as was shown before in Table 9, the focus in this research for primary agricultural residues was only on wheat residues.

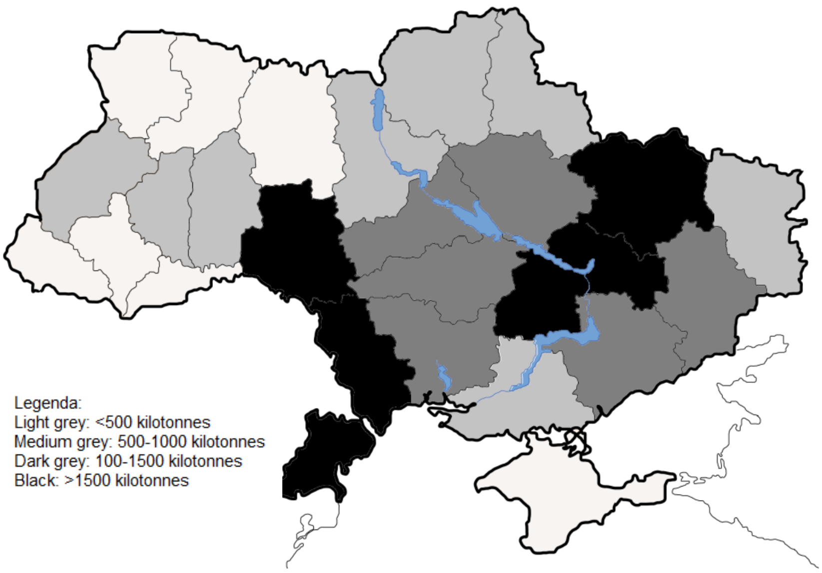
There is a large difference in technical potential per oblast. The top five oblasts with the highest technical potential of wheat residues are shown in Table 10.

Table 10: Technical potential of wheat residues in top oblasts

Oblast:	Technical potential (kt):	Technical potential (PJ):
Kharkiv	2027	26.9
Dnipropetrovsk	1769	23.5
Odesa	1634	21.7
Vinnytsya	1521	20.2
Zaporizhya	1481	19.7

These five oblasts with the most wheat residues together have 38% of the total Ukrainian potential. A map highlighting these oblasts is shown in Figure 3.

Figure 3: Map of technical potential of wheat residues of oblasts



3.1.2. Technical potential of secondary agricultural residues

Estimates on the technical potential of secondary agricultural residues range from 18 PJ (Lakyda et al. 2010) to 33 PJ (Gielen et al. 2015) as shown in Table 1. However, for secondary agricultural residues, the focus was on sunflower husk. The technical potential was determined by multiplying the production of sunflower, which was shown in Table 5, with the percentage of husk that can be used to produce pellets. This percentage was 17.5 according to an interviewed expert (H). Another interviewed expert (I), who produced sunflower oil, stated that the amount of husk he retrieved was 12% of the sunflower production. In this research, the average was taken of these two estimates.

The technical potential of sunflower husk in Ukraine was therefore 1.6 megatonnes. This estimate is almost similar to the estimate by Zheliezna (n.d.), who stated the potential of sunflower husk is 1.59 megatonnes. It is slightly more than the estimate of the Institute of

Energy Crops and Sugar Beet of the NAAS, which stated the technical potential of sunflower husk in Ukraine is 1.4 megatonnes.

To determine the technical potential in petajoule, the LHVs from various studies were used to calculate an average. The LHVs as well as the average are shown in Table 11. See Appendix A for the calculation of the LHV for Demirbaş (2002), Haykiri-Acma & Yaman (2009) and IEA Bioenergy Task 32 (n.d.) based on the HHV.

Table 11: Lower heating value of sunflower husk

Source:	LHV (MJ/kg):
Demirbaş (2002)	14.0
Haykiri-Acma & Yaman (2009)	13.6
IEA Bioenergy Task 32 (n.d.)	16.2
SEC Biomass (2015)	16
Average	14.9

When using the average LHV of 14.9 MJ/kg the technical potential equals 24 petajoule. An overview of the technical potential of all oblasts can be found in Appendix C. The oblasts with the highest technical potential are shown in Table 12

Table 12: Technical potential of sunflower husk in top oblasts

Oblast:	Technical potential (kt)	Technical potential (PJ)
Kirovohrad	181	2.71
Dnipropetrovsk	173	2.58
Kharkiv	165	2.46
Mykolayiv	139	2.07
Zaporizhya	136	2.03

Together, these five oblasts have 49% of the total technical potential.

3.1.3. Technical potential of forest residues

The amount of primary and secondary forest residues was determined based on Lakyda et al. (2013) and is shown in Table 13 both in megatonnes and petajoule. The authors assumed a LHV of 16.0 MJ/kg for primary forest residues and 17.9 MJ/kg for secondary forest residues.

Table 13: Technical potential of forest residues in Ukraine

	Technical potential (Mt)	Technical potential (PJ)
Primary residues	1.41	22.6
Secondary residues	0.92	16.5

The technical potential of primary and secondary forest residues was calculated for all oblast. An overview of the oblasts with the highest technical potential is shown in Table 14 for primary residues and in Table 15 for secondary residues. Together, these oblasts have 46% of the technical potential.

Table 14: Technical potential of primary forest residues in top oblasts

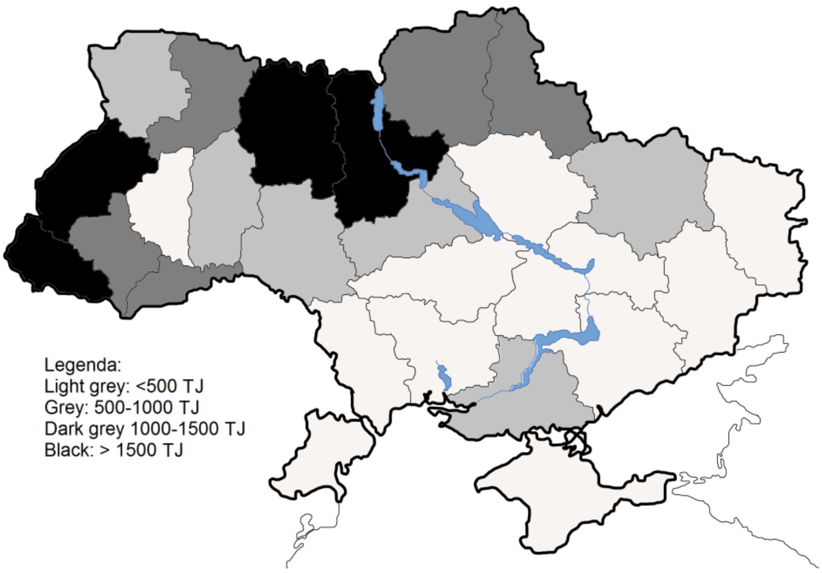
Oblast:	Technical Potential (kt)	Technical potential (PJ)
Zhytomyr	189	3.04
Zakarpattya	143	2.30
Lviv	110	1.76
Kyiv	108	1.74
Chernihiv	93	1.49

Table 15: Technical potential of secondary forest residues in top oblasts

Oblast	Technical Potential (kt)	Technical potential (PJ)
Zhytomyr	123	2.21
Zakarpattya	93	1.67
Lviv	72	1.29
Kyiv	71	1.27
Chernihiv	61	1.09

A map showing the technical potential of forest residues of oblasts is shown in Figure 4. An overview of the technical potential for each oblasts is given in Appendix D

Figure 4: Map of technical potential of primary forest residues of oblasts



3.2 Sustainable potential

In this section the sustainable potential of wheat residues is determined first. Hereafter, the sustainable potential of primary forest residues is determined. As explained in the methodology section, no separate sustainable potential was determined for secondary agricultural residues and secondary forest residues. Instead, the sustainable potential of these residues can be considered to be equal to the technical potential.

3.2.1 Sustainable potential of wheat residues

The sustainable removal rates for all oblasts are shown in Appendix E. The weighted average of the sustainable removal rates of the various oblast is 58%. So the sustainable potential in Ukraine of wheat residues forms 58% of the technical potential. This amounts to 13.0 megatonnes and 172 PJ. Data for all oblasts can be found in Appendix E. The sustainable potential for the top oblasts is given in Table 16.

Table 16 Sustainable potential of wheat residues of top oblasts

Region:	Sustainable potential (kt):	Sustainable potential (PJ):
Kharkiv	2027	26.9
Dnipropetrovsk	1656	22.0
Donetsk	1387	18.4
Poltava	1151	15.3
Kirovohrad	1115	14.8

3.2.2. Sustainable potential of primary forest residues

The soil types of forest in Ukraine are mainly cambisol, podzoluvisol and fluvisol. According to the EEA, these types of soil are highly suitable for residues removal and have an extraction rate of 60%. However, 20% of the forest were reclassified as moderately suitable, which have an extraction rate of 40%, based on the low base saturation. On average, this gave an extraction rate of 56%. This extraction rate is similar to the one stated by an expert of the Institute of Forestry and Landscape-Park Management of the NULES (personal communication).

When the theoretical potential of primary forest residues is multiplied with the removal rate, the sustainable potential for forest residues in Ukraine was 16.1 PJ. The oblasts with the highest sustainable potential are shown in Table 17.

Table 17: Sustainable potential of primary forest residues

	Sustainable potential (kt)	Sustainable potential (PJ)
Zhytomyr	118	1.89
Zakarpattya	93	1.49
Lviv	85	1.37
Ivano-Frankivsk	76	1.21
Kyiv	58	0.94

3.3 Sustainable surplus

The sustainable surplus is determined first for primary and secondary agricultural residues and hereafter for primary and secondary forest residues. Finally, an overview is given of the total sustainable surplus in Ukraine.

3.3.1. Sustainable surplus of primary agricultural residues

The sustainable surplus of wheat residues was calculated by subtracting the domestic demand from the sustainable potential. The domestic demand consisted out of the various ways in which the straw is used at the moment. Based on literature and the interviews, various ways of using agricultural residues were identified. Furthermore, the domestic demand per category was estimated as a percentage of the technical surplus.

Fodder

Even though the nutritional value is low, straw is used as fodder (animal feed) for cattle (Geletukha & Zheliezna 2014). An interviewed expert (A) estimated that at the moment 5%[3] of all straw is used for fodder, while another interviewed expert (E) made an almost similar estimate of 4%. One interviewed expert (C) believed this figure was higher and he claimed 27% of all straw is used as fodder.

Bedding
Straw is also used at farms for animal bedding (Geletukha & Zheliezna 2014; Kuznetsova 2010). An interviewed expert (A), working at a research institute, believed only 5% of the straw is used as bedding. This was confirmed by a second interviewed experts (E), who believed the value was 6%. According to another interview experts (C), the value is much higher and this amount to 35% of all available straw, which was confirmed by an interviewed expert (D) who estimated the value was 30%.

Left on field
In the last decades, the use of mineral fertilizers has decreased strongly in Ukraine. While an upwards trend in the use of chemical fertilizers is visible since 2000, the amount used in 2013 was still only around half of the amount used in 1990. Instead of chemical fertilizers, agricultural residues such as wheat and maize residues are used as a fertiliser in Ukraine, since it is much cheaper than chemical fertilisers (Geletukha & Zheliezna 2014). Therefore these residues cannot be used as sustainable biomass. The experts had different opinions on the amount of residues that is left on the field. An experts (C) believed this value was 34%, while according to another interviewed expert (A), 65% of straw was left on the field. A farmer (D) believed it was even 70% and another interviewed expert (E) believed it was almost 90%. Part of these residues have to be left on the field anyway to prevent erosion and the reduction of soil organic matter. However, part of this could be replaced by other types of fertilizers.

Burned on the field
A substantial amount of this straw that is left on the field is, even though it is illegal, burned on the field. Van der Hilst (2012: 236) noted that "it is however not recorded how much and where straw is burned". Estimation of how much straw is burned on the field vary. One of the experts (E) believed this amounted to only 5%, while an interviewed farmer (D) believed this amounted to at least 40%. An interviewed expert (A) believed around 15% of the total amount of straw was burned.

