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

S2Biom Project Grant Agreement n°608622

Case study on supplying large scale Biofuel production plants in North-East Germany and North West Poland with lignocellulosic feedstock from the region

June 2016

About S2Biom project

The S2Biom project - Delivery of sustainable supply of non-food biomass to support a "resource-efficient" Bioeconomy in Europe - supports the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, and roadmaps that will be informed by a "computerized and easy to use" toolset (and respective databases) with updated harmonized datasets at local, regional, national and pan European level for EU28, Western Balkans, Moldova, Turkey and Ukraine. Further information about the project and the partners involved are available under www.s2biom.eu.

Project coordinator

Scientific coordinator

Project partners

About this document

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Executive summary

The S2Biom[1] project investigates sustainable feedstock supply for bioenergy and bio based products throughout the European Union, their Eastern Neighbors as well as the South Eastern Balkan States.

The results obtained in a case study aiming at throughout investigation of the value chain of synthetic Biofuel production from wood and agricultural residues in Northern Germany and Eastern Poland will be presented. The biomass potential of the regions has been determined and the data are used to feed a value chain model developed earlier within a previous EU project[2]. The study focuses on regionally split production pathways with regional rather small to medium scale pretreatment plant producing an intermediate energy carrier which can be easily transported to new or existing facilities for upgrading to transportation fuel. This approach is studied on economic and logistic, properties, including fuel production cost and distribution of added value.

The optimization model will provide information on capacity and location of new built plants for pretreatment and conversion, takes into account existing refinery capacity and models fuel amount and cost. Conclusion will be drawn on the feasibility of biofuel production in the studied regions.

[1] S2Biom GA 608622 www.s2Biom.eu
[2] BioBoost GA 282873, www.bioboost.eu

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Strategic Case Studies
Terms of Reference

Work Package	**WP9**
Task	**T9.3.1/2**
Deliverable N.	**D9.6**
Author	**Magdalena Borzecka-Walker, Simon Kühner, Rafal Pudelko, Klaus Lenz**
Date	**1.10.2015 duration 9 Months**
Status	**finished**

These Terms of Reference provide a short description of the methodology, scope and expected results of each Advanced/ Strategic Case Study implemented in the framework of S2BIOM, Tasks 9.3.1 & 9.3.2, and are thus an integral part of the Deliverable D9.6 “Compilation of all reports on the performance and outcome of each SCS”.

OVERVIEW

Title of the Study	Case study of Supplying large scale Biofuel production plants in North-East Germany and North West Poland with lignocellulosic feedstock from the region
Topic	Biofuel production
Geographical Area	North-East Germany and North-West Poland
Country or Region	Germany and Poland

Scope	• Determine the ligno-cellulosic feedstock potentials available in the study area for sustainable biofuel production.
	• Investigate optimal capacities and locations of decentral and central plants for two production pathways.
	• Determine costs of production of transportation fuels in North-East Germany and North West Poland depending on the amount of wood residues and straw used.
	  • Investigate two production pathways:
	    ○ Decentral catalytic pyrolysis of wood chips and upgrading of (CP) oil in existing refineries to synthetic biofuel
	    ○ Decentral fast pyrolysis (FP) of straw and erection of new gasification and synthesis capacities for synthetic biofuel
	• Investigate the establishment of new refinery capacities and compare it with the use of existing refinery capacities in the region and possibly outside the region.

Implemented by:	SYNCOM, IUNG
Other participants:	
Stakeholders:	Refineries, fuel producers, feedstock suppliers, local and regional governments
Relation to other projects:	Modelling tool developed in BioBoost (282873)
Description:	The project addresses the complete value chain from feedstock potential, the investigation of fast pyrolysis and catalytic pyrolysis conversion technologies, the optimisation of transport and logistics to the exploitation of the energy carrier. The techno/economic assessment includes the complete supply chain.
Relation to Theme:	3
Relation to WP:	9
Tool Validation:	Biomass supply, comparison of supply data, effects on fuel production

DESCRIPTION OF THE STUDY

Outline

Value chain

The S2Biom project investigates sustainable feedstock supply for bioenergy and bio based products throughout the European Unions, their Eastern Neighbours as well as the South Eastern Balkan States.

Within the project a number of advanced case studies are prepared to demonstrate relevance of the conducted research activities.