Used at farm
Part of the residues is used at the farm itself. Not only for domestic heating, but also to dry grain, according to an interviewed expert (A) working at a research institute. He believed this amounted to 10% of the total amount of straw. However, other interviewed experts (C, E) believed the amount was far less and estimated only 1% or 0.1% of the available straw was used this way.

Used in region
Part of the residues is used for heating regionally. According to the interviewed expert (A), this amounted to 4% of the total amount of straw available. Similar to the heat used at the farm, two other interviewed experts (C) stated a lower value of 2% and 0.2%.

Other
Some of the interviewed experts (C,E) noted that a part of the straw is also used for other purposes, mainly for the production of mushrooms. However, none believed this amounted to more than 1% of the total potential.

[3] Note that the percentages in this section indicate parts of the technical potential, not of the sustainable potential.

Pellet production
The remainder of the residues can be used for the production of pellets. Estimates on how much remains vary per expert. An interviewed expert (A), working at a research institute, believed at the moment 5% of the residues could be used this way. Two other experts (C, E) stated this amount was much lower and constituted less than 1% percent of the total amount of straw available.

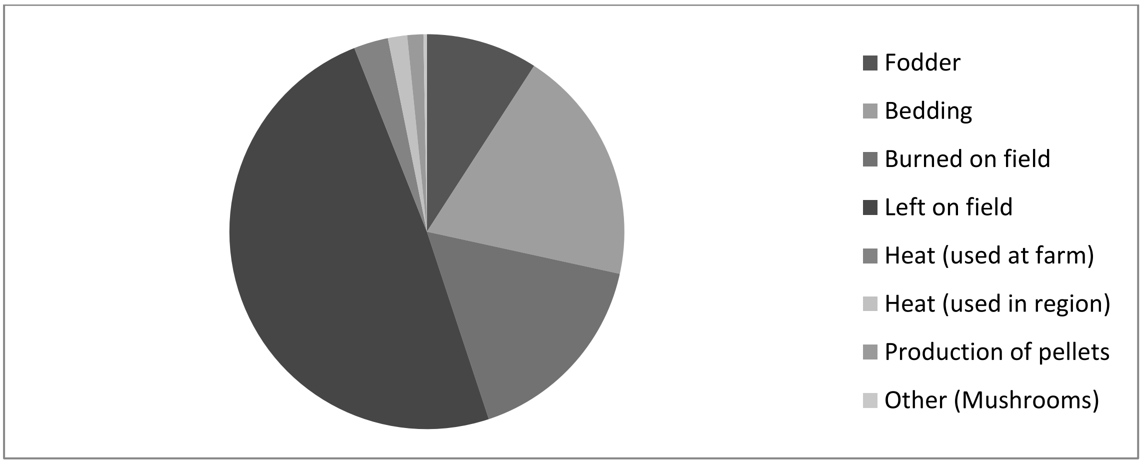
An overview of the various estimates per category is shown in Table 18 below.

Table 18: Estimates of the domestic demand of wheat residues

Category:	[A]	[C]	[D]	[E]
Fodder	5%	27%	0%	4.0%
Bedding	5%	35%	30%	6.0%
Burned on field	15%	0%	45%	5.0%
Left on field	50%	34%	25%	84.4%
Heat (used at farm)	10%	1%	0%	0.1%
Heat (used in region)	4%	2%	0%	0.2%
Production of pellets	5%	0%	0%	0.2%
Other (mushrooms)	0%	1%	0%	0.1%

Total domestic demand
The average total domestic demand for wheat residues is based on the average of the estimates of the interviewed experts and is shown in Figure 5.

Figure 5: Average domestic demand of wheat residues



It can be seen the majority of the straw is left on the field or burned on the field. The most important ways to use the straw are for bedding and fodder.

Surplus of agricultural residues
To determine the surplus, the sustainable potential is reduced by the domestic demand, as described in the methodology. However when determining the sustainable surplus of wheat residues, the current use for pellets, bedding and left and burned on the field was not included. The former was excluded because pellet production forms part of the surplus. The amount burned on the field was excluded because straw is burned only when there is no better option for use. Therefore using the straw for pellet production instead of burning it is not considered a distortion of a market.

The amount left on the field is excluded because the amount that should be left on the field was already taken into account when determining the sustainable surplus. Also the current use for bedding was excluded, because bedding is returned to the field after use. While this means it is not available for pellet production, bedding was qualified as “sustainable use” and included in the percentage that should remain on the field due to the sustainability issues. To prevent double counting (i.e. including left on the field and bedding both in what should remain on the field and in the domestic demand), these two uses were also excluded from the domestic demand.

The domestic demand excluding pellet production, bedding and left and burned on the field is on average 14%. Due to the large differences between estimates of experts, instead of the average the full range is considered, which is between 0 and 31% of the technical potential.

An interviewed expert from a pellet factories (K) stated that there is no loss of straw during the pre-treatment process, only a decrease of moisture content. According to another expert, the loss of mass was 1% (J). Since a potential loss would be very small, no correction is made in the sustainable surplus.

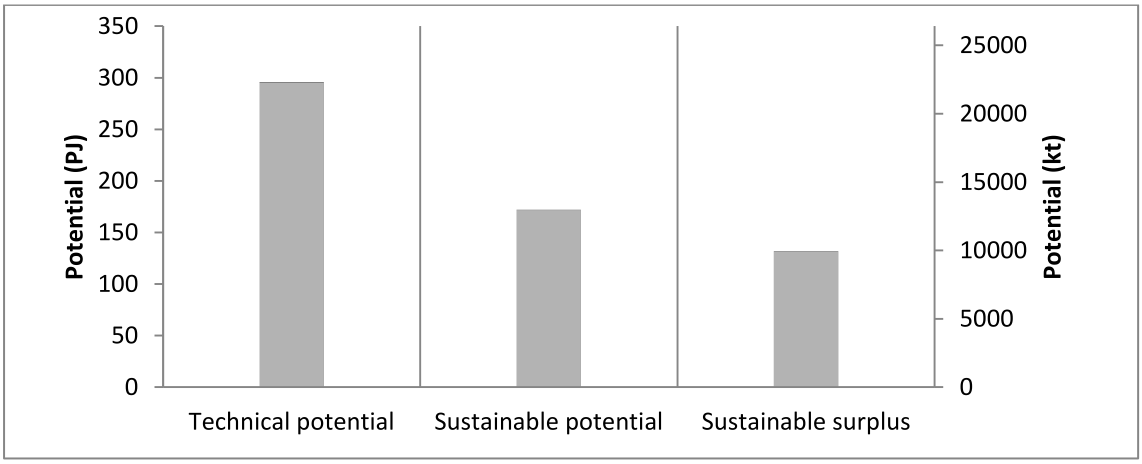
Since the sustainable potential formed 58% of the technical potential, and the domestic demand between 0 and 31%, the surplus is between 27 and 58% of the technical potential. This amounts to between 80.4 and 172.0 PJ for Ukraine. An overview of the average sustainable surplus is shown in Appendix G for all oblasts. The minimum and maximum sustainable surplus of the oblasts with the highest sustainable surplus are shown in Table 19.

Table 19: Sustainable surplus of wheat residues of top oblasts

Oblast:	Minimum sustainable surplus (PJ):	Maximum sustainable surplus (PJ):
Kharkiv	18.6	26.9
Dnipropetrovsk	14.7	22.0
Donetsk	12.7	18.4
Poltava	10.5	15.3
Kirovohrad	10.2	14.8

Figure 6 compares the technical potential, sustainable potential and sustainable surplus of wheat residues in Ukraine.

Figure 6: Overview of wheat residue potentials



3.3.2. Sustainable surplus of secondary agricultural residues

A large part of the sunflower residue is already used for the production of pellets. According to Andriyenko (2013) the amount of sunflower husk pellet produced in 2012 was 1.1 megatonnes. This was confirmed by data from the Ukrainian Biofuel Portal (2015) which determined the export value in 2014 to be 1.1 megatonnes. An interviewed expert (J) confirmed that all pellets are exported. He explained his company sold only 1% of the production in Ukraine, and nothing before 2014. Assuming a LHV of sunflower husk pellets of 16 GJ/tonne (Verma et al. 2012), this means a domestic demand of 17.7 GJ, as can be seen in the overview in Table 20. So the current production of pellets amount to 73% of the technical potential.

The remainder of the sunflower husk is burned at the production site. As an interviewed expert (I) explained, the husk is burned to produce heat, which is used in the production process. This was confirmed by Lakyda et al. (2010: 24), who wrote that "practically all the oil-extraction plants have boilers which produce heat from sunflower husks". According to this interviewed expert (I), around halve of the available sunflower husk is needed for this process.

While the heating in the process could be replaced by other sources of heating such as natural gas, making more sunflower husk available for the production of pellets, this would mean a sustainable source of energy is replaced by fossil fuels and a distortion of a market. Therefore it was assumed the supply of pellets would stay constant. This would continue the current trend, which shows the production of pellets from sunflower husk was stable in recent years (Andriyenko 2013; Ukrainian Biofuel Portal 2015).

Table 20: Domestic demand for sunflower husk

Type of use	Domestic demand (PJ):	Domestic demand (%):
Production of pellets	17.7	73
Heat	6.6	27
Total	24.3	100

So the sustainable surplus is equal to the current production of pellets of 17.7 PJ. The sustainable surplus is shown per oblast in Appendix G.

3.3.3. Sustainable surplus of primary forest residues

Primary forest residues are not collected in Ukraine at the moment, according to Tebodin (2013) and Lakyda et al. (2010). Because the residues are not available, there is no domestic demand. According to an expert of SEC Biomass, the cost of retrieving the residues is deemed to be too high to use primary forest residues as a source for the production of pellets. Therefore the sustainable surplus of primary forest residues could not be determined and primary forest residues were not taken into account in the remainder of this research.

3.3.4. Sustainable surplus of secondary forest residues

A significant share of the secondary forest residues is used for the current production of wood pellets. According to FAOSTAT (2013c), the production of pellets in Ukraine amounted to 210 kilotonnes in 2012. Assuming a LHV of 17 GJ per tonne (Verma et al. 2012), this amounts to 3.6 PJ.

Secondary forest residues are also used to produce wood chips. The amount produced in Ukraine, excluding wood chips made directly in the forest from roundwood, is 0.56 million m^3

(FAOSTAT 2013c). Since the LHV of wood chips is 3.1 GJ/m^3 (Biomass Energy Centre 2011), this amounts to 1.7 PJ.

The remainder of the secondary residues are almost completely used by the wood industry for heating, according to experts at SEC Biomass. However, it is unknown how much of the residues is exactly used for heating in the wood processing industry.

According to (Tebodin 2013) only 0,45 million m^3 of secondary residues was not yet used. Assuming an LHV similar to the LHV of wood chips, this amounts to 1.4 PJ, or 8% of the technical potential.

Following the experts of SEC Biomass, it was assumed that the demand for heat is responsible for the remaining 59% of the technical potential. Therefore the domestic demand amounts to 92% including the current pellet production. An overview is given in Table 21.

Table 21: Domestic demand of secondary forest residues

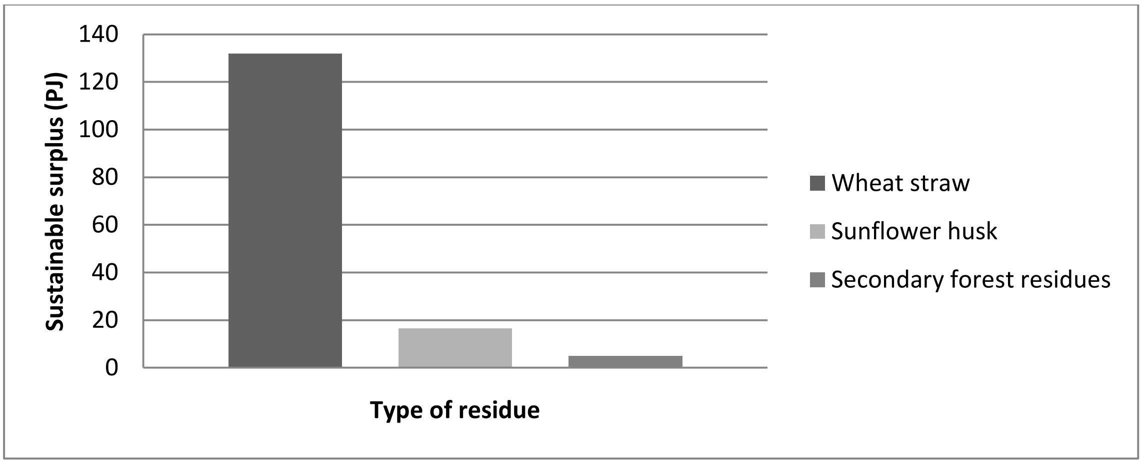
Type of use	Domestic demand (PJ):	Domestic demand (%):
Production of pellets	3.6	22
Wood chips	1.7	11
Heat	9.8	59
Unused	1.4	8
Total	16.5	100

The sustainable surplus consist out of the amount of unused secondary residues and of the current production of pellets, in total 30% of the technical potential. This amounts to 5.0 PJ. The sustainable surplus is shown for each oblast in Appendix G.

3.3.5. Comparison of sustainable surplus

The sustainable surplus of wheat straw, sunflower husk and secondary forest residues is shown in Figure 7.

Figure 7: Sustainable surplus of residues



3.4 Cost of biomass

In this section, first the costs of the various residues are estimated. Secondly the costs of producing pellets out of the residues are discussed. Hereafter, the transportation costs are determined. Finally the total costs are calculated and shown in cost-supply curves.

3.4.1. Cost of residue

The cost of residue are zero for some residues because the residues are a by-product of producing crops. However, this is not the case for wheat straw. Since straw has value, this should be included in the cost. The cost of straw depends first of all on whether collection is included (Kuznetsova 2012). In other words, if it is about the cost of straw loose on the field or baled. In this research, it was assumed collected, baled straw. The cost was highly variable, according to interviewed experts of the Ukrainian Pellet Union. They explained it could vary between 22 and 44 euro. Literature studies confirmed this variability, showing a wide range of estimations by various authors. While Poppens et al. (2013) assumed a price of 27 euro for straw, Kuznetsova (2012) believed straw could be retrieved for as little as 13 euro. Unpublished figures by an expert of SEC Biomass (Kramar 2015) estimated the cost to be 36 euro, but included delivery, cleaning and drying. Since all these costs were relevant for this research and this estimate was the most recent, this value from Kramar (2015) was used. The cost was assumed to be the same in each oblast.

Sunflower husk and secondary wood residues are residues that did not have other uses except for burning for heat, as discussed in the sustainable surplus section. The cost was therefore very low. However, it was not possible to determine the exact cost of collecting sunflower husk and secondary wood residues, since interviewed expert from pellet factories were unwilling to discuss their costs. But since the cost was assumed to be low compared to the pelletisation and transportation costs, the cost was included in the method to determine the cost of producing pellets and were not estimated separately. See the section of pre-treatment cost for a further elaboration.

3.4.2. Cost of pre-treatment

The main part of the cost of pre-treatment is the cost of pelletizing. But before pelletizing is possible, the straw has to be transported to the pellet factory. The cost of this relative short distance transport was estimated by an interviewed expert (E) involved in a biomass project (which required straw collection) to be around 22 eurocents per tonne per kilometre. However, the price depended strongly on the deal that could be made with the transportation company. According to the interviewed expert (E), a price of nine eurocents was also possible. Kuznetsova (2012) assumed even a price of three eurocents per tonne per kilometre. However, the cost of transport of the straw to the pellet factory was already included in the estimate of an expert of SEC Biomass (Kramar 2015), which was used in this research.

The cost of pelletizing was estimated to be 22 euro per tonne of pellets by an expert of SEC Biomass (Kramar 2015). This is close to the estimation of 28 euro by Poppens et al. (2013) and similar to the estimation of the interviewed experts (B) of the Ukrainian Pellet Union, who also believed the cost was 22 euro. Interviewed experts from pellet factories were unwilling to discuss their production cost.

According to Kramar (2015) the main cost of producing pellets is the straw, as discussed in the section before, and electricity. An interviewed expert (K), working at a pellet factory, added that maintenance and repairs of the machinery was another important cost, especially when the materials had to be imported.

To check the estimations of the costs of production and pre-treatment, the total of these two costs was compared to the price of pellets. A unpublished study by SEC Biomass on the prices in various oblast gave a range of 48 to 97 euro per tonne (SEC Biomass 2015). The average of the average prices in the oblasts is around 71 euro per tonne. This confirms the estimate of the cost, since the average price is slightly higher than the estimated cost, probably due to a profit margin. Therefore the estimation of Kramar (n.d.) was used, which totalled around 58 euro for production and pre-treatment.

It was not possible to determine the cost for pre-treatment of sunflower husk and secondary agricultural residues. Instead, the price of pellets was determined and used as a proxy for the cost. Since prices are mostly set to compensate for all costs, both for the production of residues and the pre-treatment, the price of the pellets was the best available proxy for the cost of the pellets.

For both wood pellets and sunflower husk pellets, experts from SEC Biomass examined the prices in various oblast. Prices for sunflower husk pellets were in a range from 37 to 89 euro/tonne (SEC Biomass 2015). For each of the six oblasts, experts of SEC Biomass determined the average price. The average of these averages prices is around 71 euro/tonne. Prices for wood pellets were between 57 and 161 euro/tonne (SEC Biomass 2015). When using a similar method as with sunflower husk pellet, the average price per tonne of wood pellets is around 102 euro.

It is assumed that the profit margin of the production of sunflower husk and wood pellets is similar to the profit margin of wheat straw pellets. Therefore the costs are assumed to form 82% of the price. The cost per GJ are based on the assumption of an LHV of 15 GJ/tonne for straw pellets, 16 GJ/tonne for sunflower husk pellets and 17 GJ/tonne for wood pellets (Verma et al. 2012). Table 22 shows the price and cost of pellets of wheat residues, sunflower husk and forest residues.

Table 22: Price and cost of pellets

Feedstocks	Price (euro/tonne)	Cost (euro/tonne)	Cost (euro/GJ)
Wheat straw	71	58	3.8
Sunflower husk	71	58	3.6
Forest residues	102	83	4.9

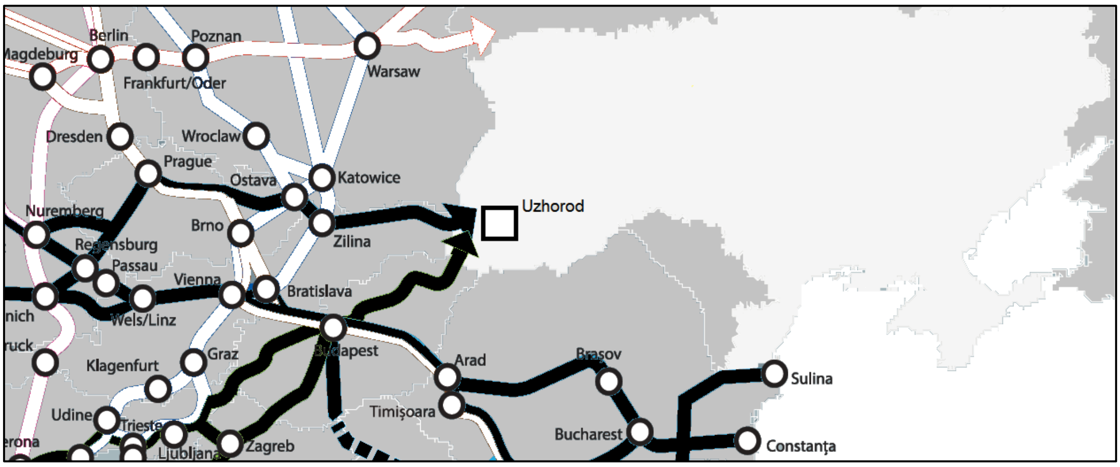
3.4.3. Cost of transport

First, three transport hubs on the border of Ukraine have been selected as end-points for the transport cost calculations. All three hubs offer a different way of continuing transportation of pellets to the EU. Hereafter the method to transport the pellets to the transportation hub is determined. Finally, the transport cost per tonne is calculated.

Export by train

Ukraine is connected to the trans-European transport network via two of the European core network corridors, namely the Mediterranean corridor and a branch of the Rhine-Danube corridor (European Commission 2013). These corridors, which consist largely out of train tracks, both end officially at the border between the EU and Ukraine, since Ukraine is not a member of the EU and therefore not part of the corridor. However, the city of Uzhhorod, which is located on the border between Ukraine and Slovakia and close to the border with Hungary, is only 30 kilometres away from the point where the corridors end and is connected by railway to both corridors. Figure 8 shows the location of the corridors (including the Mediterranean and Rhine-Danube corridor in black) as well as of Uzhorod. Since the corridors cross multiple other corridors, many European countries can be reached by train from Uzhorod.

Figure 8 Map with corridors and location of Uzhorod



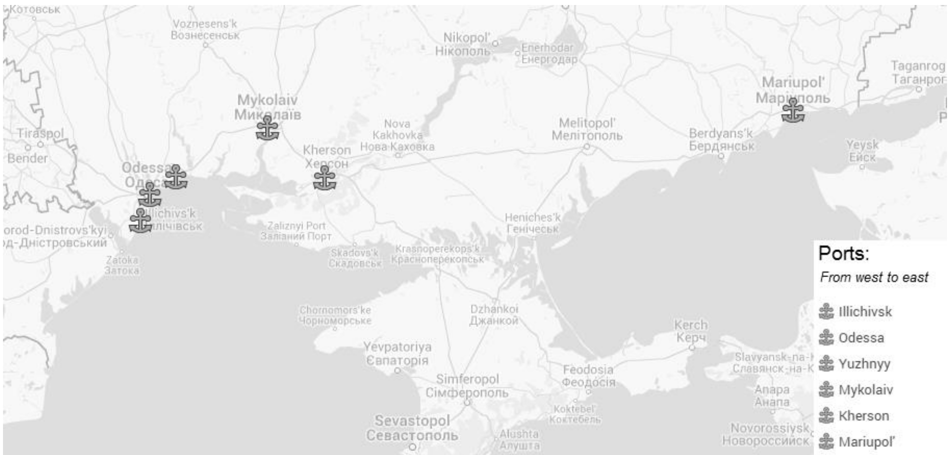
Export by river

The largest river flowing through the EU, the Danube, has a branch ending in Ukraine. Multiple Ukrainian ports are located along this part of the Danube. However, most ports are small. The largest port is Izmail. The port has a railway station, allowing delivery by train and has facilities allowing the loading of pellets with a capacity of more than five kilotonnes per day (Sif-Service 2015a). While the port is connected to the Black sea via the Danube, the relative shallow draft makes it unsuitable for transport by larger sea ships.

Export by sea

Ukraine has eighteen seaport along the Black Sea and the Sea of Azov (Sif-Service 2015b). The main seaport are Odessa, Ilyichevsk , Yuzhniy, Nikolaev, Sebastopol, Kherson and Kerch along the Black Sea and Mariupol along the Sea of Azov (World Port Source 2015). Due to the Crimean crisis and the annexation of the Crimea by the Russian Federation in 2014, the ports located in Crimea (Sebastopol and Kerch) are de-facto no longer part of Ukraine. Therefore these ports were deemed to be unsuited for export. This left six seaports for further consideration, which are shown on a map in Figure 9.

Figure 9: Map of the largest sea ports of Ukraine



From these options, Mariupol and Kherson were deemed unsuited and not taken into account, because these two ports are unable to accommodate bulk carriers, which are the ships used for oversea transportation of pellets (EUBIA 2009; Stelte 2012). Even the draft of the smallest category of bulk carriers (handysize vessels), is higher than the maximum draft of the ports of Mariupol and Kherson (Danish Ship Finance 2012; Hudson 2015; Sif-Service

2015b). Also, recent fighting close to Mariupol (Radio Free Europe 2015) casted doubt on the safety of using this port

From the remaining Ukrainian seaports, Odessa was selected. While all four ports could be used for export, Odessa has a central location between the four ports. Therefore the distance (and thereby transport cost) to Odessa was a good proxy for the distance to all four seaports.