The value chains considered in this study aim at the thermochemical production of drop-in synthetic biofuels from wood chips and straw via catalytic and fast pyrolysis pretreatment. The process chains are split or staged chains, meaning that first an intermediate bioenergy carrier is produced in a region which is then transported to an existing or new built facility for fuel production. The study focuses on regionally split production pathways with a regional rather small to medium scale pretreatment plant producing an intermediate energy carrier which can be easily transported to new or existing fuel production facilities. This approach generally referred to as the decentral vs a central approach is studied on economic and logistic properties, including fuel production cost and added value wealth. The geographic scope will be North-East Germany and North-West Poland. The geographic resolution will be on NUTS 3 level. The chains considered are:

- *Catalytic pyrolysis (CP) of forestry residues produces a pyrolysis oil with low oxygen content which is transported to a refinery for integrated production of transportation fuels.*
- *Fast pyrolysis (FP) of straw yields a biosyncrude transported for gasification followed by chemical synthesis to transportation fuel.*

This Case study is performed by the INSTYTUT UPRAWY NAWOZENIA I GLEBOZNAWSTWA (IUNG) at Pulawy in Poland and the consultancy SYNCOM Forschungs- und Entwicklungsberatung GmbH in Ganderkesee, Germany.

IUNG determines the biomass potential of the regions in the study area. The data are used by SYNCOM to feed a value chain model developed by the Fachhochschule Oberösterreich within a previous EU project[3]. The optimization model will provide information on capacity and location of new built plants for pretreatment and conversion, takes into account existing refinery capacity and models fuel amount and cost. The feasibility of biofuel production is investigated.

[3] BioBoost GA 282873

	Agricultural biomass	*Forest biomass*	*Cropped biomass*	*Wastes*
Heat[4] *(D, C, Ind, DH)*	*n/a*	*n/a*	*n/a*	*n/a*
Electricity (CHP)	*n/a*	*n/a*	*n/a*	*n/a*
Advanced Biofuels	*Straw*	*Forestry residues*	*n/a*	*n/a*

n/a: not applicable

Objectives

- *Determine the feedstock potentials of straw and forestry residues available locally for sustainable biofuel production*
- *Determine costs and amount of production of transportation fuels via CP and FP in NE Germany and NW Poland.*
- *Investigate capacities and location of decentral pyrolysis plants for CP and FP pathways.*
- *Investigate the repowering of refineries (e.g. steam methane reformer for hydrogen production in existing refineries for fossil crude to further increase the CP-oil upgrading capacity and compare it with the use of existing refinery capacities in the region and outside the region*

[4] D: Domestic; Commercial; Ind: Industry; DH: District Heating

1. Geographic coverage: North-East Germany and North-West Poland

The area of interest for the case study on large-scale fuel production covers north-eastern Germany and north-western Poland. The area includes four large crude oil refineries located in Gdansk (PL), Plock (PL), Schwedt (DE) and Leuna (DE). The area and the refineries are highlighted in the figure below and its entities are listed in the table below.