Transportation to export hub
The transportation of the pellets from the factory to each of the three selected end-point is done by train. Experts from SEC Biomass have determined that the cost of transportation of pellets by train is lower than the cost of transportation by either truck or by ship over the Dnieper river. This was confirmed by interviewed experts working at pellet factories (J,K), who explained all pellets from their production locations were transported by train. It should be noted that according to an interviewed expert (J) transport by train requires a minimum amount of 60 tonnes of pellets, which is not the case with transport by truck. Only in the case the distance between the pellet factory and end-point is less than 300 kilometres, which is the limit set by the European Biomass Industry Association (EUBIA 2009), transportation is assumed to be per truck.

Cost of transport to transport hub:
The cost of long distance transport by train was around 1.5 eurocents per tonne per kilometre, according to an interviewed expert from a pellet factory, who exported by train to Poland. According to experts of SEC Biomass, the cost was slightly lower. They estimated the cost for transport by train to be 1.3 eurocents per tonne per kilometre. Poppens et al. (2013) [4] estimated the cost to be slightly higher and believed it was 2.0 eurocents per tonne per kilometre. Since the cost of the interviewed experts was his real cost in 2015 and is within the range of estimates by SEC Biomass and Poppens et al. (2013), a value of 1.5 eurocents per tonne per kilometre is used in this research.

Since none of the interviewed experts working at a pellet factory used trucks for transport of pellets (because all exported over a long distance) the cost of transport by truck is based on data from literature. While Poppens et al. (2013) assumed a cost of 2.2 eurocents per tonne per kilometre, experts from SEC Biomass believed the cost was higher. In an unpublished study the cost was estimated to be 4.3 eurocents, while in another unpublished study an estimation of 6.5 eurocents per tonne per kilometre was given. The latter was higher because it assumed the truck would return empty. For this research an average value of 4.3 eurocents per tonne per kilometre was taken.

The distance over which the pellets have to be transported by train is shown in Appendix H for each of the three possible destinations. Only in five out of 78 cases the distance was lower than 300 kilometres, in which transport by truck was assumed. For the oblasts with the highest sustainable surplus of agricultural and secondary forest residues combined, the distances are shown in Table 23

[4] Own calculation based on (Poppens et al. 2013). The authors found the cost in 2013 to be 28,6 euro per tonne, for a distance of around 700 kilometres. For more information on the exchange rate, see the methodology section.

Table 23: Distance between transport hubs and top oblasts

From / to (kilometre)	Odessa	Uzhorod	Izmail
Kharkiv	725	1358	991
Dnipropetrovsk	480	1210	748
Donetsk	725	990	1486
Kirovohrad	317	944	572
Poltava	560	1105	818

The transportation cost was estimated by multiplying the distance with the transportation cost per kilometre. An overview of the transportation cost per tonne is shown for each oblast in Appendix I. For the oblasts with the highest surplus of agricultural and secondary forest residues combined, the transportation cost is shown in Table 24. An average is determined of the transportation costs to all three hubs.

Table 24: Transportation cost from top oblasts to transportation hubs

From / to (euro/tonne)	Odessa	Uzhorod	Izmail	Average
Kharkiv	11	20	15	15
Dnipropetrovsk	7	18	11	12
Donetsk	11	15	22	16
Kirovohrad	5	14	9	9
Poltava	8	17	12	12

3.4.4. Total costs

The average total costs are different per feedstock and per oblast. For each feedstock, a costs-supply curve was created of the average total cost and sustainable surplus. For wheat residues, the average sustainable surplus was used. Figure 10 shows the cost-supply curve of wheat. Figure 11 shows the cost-supply curves of sunflower residues and secondary forest residues. The average total costs are shown in euro per gigajoule. The sustainable surplus is shown cumulative in petajoule.

Figure 10: Cost-supply curve of wheat residues

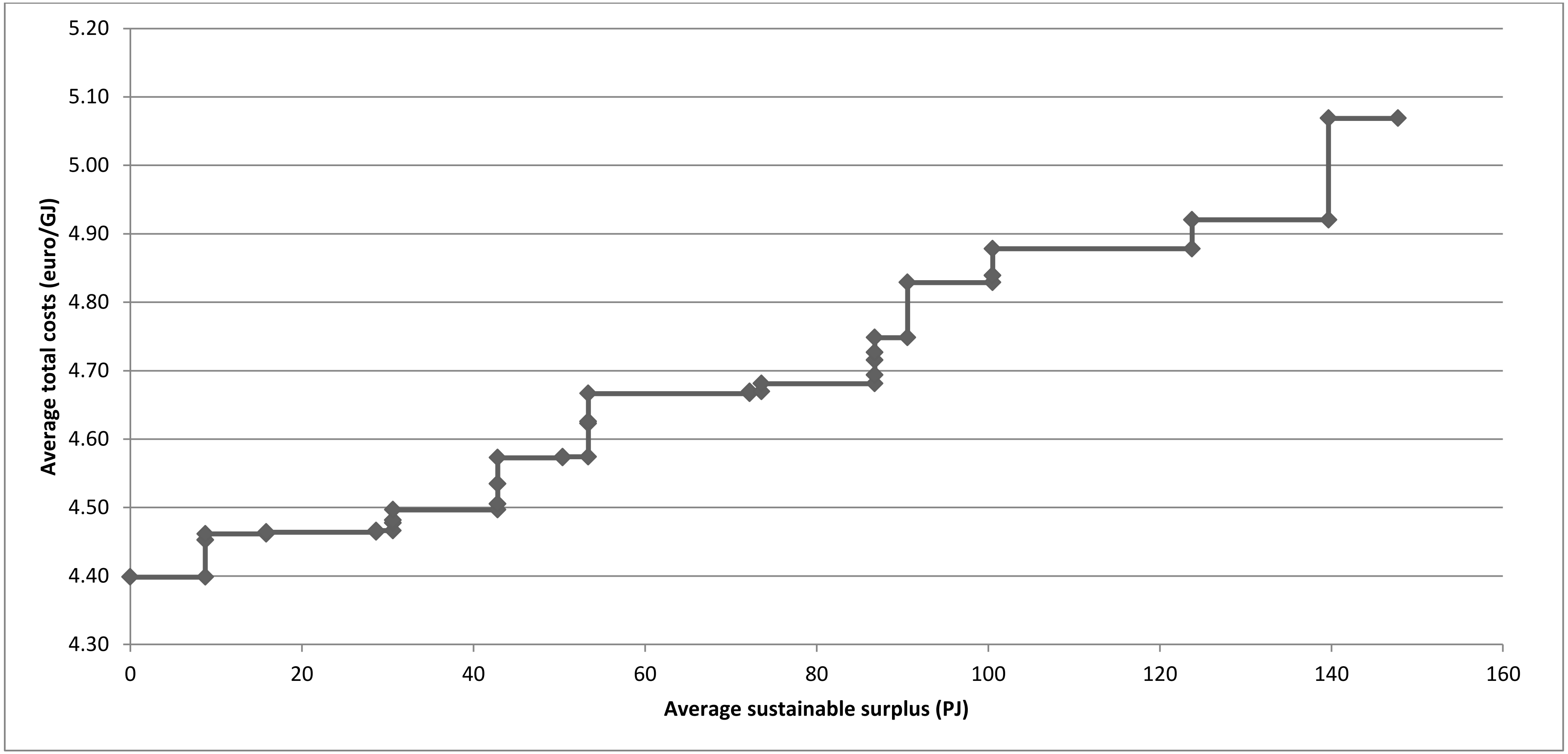
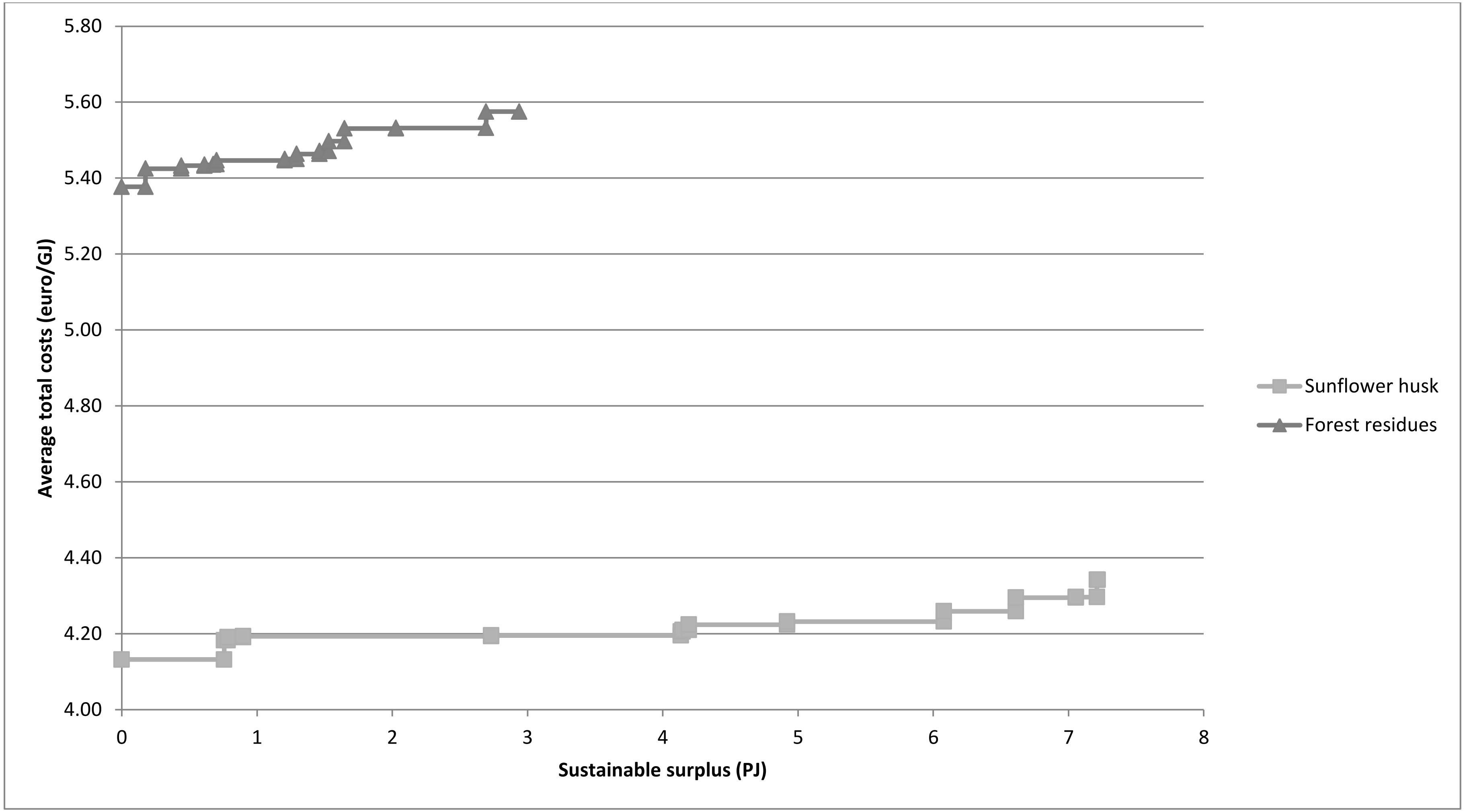


Figure 11: Cost-supply curve of sunflower husk and secondary forest residues



3.5. Trends

Various trends in Ukraine might influence the future potential of biomass from agricultural and forest residues.

The technical potential of agricultural residues is expected to increase, because the yield of various crops including wheat, sunflower, maize and barley has been increasing since 2000 (Vlasenko 2014). A higher yield means a higher production and also more residues. For example, the average increase per year of the technical potential of wheat residues was 7% between 2010 and 2013. Furthermore, the yield of barley and maize in Ukraine is lower than it was before the collapse of the Soviet-Union (Vlasenko 2014), which confirms that the yields in Ukraine can be much higher than it is today.

The sustainable surplus might also increase because more farmers will collect straw. At the moment, a significant part of wheat straw and almost all straw from sunflower and maize is not collected. If more equipment will become available, the amount of available agricultural residues will increase. Another reasons why the sustainable surplus of wheat straw might increase is that the use of straw for fodder is expected to decrease, according to an interviewed expert (C). He expected the demand for fodder to disappear completely, because he expected farmers to switch to other sources of fodder with a higher nutritional value. Furthermore, the amount of livestock is decreasing in Ukraine: the number of cattle halved since 2000 (FAOSTAT 2013d).

On the other hand, the sustainable surplus might decrease because the demand for straw for local heating is expected to increase, according to two interviewed experts (C, E). One of them expected the demand for straw for heating to increase tenfold in the next five years, while another even expected a fiftyfold increase. This trend is already visible in the domestic market for pellets, which increased fourfold between 2009 and 2012 (Tebodin 2013). Interviewed experts (B) believed this increase continued in recent years. However, according to interviewed experts (J,K) working at pellet factories, the domestic market for pellets is still small. One of them explained that 99% of the pellet production in his factory was exported, while another stated that everything was exported. According to an interviewed expert (K) the main limitation is the lack of local equipment for burning pellets. Therefore the main part of this expected increase in local demand for biomass will not be caused by a larger use of pellets, but by burning biomass directly for heat.

There are two main reasons for this expected increase. First of all, the main source for local heating in Ukraine is natural gas and the price of natural gas from Russia has increased more than 80% in recent years (Burmistrova & Zinets 2014). While the gas price for households is set by the state and heavily subsidized (Mitra & Atoyan 2012), this price was also raised (Geletukha et al. 2015). A higher gas price means heat from biomass becomes more interesting and this will increase the domestic demand for biomass.

Secondly, the Ukrainian government support the use of biomass with dedicated policy. The government is determined to decrease Ukraine’s dependency on energy imports (IEA 2014) and therefore wants to stimulate the replacement of natural gas by biomass. It has set ambitious biomass targets in its National Renewable Energy Action Plan (State Agency for Energy Efficiency and Energy Saving of Ukraine 2013). To reach these targets, the government has created a feed-in tariff for electricity produced from biomass (IEA 2015). The feed-in tariff guaranties a fixed price for electricity produced from biomass that is higher than the normal electricity price. According to Baker & McKenzie (2013) the feed-in tariff in Ukraine is one of the highest in the world. Furthermore, companies that produce electricity or heat from biofuels are exempt from paying corporate income tax until 2020 (Baker & McKenzie 2013). These policy measures stimulate the use of biomass for energy in Ukraine.

So it is unsure how the sustainable surplus will develop in the future. While the technical potential is expected to increase, an increase in the domestic demand might mean that the sustainable surplus will not increase.

4. Discussion

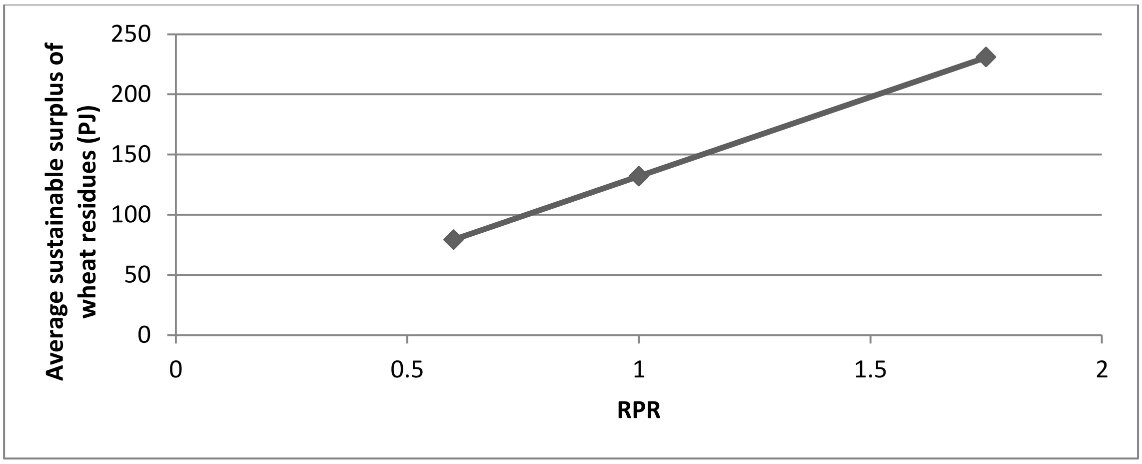
In this section the results are discussed. First of all, a sensitivity analysis is used to determine the influence of various factors on the final outcomes. Secondly, the limitations of this research are discussed. Hereafter, the implication are discussed and recommendation are made. Finally, recommendation for further research are made.

4.1. Sensitivity analysis

The sustainable surplus of wheat residues depends on various factors: the production of wheat, the residue-to-product ratio, the LHV, the domestic demand and the amount of straw that should be left on field to prevent erosion and maintain soil organic matter. The largest uncertainty is in the RPR and the domestic demand. A range was taken for the latter because of this uncertainty.

The influence of the RPR on the sustainable surplus is linear. The relative change in the sustainable surplus is equal to the relative change in production of wheat. So when a 20% higher RPR is chosen, a 20% higher sustainable surplus is determined. Figure 12 shows the influence of the RPR on the average sustainable surplus. The low value of 0.6 and the high value of 1.75 are the lowest and highest value found in the literature review of Scarlat et al. (2010).

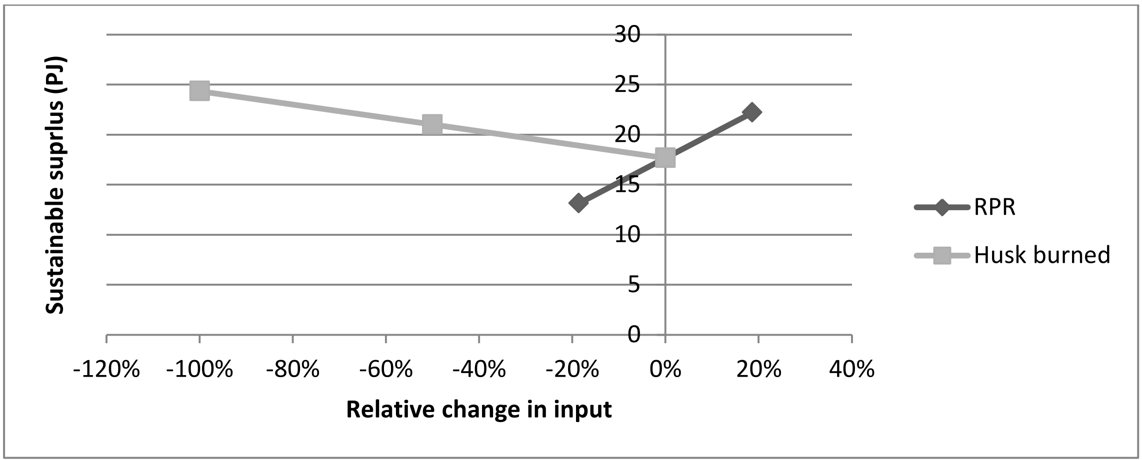
Figure 12: Influence of variation in the RPR on the average sustainable surplus of wheat straw



The sustainable surplus of sunflower husk is influenced by the production of sunflower, the amount of usable husk per sunflower, the current use and the LHV. The largest uncertainty is in the domestic demand and in the amount of usable husk per sunflower. Regarding the domestic demand, it was assumed that all husk that was not used for pellet production was burned to produce heat. Figure 13 shows the sustainable surplus if half or all of this husk is used instead of burned. If the amount of husk that is burned is lowered, the sustainable surplus increases.

The range in the amount of husk available is between the highest and lowest estimate of interviewed experts. This gives a range between 17.5 and 12% of the sunflower production. On a relative scale, this means the variable can be 19% higher or 19% lower than the value used in this research. Figure 13 shows this influence of this range on the sustainable surplus.

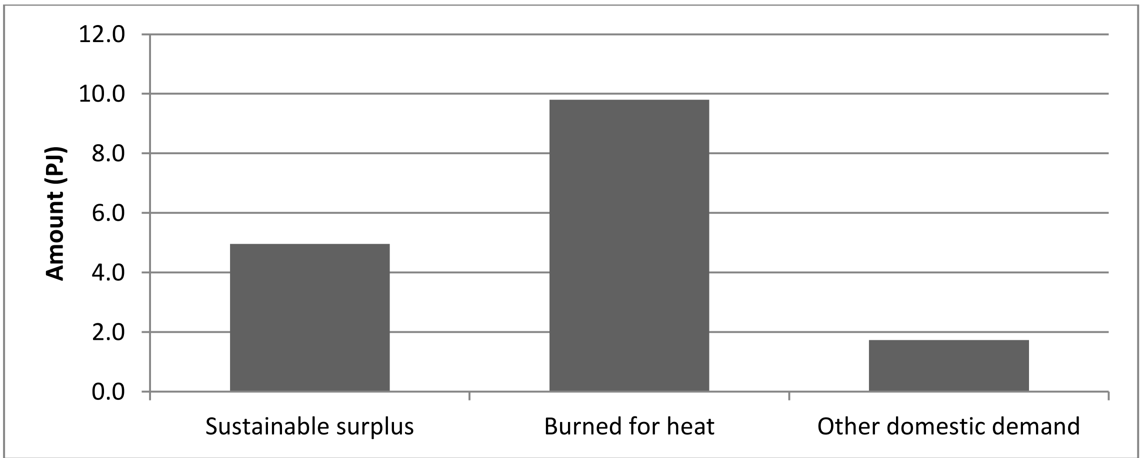
Figure 13: Influence of variation inputs on the sustainable surplus of sunflower husk



The sustainable surplus of secondary forest residues depends on the amount of forest biomass, the share of secondary forest residues within the forest biomass, the domestic demand and the lower heating value. The largest uncertainty is in the domestic demand. It was assumed that all forest biomass of which the use was unknown was burned to produce heat.

The amount of burned residues is large compared to the other domestic demand and the sustainable surplus, as shown in Figure 14. A change in the amount of burned residues has a strong and direct influence on the sustainable surplus. In the extreme option that all currently burned residues would become available for pellet production, the sustainable surplus would be almost 200% larger.

Figure 14: Comparison of sustainable surplus to domestic demand



The total cost are determined by the production cost and the transport cost. For the production cost, the examined range was based on the estimates of the price of pellets in Ukraine, determined by SEC Biomass (2015). An overview is given in Table 25..

Table 25: Range in production cost of feedstocks

Feedstock:	Low (euro/tonne):	Production cost (euro/tonne)	High (euro/tonne):
Wheat straw	48	58	97
Sunflower husk	37	58	89
Forest residues	57	83	161

For the transport cost, only a variation in the cost of transport by train is examined since in all but five cases, transport was done by train. The examined range of 1.3 to 2.0 eurocent per tonne per kilometre is based on values from an expert of SEC Biomass and from Poppens et al. (2013). The influence of production and transport costs is shown in Figure 15 for wheat residues. The total average cost is the average of all oblasts and all three transport hubs.