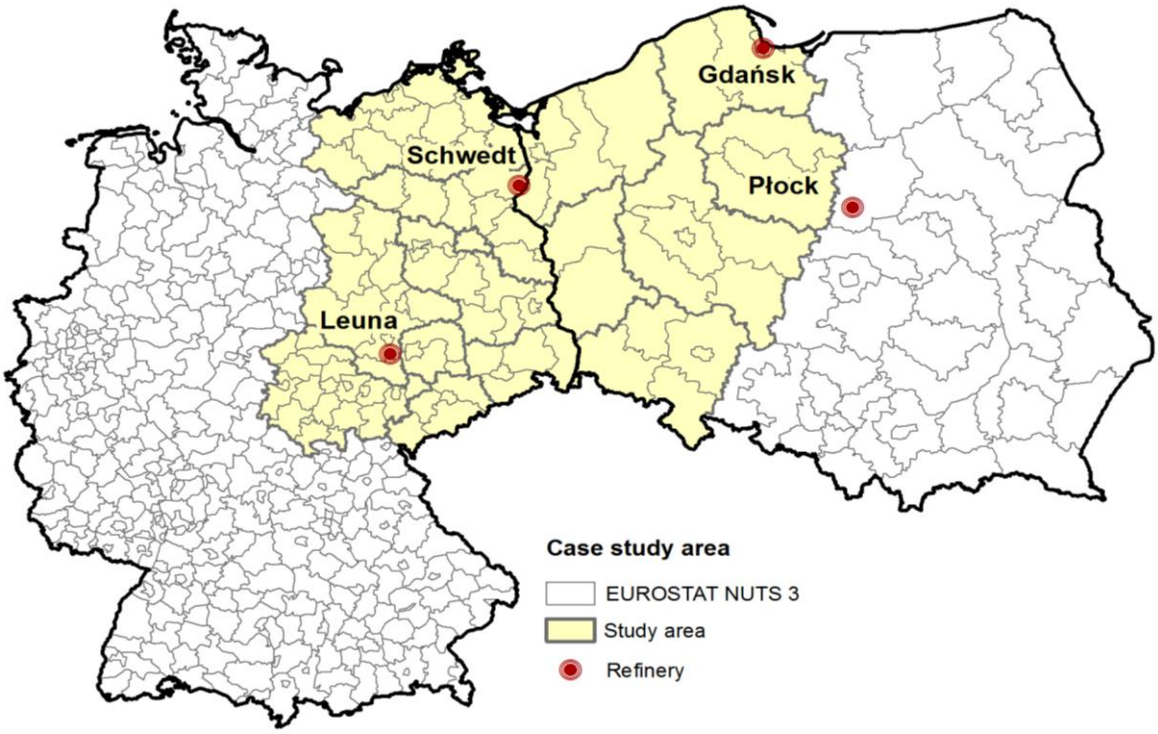


Figure 1 Location of the case study area (highlighted) in Germany and Poland. Large NUTS 3 regions were split up to areas of less than 7500 km² (thin straight lines) to increase the performance of the optimisation model. Locations of refineries relevant for the study area are indicated by red dots.

Table 1: Name and NUTS of the entities in the study area. Plock was added due to its importance for the study area.

Name	NUTS	Name	NUTS
Sachsen	DED	Wielkopolskie	PL41
Sachsen-Anhalt	DEE	Zachodniopomorskie	PL42
Thüringen	DEG	Lubuskie	PL43
Berlin	DE3	Dolnośląskie	PL51
Brandenburg	DE4	Kujawsko-Pomorskie	PL61
Mecklenburg-Vorpommern	DE8	Pomorskie	PL63

2. Determination of feedstock potential

The analysis of feedstock potential is based on the work done in BioBoost project as potentials from S2Biom were not available. Estimates were made for spatial unit's NUTS-3, which are small regions with geocode standard for referencing the subdivisions of countries for statistical purposes. Estimates were made for the following types of biomass:

- *agricultural (straw, orchard's pruning, hay) and animal residues (manure surplus),*
- *forestry residues,*
- *natural conservation matter (management of urban green areas, hay and shrubs),*
- *roadside vegetation,*
- *urban and industrial waste (biodegradable municipal waste, selected waste from the food, and wood industry).*

2.1. Feedstock potentials in Case study area

The case study focuses on straw residues and forestry residues. The analysis was done for the area of North-East Germany and North-West Poland. The case study covers an area of 231,164 km^2 with an utilised agricultural area of 114,614 km^2. From the 93,877 km^2 arable land, cereals are cultivated on 58,691 km^2. The total agricultural area has slightly decreased in 2013 compared to data from 2005. In Germany the agricultural area has decreased by 0.9%, while in Poland an increase of 1% was noticed. These bigger changes on the Polish part of case study area are linked to transformations due to the introduction of new instruments of the Common Agricultural Policy (CAP). This is in agreement to similar experiences made earlier in the old Member States, where introduction of the CAP instruments let to profound land use changes, too.