Figure 15: Influence of variation in production and transport costs on total cost of wheat residues

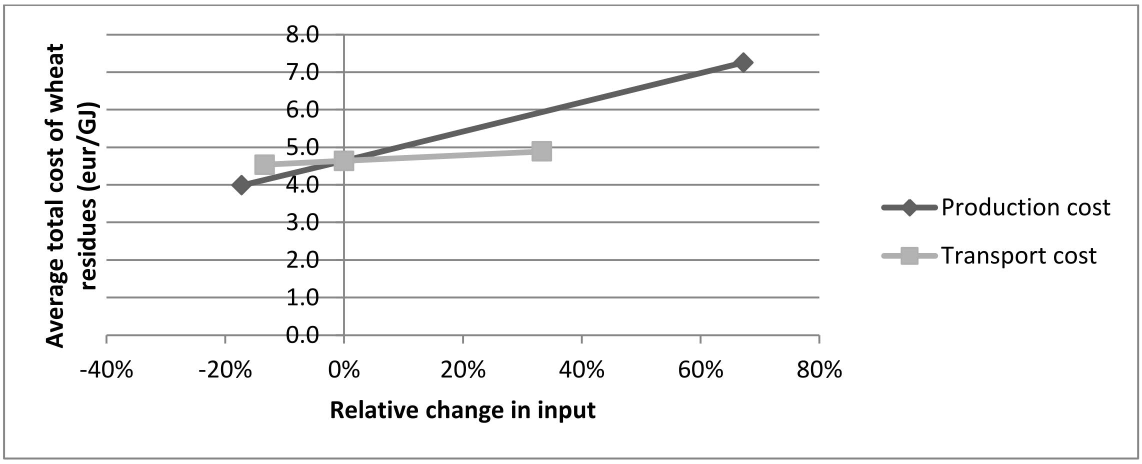


Figure 15 shows that the influence of production cost on the total costs of wheat is larger than the influence of transport costs. This is due to the fact that production cost form a larger part of the total costs than transport cost. Figure 16 shows the influence of production and transport costs on the average total costs of sunflower husk.

Figure 16: Influence of variation in production and transport costs on total cost of sunflower husk

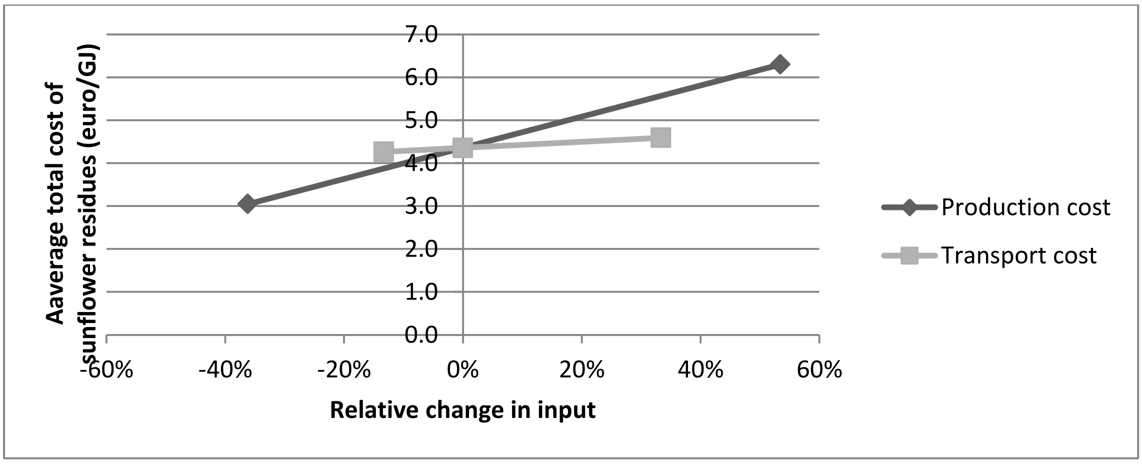
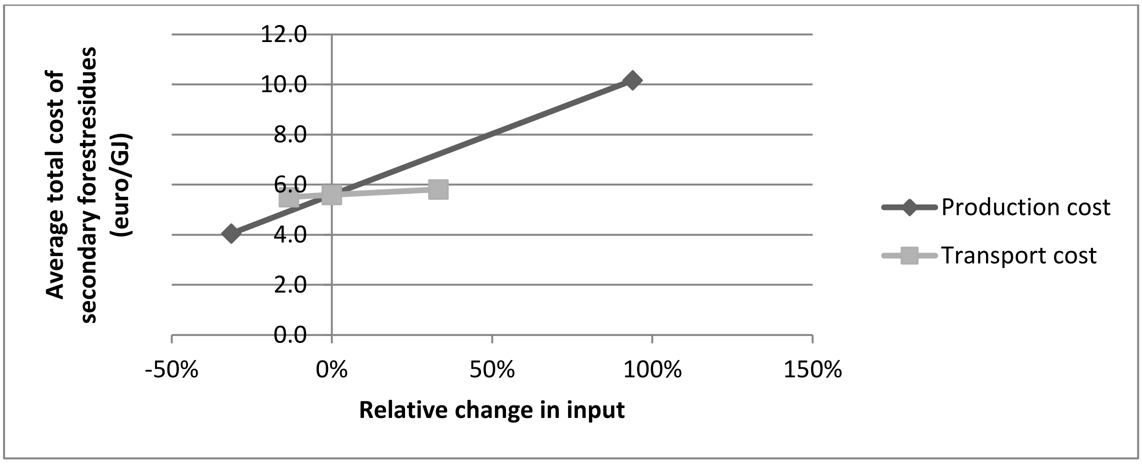


Figure 16 reveals that the production cost not only had a much wider range of uncertainty than transport cost, but also a much stronger influence on the average total costs. Figure 17 shows the sensitivity analysis for secondary forest residues.

Figure 17: Influence of variation in production and transport costs on total cost of secondary forest residues



Again the effect of production cost was stronger than the effect of transport cost. The difference is even larger for secondary forest residues, since the transportation cost form a smaller share of the total costs. This is caused by the higher production cost and the lower transport cost of forest residues. The latter is due to the higher density of wood pellets: since transport cost are per tonne, a higher density allows for a higher transport of energy for the same cost.

4.2. Limitations

The used research methods have some limitations, which could impact the outcomes of this research.

First of all, the selection of experts for interviews was rather arbitrary. While a large group of organisations was contacted with an interview request, only a relative small part reacted and agreed to an interview. Furthermore, since most of the times the organisation was contacted instead of a specific expert, there was almost no influence on the selection of the expert for the interview, because this was done by the organisation. These issues could mean some experts with a different view or more knowledge about the subject have been missed, which could have had a negative influence on the reliability of the results.

The possible negative consequences of this limitation have been reduced by interviewing multiple experts in the same field. For example, multiple pellets factories have been visited as well as multiple experts on the sustainable removal of agricultural residues. Despite these measures, the research might have benefited from a more structured approach to the selection of experts for interviews.

Secondly, the focus in the literature study was mainly on English literature, since the author did not understand the Ukrainian nor Russian language. Therefore national publications which might have contained relevant information have been overlooked.

The possible negative consequences of this limitation have been reduced by not depending on literature only, but interviewing local experts (with help of a translator). Secondly, the research included an internship at a research company in Kyiv. This way access to local and recent insights was retrieved.

4.3. Implications and recommendations

By determining the technical and sustainable potential, the sustainable surplus as well as the cost of biomass from agricultural and forest residues, this research contributes both to theory as well as practice. It fills a gap in the literature about which part of the technical potential in Ukraine is sustainable and which part of the technical potential is already in use. Besides, it has identified the costs of retrieving the technical potential. Thereby it contributes to a better understanding of this technical potential.

It has value to society for multiple reasons. First of all, the identification of the sustainable surplus of various agricultural and forests feedstocks give a better understanding about the potential of Ukraine as a source of biomass for the European Union. Secondly, the estimation of the transport and production costs gives valuable information to entrepreneurs about the possible profitability of importing biomass from Ukraine.

Based on the results, some recommendations regarding the best options for the export of biomass from Ukraine can be made. The most interesting method for transportation of pellets within Ukraine is transportation by train, because of the low costs as well as the experience and existing facilities available in Ukraine.

The most interesting feedstocks are wood from secondary forest residues, wheat residues and sunflower husk, because these feedstocks are abundantly available, are relatively easy to retrieve and there is significant experience in Ukraine with production of pellets from these sources.

The oblasts with the lowest transportation cost are the oblast that are close to one of the three transport hubs Odessa, Izmail and Uzhorod.

4.4. Recommendations for further research

Based on the outcomes of this research, interesting directions for further research can be identified.

First of all, the research revealed there is limited knowledge about the sustainable removal rate of primary agricultural residues. A more in-depth analysis of this issue, for example by analysing the soil quality or testing the effect of removing residues in practise, might provide more evidence on the actual impacts.

Secondly, there is also limited knowledge about the sustainable removal rate of primary forest residues in Ukraine. A more extended and detailed analysis following the criteria of the European Environmental Agency could give a more reliable and specific removal rate. Thereby it could lead to a better estimate of the sustainable potential of primary forest residues.

Thirdly, it became clear that there is very little information available on the current use of secondary forest residues in Ukraine. More research on this topics, for example by contacting many more wood processing factories, might lead to more data on the actual use and might shine a light on the potential for increasing the production of wood pellets in Ukraine.

5. Conclusion

The goal of this research was to answer the following research question:

What is the sustainable potential of biomass from agricultural and forest residues for export from Ukraine to the European Union?

This was done by answering the six sub-research questions described in the introduction:

The technical potential of biomass from primary agricultural residues amount to 865 petajoule and consists out of residues from the feedstocks barley, maize, rapeseed, sunflower and wheat. The main residues that is collected in Ukraine is straw from wheat, which has a technical potential of 296 petajoule. The main residue from the secondary agricultural residues is sunflower husk, which has a technical potential of 24 petajoule.

The technical potential of biomass from forest residues is 39.1 petajoule. The largest part consists out of primary forest residues, which has a technical potential of 22.6 petajoule. For secondary forest residues, the technical potential is 16.5 petajoule.

The main sustainability constraints for primary agricultural and forest residues are preventing erosion and maintaining soil organic matter, which limit the potential by requiring that 42% of the technical potential of agricultural residues is left in the field and 44% of the theoretical potential of forest residues is left in the forest

The domestic demand for residues from wheat consist mainly out of leaving the residues on the field, burning it on the field and use as bedding. The domestic demand for sunflower husk consist out of the current production of pellets and burning sunflower husk for the production of heat. The domestic demand for secondary forest residues consists mainly out of burning the residues to produce heat and the production of pellets and woodchips.

The sustainable surplus of biomass from agricultural and forest residues in Ukraine is equal to the sustainable potential minus the domestic demand. This amounts to between 80 and 172 petajoule for wheat residues, 16.5 petajoule for sunflower husk and 5.0 petajoule for secondary forest residues.

The cost of exporting the biomass depends on the oblasts in which the biomass is produced and on which transport hub on the border of Ukraine is chosen for export. For wheat, the average cost of production and transportation is 4.6 euro per gigajoule. For sunflower husk, the average cost is somewhat lower, with 4.4 euro per gigajoule. Biomass from secondary forest residues is more expensive, with an average cost of 5.6 euro per gigajoule.

Overall, it can be concluded that the sustainable potential of biomass from agricultural residues for export from Ukraine to the European Union is between 80 and 172 petajoule for wheat residues and 16.5 petajoule for sunflower husk. Regarding biomass from forest residues, the sustainable potential for export is 5.0 PJ for secondary forest residues.

6. References

Alakangas, E., 2010. New European Pellet Standards. In *European Pellet Conference*. Wels.

Andriyenko, V., 2013. Ukrainian market of solid biofuels. Structure, trends, prospects. In *Presentation at 9th International Conference on Biomass for Energy, 24-25 September 2013*. Kyiv, p. [in Russian].

Annamalai, K., Sweeten, J.M. & Ramalingam, S.C., 1987. Estimation of Gross Heating Values of Biomass Fuels. *Transactions of the ASAE*, 30(4), pp.1205–1208.

Baker & McKenzie, 2013. Green Energy in Ukraine - New Opportunities for High-Growth Investment. Available at: http://www.bakermckenzie.com/files/Publication/ad67e6c0-4f27-4fe0-8612-da5ebd556bd4/Presentation/PublicationAttachment/8b377baf-df40-48c6-a489-e40d03cd29d8/nl_kyiv_greenenergy_nov13.pdf.

Batidzirai, B., 2013. Design of sustainable biomass value chains.

Batidzirai, B., Smeets, E.M.W. & Faaij, A.P.C., 2012. Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments. *Renewable and Sustainable Energy Reviews*.

Bentsen, N.S. & Felby, C., 2012. Biomass for energy in the European Union - a review of bioenergy resource assessments. *Biotechnology for Biofuels*, 5(25).

Berndes, G., Hoogwijk, M. & Broek, R. van den, 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, 25(1).

Biomass Energy Centre, 2011. Typical calorific values of fuels. Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal&_schema=PORTAL.

BioTrade2020plus, 2015. Welcome to the BioTrade2020plus project website! Available at: http://www.biotrade2020plus.eu/.

Blok, K., 2007. *Introduction to Energy Analysis*, Amsterdam: Techne Press.

Burmistrova, S. & Zinets, N., 2014. Russia raises gas prices for Ukraine by 80 percent. *Reuters*. Available at: http://uk.reuters.com/article/2014/04/04/uk-ukraine-crisis-gas-idUKBREA330C520140404.

Carbo, M. et al., 2014. *New results of the SECTOR project: production of solid sustainable energy carriers from biomass by means of torrefaction*, Freiburg. Available at: https://sector-project.eu/fileadmin/downloads/presentations/SECTOR_presentation_Freiberg_Conference__ECN_.pdf.

Danish Ship Finance, 2012. Dry Bulk Vessels - Segments. Available at: http://www.shipfinance.dk/en/SHIPPING-RESEARCH/Toerlastskibe/Segmenter.

Demirbaş, A., 2002. Fuel Characteristics of Olive Husk and Walnut, Hazelnut, Sunflower, and Almond Shells. *Energy Sources*, 24(3), pp.215–221.

Dubrovin, V.O., 2013. Generalised method for the assessment of technically available energy potential of biomass. Available at: http://www.journal.esco.co.ua/industry/2013_11/art225.pdf.

EEA, 2007a. *Environmentally compatible bio-energy potential from European forests*, Copenhagen.

EEA, 2007b. *Estimating the environmentally compatible bioenergy potential from agriculture*, Copenhagen.

Elbersen, W. et al., 2013. *Pellets for Power: sustainable biomass from Ukraine*, Wageningen.

Ericsson, K. & Nilsson, L.J., 2006. Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass and Bioenergy*, 30, pp.1–15.

EUAS, 2015. A look at the EU-Ukraine Association Agreement. Available at: http://eeas.europa.eu/top_stories/2012/140912_ukraine_en.htm.

EUBIA, 2009. *Logistic management of wood pellets: Data collection on transportation, storage and delivery management*, Brussels. Available at: European Biomass Industry Association.

European Commission, 2013. New EU transport infrastructure policy – background. Available at: http://europa.eu/rapid/press-release_MEMO-13-897_en.htm.

FAOSTAT, 2013a. Food and Agricultural commodities production / Commodities by country. Available at: http://faostat3.fao.org/browse/rankings/commodities_by_country/E.

FAOSTAT, 2013b. Food and Agricultural commodities production / Countries by commodity. Available at: http://faostat3.fao.org/browse/rankings/countries_by_commodity/E.

FAOSTAT, 2013c. Forestry Ukraine. Available at: http://faostat3.fao.org/browse/F/*/E.

FAOSTAT, 2013d. Production / Live Animal. Available at: http://faostat3.fao.org/browse/Q/QA/E.

FNR, 2013. *Biomethane*, Gülzow.

Geletukha, G. et al., 2015. *Prospects for the development of bioneergy as an instrument for natural gas replacement in Ukraine*, Kyiv.

Geletukha, G., Kucheruk, P. & Matveev, Y., 2014. *Prospects of biomethane production and use in Ukraine*, Kyiv. Available at: http://www.uabio.org/img/files/docs/position-paper-uabio-11-en.pdf.

Geletukha, G., Kucheruk, P. & Matveev, Y., 2013. *The prospects of biogas production and use in Ukraine*, Kyiv. Available at: http://www.uabio.org/img/files/docs/position-paper-uabio-4-en.pdf.

Geletukha, G. & Zheliezna, T., 2014. *Prospects for the use of agricultural residues for energy production in Ukraine*, Kyiv.

Gielen, D., Saygin, D. & Wagner, N., 2015. *REmap 2030 Renewable Energy Prospects for Ukraine.*, Abu Dhabi. Available at: http://www.irena.org/remap/IRENA_REmap_Ukraine_paper_2015.pdf.

Golub, G., *Integrated use of Bioenergy Conversion Technologies in Agroecosystems*, Kyiv.

Haykiri-Acma, H. & Yaman, S., 2009. Effect of biomass on burnouts of Turkish lignites during co-firing. *Energy Conversion and Management*, 50, pp.2422–2427.

Van der Hilst, F., 2012. *Shades of green*. Universiteit Utrecht.

Hoogwijk, M. et al., 2003. Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, 25, pp.199–133.

Hudson, 2015. Vessel Info. Available at: http://hudsonshipping.com/?q=node/95.

IEA, 2015. Green Tariff (Feed-in Tariff). Available at: http://www.iea.org/policiesandmeasures/pams/ukraine/name-38470-en.php.

IEA, 2014. Law on promotion on biofuels. Available at: http://www.iea.org/policiesandmeasures/pams/ukraine/name-38609-en.php.

IEA Bioenergy Task 32, Biomass Databank. Available at: http://ieabcc.nl/database/biomass.php.

Jamblinne, P. de et al., 2013. *Market potential of Ukrainian herbaceous biomass: analyzing market obstacles and promoting business strategies*,

Koopmans, A. & Koppejan, J., 1997. *Agricultural and forest residues - Generation, utilization and availability*, Kuala Lumpur. Available at: http://www.fao.org/docrep/006/AD576E/ad576e00.pdf.

Kramar, V., 2015. *Costs for straw pellets production*,

Kuznetsova, A., 2012. *Pellet production in Ukraine: a profitable option for sustainable development?*, Kyiv. Available at: http://www.ier.com.ua/files/publications/Policy_papers/Agriculture_dialogue/2012/PP_37_Pellets_ENG_f.pdf.

Kuznetsova, A., 2010. *Straw use in Ukraine – opportunities and options*, Kyiv.

Lakyda, P. et al., 2010. *Biomass Energy Europe Illustration case for Ukraine*,

Lakyda, P. et al., 2013. Potentials of forest biomass for energetic use in Ukraine. *International Scientific Electronic Journal Earth Bioresources and Life Quality Founded by National University of Life and Environmental Sciences of Ukraine (NUBiP of Ukraine) and Global Consortium of Higher Education and Research for Agriculture (GCHERA)*, 3.

Lal, R., 2008. Crop residues as soil amendments and feedstock for bioethanol production. *Waste Management*, 28, pp.747–758.

Lal, R., 2009. Soil quality impacts of residue removal for bioethanol production. *Soil & Tillage Research*, 102, pp.233–241.

Mai-Moulin, T. et al., 2014. *General methodologies for the analysis and projection of sustainable biomass potentials of biomass in international sourcing regions and the potential surplus to import to the European Union*,

Mani, S., Tabil, L.G. & Sokhansanj, S., 2004. Grinding performance and physical properties of wheat and barley straws,corn stover and switchgrass. *Biomass and Bioenergy*, 27, pp.339–352.

Marshall, A.J. (Sandy), 2013. *Commercial Application of Pyrolysis Technology in Agriculture*, Guelph. Available at: http://www.ofa.on.ca/uploads/userfiles/files/pyrolysis report final.pdf.

McKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, 83(1), pp.73–46.

Ministry of Economic Development and Trade of Ukraine, Ukraine. Transportation (2007). Available at: http://www.ukrexport.gov.ua/eng/economy/ukr/162.html.

Mitra, P. & Atoyan, R., 2012. *Ukraine Gas Pricing Policy: Distributional Consequences of Tariff Increases*,

Muth, D.J. et al., 2012. Modelling sustainable agricultural residue removal at the subfield scale. *Agronomy Journal*, 104(4), pp.970–981.

NAAS, 2012. *Letter No. 5-2/256*, Kyiv.

Nelson, R. et al., 2004. Methodology for Estimating Removable Quantities of Agricultural Residues for Bioenergy and Bioproduct Use. *Applied Biochemistry and Biotechnology*.

Nordin, A., 1994. Chemical elemental characteristics of biomass fuels. *Biomass and Bioenergy*, 6(5), pp.339–347.

Ojala, L. et al., 2010. *Ukraine: Trade and Transit Facilitation Study*, Kyiv.

Poppens, R. et al., 2013. *Herbaceous biomass supply chains*, Wageningen.

Pöttering, H.-G. & Erlandsson, E., 2009. *Directive 2009/72/EC of the European Parliament and of the Counsil of 13 July 2009 concerning common rules for the internal market in electricity* , Strasbourg. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF.

Radio Free Europe, 2015. Ukraine Reports Intense Battles Near Mariupol. Available at: http://www.rferl.org/content/ukraine-intense-fighting-mariupol/27185775.html.

Raslavičius, L., Grzybek, A. & Dubrovin, V., 2011. Bioenergy in Ukraine—Possibilities of rural development and opportunities for local communities. *Energy Policy*, 39(6), pp.3370–3379.

Safar, Z., 2014. Biomass Pelletization Process. , pp.13–26. Available at: http://www.bioenergyconsult.com/biomass-pelletization/.

Scarlat, N., Martinov, M. & Dallemand, J.-F., 2010. Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Management*, 30, pp.1889–1897.

SEC Biomass, 2013. About company. Available at: http://biomass.kiev.ua/en/.

SEC Biomass, 2015. *Biomass availability and logistics analysis in Ukraine*, Kyiv.

Sheng, C. & Azevedo, J.L.T., 2005. Estimating the higher heating value of biomass fuels from basic analysis data. *Biomass and Bioenergy*, 28, pp.499–507.

Sif-Service, 2015a. Izmail sea port. Available at: http://www.sifservice.com/index.php/en/directory/ports-ukraine/sea-ports/item/139-izmail-sea-port.

Sif-Service, 2015b. Sea Ports of Ukraine. Available at: http://www.sifservice.com/index.php/en/directory/ports-ukraine/sea-ports.

Smeets, E.M.W. & Faaij, A.P.C., 2010. The impact of sustainability criteria on the costs and potentials of bioenergy production – Applied for case studies in Brazil and Ukraine. *Biomass and Bioenergy*, 34, pp.319–333.

State Agency for Energy Efficiency and Energy Saving of Ukraine, 2013. *National Renewable Energy Action Plan (NREAP) through 2020*, Available at: http://saee.gov.ua/documents/NpdVE_eng.pdf.

Statista, 2015. Amount of freight transported by inland waterway in Ukraine from 2006 to 2012 (in million tonne-kilometres). Available at: http://www.statista.com/statistics/435638/ukraine-tonne-kilometres-of-freight-transported-by-inland-waterway/.

Sultana, A. & Kumar, A., 2014. Development of tortuosity factor for assessment of lignocellulosic biomass delivery cost to a biorefinery. *Applied Energy*, 119, pp.288–295.

Tebodin, 2013. *Bioenergy & Biobased Opportunities in Ukraine*,

Ukrainian Biofuel Portal, 2015. Export of sunflower husk pellets 2014-2015. , p.[in Russian]. Available at: http://pelleta.com.ua/base-baza-ukrainskix-kompanij-eksporterov-pellet-iz-luz-84.html?utm_source=August_2015_husk_pellet_export&utm_medium=email&utm_campaign=%D0%90%D0%B2%D0%B3%D1%83%D1%81%D1%82+2015+-.

Verma, V.K. et al., 2012. Agro-pellets for domestic heating boilers: Standard laboratory and real life performance. *Applied Energy*, 90, pp.17–23.

Vis, M.W. & Berg, D. van den, 2010. *Best Practices and Methods Handbook*,

Vlasenko, N.S., 2014. *Agriculture of Ukraine Statistical Yearbook*, Kyiv.

Wilhelm, W.W. et al., 2007. Corn Stover to Sustain Soil Organic Carbon Further Constrains Biomass Supply. *Agronomy Journal*, 99(6), pp.1665–1667.

Wilhelm, W.W. et al., 2004. *Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review*, Lincoln, Nebraska.

World Bank, 2015. Inflation, GDP deflator (annual %). Available at: http://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG/countries/UA?display=graph.