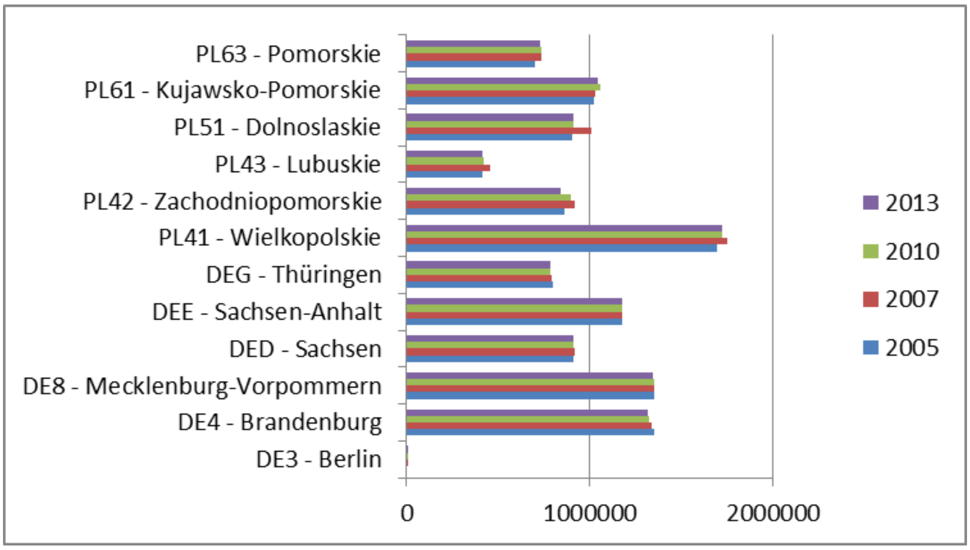


Figure 2. Utilised agricultural area (sources: Eurostat)

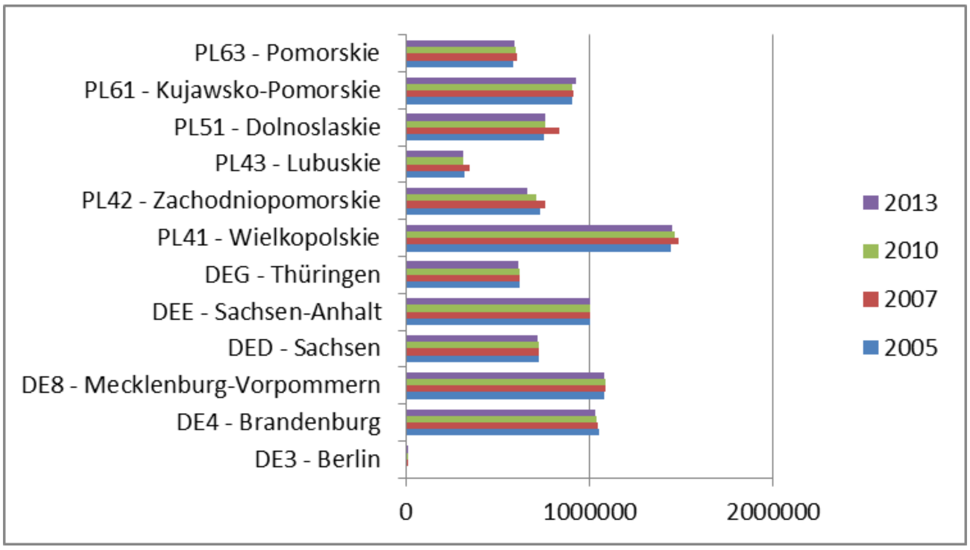


Figure 3. Arable land (sources: Eurostat)

The farm structure in the case study area varies between the countries and the regions. In Eastern Germany most farms are over 100 hectare while in Poland there is a very wide variation (Figure 4). In Zachodniopomorskie 54% of farms are bigger than 100 ha, while in Wielkopolskie 41 % of farms is smaller than 20 ha.