World Port Source, 2015. Ukraine Satellite Map of Ports. Available at: http://www.worldportsource.com/ports/UKR.php.

XE, 2015. UAH per 1 EUR. Available at: http://www.xe.com/currencycharts/?from=EUR&to=UAH&view=5Y.

Yagi, K. & Nakata, T., 2011. Economic analysis on small-scale forest biomass gasification considering geographical resources distribution and technical characteristics. *Biomass and Bioenergy*, 35, pp.2883–2892.

Zheliezna, T., *Assessment of sustainable lignocellulosic feedstock potentials in the Ukraine and perspective conversion pathways, including recommendations for the strengthening of the biomass market*, Kyiv.

Appendix A: Calculation of Lower Heating Value

To determine the LHV of various primary agricultural residues, the HHVs from Nordin (1994) and IEA Bioenergy Task 32 (n.d.) were calculated to LHV, using the formula from Blok (2007) which was given in the methodology section. The used moisture content is given in Table 7 and the hydrogen content in the table below.

	Nordin (1994)		IEA Bioenergy Task 32 (n.d.)	
Feedstock	**HHV (MJ/kg):**	**H-content:**	**HHV (MJ/kg):**	**H-content:**
Barley	18.6	0.057	18.5	0.055
Maize	N/A	N/A	18	0.054
Rapeseed	18.2	0.057	22	0.069
Sunflower	N/A	N/A	18.1	0.05
Sunflower husk	N/A	N/A	20.8	0.066
Wheat	18.9	0.058	17.1	0.053

To determine the LHV of sunflower husk, the HHV from IEA Bioenergy Task 32 (n.d.), Demirbaş (2002) and Haykiri-Acma & Yaman (2009) were used. The formula of Blok (2007) as well as the moisture content is shown in the methodology. The hydrogen content is shown in the table below.

Source:	**HHV (MJ/kg):**	**H-content:**
Demirbaş (2002)	18.0	0.058
Haykiri-Acma & Yaman (2009)	17.6	0.062
IEA Bioenergy Task 32 (n.d.)	20.8	0.066

Appendix B: Technical potential of primary agricultural residues per oblast

Region	Barley (kt)	Maize (kt)	Rapeseed (kt)	Sunflower (kt)	Wheat (kt)	Barley (TJ)	Maize (TJ)	Rapeseed (TJ)	Sunflower (TJ)	Wheat (TJ)
Autonomous Republic of Crimea	167	114	30	208	351	2278	863	422	1192	4663
Vinnytsya	378	3621	442	964	1521	5151	27439	6319	5535	20196
Volyn	74	227	138	3	476	1009	1722	1981	20	6320
Dnipropetrovsk	449	1710	291	2228	1769	6122	12958	4158	12792	23497
Donetsk	320	466	26	1479	1387	4357	3529	366	8488	18414
Zhytomyr	63	2037	116	198	327	857	15436	1662	1135	4336
Zakarpattya	9	244	3	18	115	124	1850	44	106	1522
Zaporizhya	316	226	129	1750	1481	4310	1716	1847	10049	19663
Ivano-Frankivsk	60	453	116	38	219	821	3434	1664	218	2907
Kyiv	206	2824	208	564	827	2805	21398	2970	3241	10984
Kirovohrad	363	2799	227	2335	1115	4948	21210	3246	13407	14807
Luhansk	105	449	3	1215	706	1437	3403	49	6975	9369
Lviv	107	511	277	35	588	1453	3872	3959	202	7802
Mykolayiv	603	954	175	1786	1208	8215	7225	2504	10252	16039
Odesa	873	1048	353	1477	1634	11894	7942	5049	8477	21703
Poltava	263	5306	87	1386	1151	3578	40201	1252	7957	15278
Rivne	115	669	116	8	344	1569	5070	1654	45	4566
Sumy	137	3136	126	796	865	1867	23762	1803	4569	11480
Ternopil	227	1568	281	57	693	3090	11883	4024	326	9198
Kharkiv	357	2086	57	2124	2027	4860	15807	811	12193	26915
Kherson	263	489	180	678	875	3583	3702	2571	3893	11621
Khmelnytskiy	250	2373	320	146	828	3407	17978	4575	841	11001
Cherkasy	238	3462	316	926	1063	3242	26228	4526	5314	14118
Chernivtsi	39	529	54	32	164	530	4010	770	183	2178
Chernihiv	67	2932	165	544	548	915	22217	2354	3124	7280
Sevastopol	1	0	0	0	0	8	0	0	0	5

Appendix C: Technical potential of sunflower husk per oblast

Oblast:	Technical potential (kt):	Technical potential (TJ):
Autonomous Republic of Crimea	16	241
Vinnytsya	75	1118
Volyn	0	4
Dnipropetrovsk	173	2584
Donetsk	115	1714
Zhytomyr	15	229
Zakarpattya	1	21
Zaporizhya	136	2030
Ivano-Frankivsk	3	44
Kyiv	44	655
Kirovohrad	181	2708
Luhansk	94	1409
Lviv	3	41
Mykolayiv	139	2071
Odesa	115	1712
Poltava	108	1607
Rivne	1	9
Sumy	62	923
Ternopil	4	66
Kharkiv	165	2463
Kherson	53	786
Khmelnytskiy	11	170
Cherkasy	72	1073
Chernivtsi	2	37
Chernihiv	42	631
Sevastopol	0	0

Appendix D: Technical potential of forest residues per oblast

Oblast:	Primary residues (kt):	Primary residues (TJ):	Secondary residues (kt):	Secondary residues (TJ):
Autonomous Republic of Crimea	12	185	8	135
Vinnytsya	50	800	33	583
Volyn	62	991	40	722
Dnipropetrovsk	10	163	7	119
Donetsk	10	165	7	120
Zhytomyr	189	3036	123	2213
Zakarpattya	143	2297	93	1674
Zaporizhya	5	79	3	57
Ivano-Frankivsk	82	1311	53	956
Kyiv	108	1738	71	1267
Kirovohrad	18	292	12	213
Luhansk	30	478	19	348
Lviv	110	1763	72	1285
Mykolayiv	7	112	5	81
Odesa	20	315	13	230
Poltava	27	437	18	319
Rivne	69	1115	45	813
Sumy	76	1227	50	895
Ternopil	25	399	16	291
Kharkiv	59	948	39	691
Kherson	33	528	21	385
Khmelnytskiy	49	785	32	572
Cherkasy	48	770	31	561
Chernivtsi	75	1207	49	880
Chernihiv	93	1494	61	1089
Sevastopol	0	0	0	0

Appendix E: Sustainable potential of wheat residues per oblast

Oblast:	Sustainable removal rate (%):	Sustainable potential (kt):	Sustainable potential (TJ):
Autonomous Republic of Crimea	0	0	0
Vinnytsya	57	865	11490
Volyn	36	169	2250
Dnipropetrovsk	94	1656	21991
Donetsk	100	1387	18414
Zhytomyr	82	269	3577
Zakarpattya	0	0	0
Zaporizhya	0	0	2
Ivano-Frankivsk	0	0	0
Kyiv	83	683	9067
Kirovohrad	100	1115	14807
Luhansk	100	706	9369
Lviv	0	0	1
Mykolayiv	26	314	4165
Odesa	0	0	2
Poltava	100	1151	15278
Rivne	2	8	109
Sumy	100	865	11480
Ternopil	13	92	1223
Kharkiv	100	2027	26915
Kherson	0	0	1
Khmelnytskiy	78	648	8605
Cherkasy	100	1063	14118
Chernivtsi	0	0	0
Chernihiv	66	362	4807
Sevastopol	0	0	0

Appendix F: Sustainable potential of primary forest residues per oblast

Oblast:	Sustainable potential (kt):	Sustainable potential (TJ):
Autonomous Republic of Crimea	14	220
Vinnytsya	33	533
Volyn	69	1105
Dnipropetrovsk	8	121
Donetsk	8	125
Zhytomyr	118	1894
Zakarpattya	93	1486
Zaporizhya	2	29
Ivano-Frankivsk	76	1214
Kyiv	58	938
Kirovohrad	10	152
Luhansk	20	323
Lviv	85	1370
Mykolayiv	3	54
Odesa	11	174
Poltava	20	316
Rivne	85	1365
Sumy	52	841
Ternopil	21	343
Kharkiv	39	630
Kherson	9	148
Khmelnytskiy	31	503
Cherkasy	32	513
Chernivtsi	36	569
Chernihiv	75	1210
Sevastopol	0	0

Appendix G: Sustainable surplus per oblast

Oblast:	Wheat residues (Average, TJ):	Sunflower husk (TJ):	Secondary forest residues (TJ):
Autonomous Republic of Crimea	0	175	41
Vinnytsya	8744	811	176
Volyn	1391	3	217
Dnipropetrovsk	18795	1875	36
Donetsk	15909	1244	36
Zhytomyr	2987	166	666
Zakarpattya	0	16	504
Zaporizhya	0	1473	17
Ivano-Frankivsk	0	32	288
Kyiv	7573	475	381
Kirovohrad	12793	1965	64
Luhansk	8095	1022	105
Lviv	0	30	387
Mykolayiv	1984	1502	25
Odesa	0	1242	69
Poltava	13200	1166	96
Rivne	0	7	245
Sumy	9919	670	269
Ternopil	0	48	88
Kharkiv	23255	1787	208
Kherson	0	570	116
Khmelnytskiy	7109	123	172
Cherkasy	12198	779	169
Chernivtsi	0	27	265
Chernihiv	3817	458	328
Sevastopol	0	0	0

Appendix H: Distance to transport hubs per oblast

Oblast:	Distance to Odess (kilometre):	Distance to Uzhorod (kilometre):	Distance to Izmail (kilometre):
Autonomous Republic of Crimea	478	1,353	755
Vinnytsya	411	614	611
Volyn	895	457	1,097
Dnipropetrovsk	480	1,210	748
Donetsk	725	990	1,486
Zhytomyr	649	655	858
Zakarpattya	876	98	715
Zaporizhya	511	1,325	784
Ivano-Frankivsk	743	220	941
Kyiv	561	810	787
Kirovohrad	317	944	572
Luhansk	888	1,156	1,601
Lviv	841	224	1,036
Mykolayiv	463	940	436
Odesa	79	961	268
Poltava	560	1,105	818
Rivne	792	525	991
Sumy	752	1,168	1,006
Ternopil	675	338	873
Kharkiv	725	1,358	991
Kherson	306	1,163	574
Khmelnytskiy	582	459	783
Cherkasy	411	870	649
Chernivtsi	620	356	821
Chernihiv	727	993	965
Sevastopol	612	1,465	879

Appendix I: Transport costs to transport hubs per oblast

Oblast:	Cost to Odessa (euro/tonne):	Cost to Uzhorod (euro/tonne):	Cost to Izmail (euro/tonne):
Autonomous Republic of Crimea	7.17	20.30	11.33
Vinnytsya	6.16	9.21	9.17
Volyn	13.42	6.85	16.45
Dnipropetrovsk	7.21	18.16	11.23
Donetsk	10.87	14.85	22.29
Zhytomyr	9.74	9.82	12.87
Zakarpattya	13.15	4.20	10.73
Zaporizhya	7.66	19.88	11.76
Ivano-Frankivsk	11.15	9.48	14.12
Kyiv	8.42	12.16	11.80
Kirovohrad	4.75	14.16	8.57
Luhansk	13.33	17.34	24.02
Lviv	12.61	9.65	15.54
Mykolayiv	6.95	14.10	6.53
Odesa	3.41	14.41	11.52
Poltava	8.40	16.57	12.28
Rivne	11.88	7.88	14.87
Sumy	11.29	17.52	15.09
Ternopil	10.12	5.07	13.09
Kharkiv	10.87	20.37	14.87
Kherson	4.59	17.44	8.61
Khmelnytskiy	8.73	6.89	11.74
Cherkasy	6.16	13.05	9.74
Chernivtsi	9.31	5.35	12.32
Chernihiv	10.91	14.89	14.47
Sevastopol	9.19	21.98	13.19