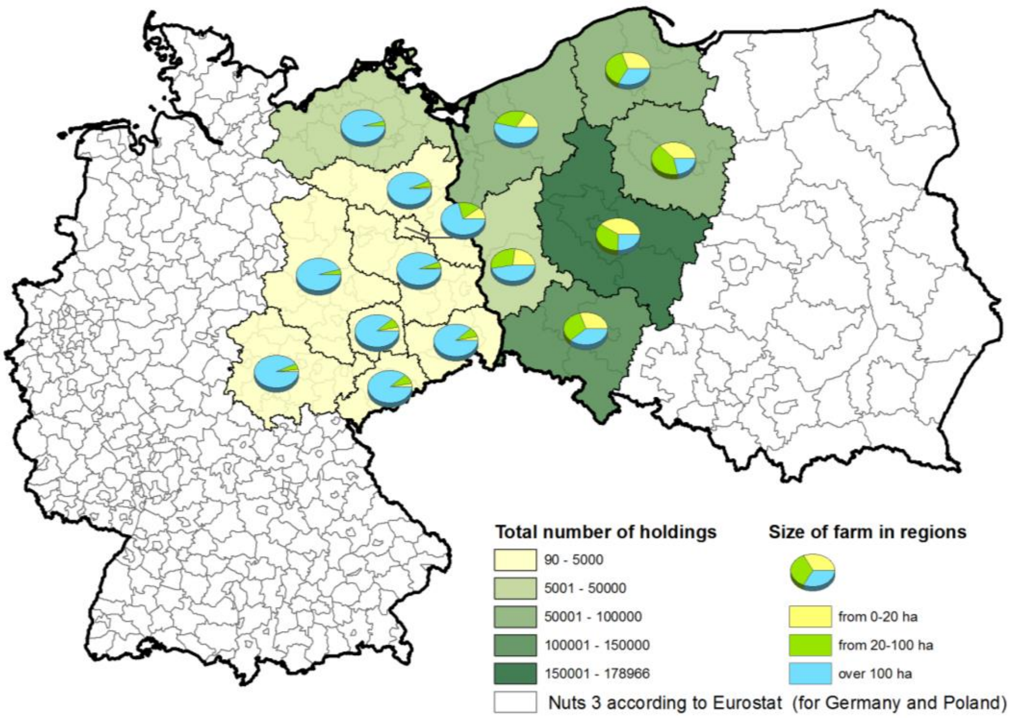


Figure 4 Farm structure (sources: Eurostat)

3. Feedstock types

3.1. Straw

Straw is one of the most common agricultural residues which can be used for energy purposes. Collection of straw depends on the cereal type and weather pattern. Cereals are typically harvested when the grain dried to the desired moisture content. Straw should not be baled until it has dried to at least 15% water content, which is sufficient for baling and storage. The straw is stored by the farmers or suppliers in field side stacks or under roof and transported continuously to the plant (here: FP). Typically, the conversion plants have storage capacity for only a few days.

From 2005-2013 the cereals production remained at a similar level in the German part of the study area, while a 10% decrease was noted in Poland (Figure 5). The most important decrease by 28% was recorded in Zachodniopomorskie. Wielkopolskie has with about 1 million ha the highest cereal production area.

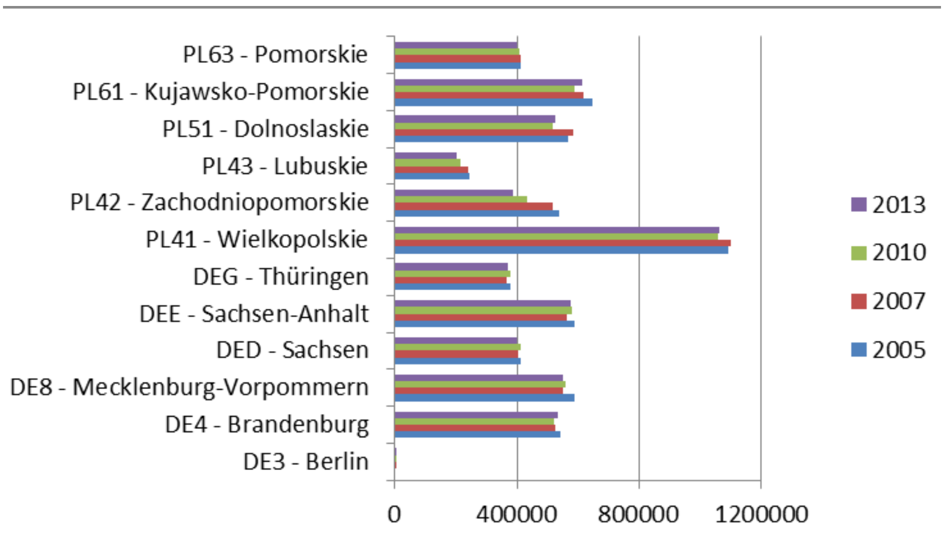


Figure 5. Development of cereals production area given in hectare [ha] in the study area regions (sources: Eurostat)

The total availability of straw (**theoretical potential**) was estimated on the basis of statistical data on cereals production (Eurostat) and the ratio between the yield of grain and straw[5]. But as food production shall not be impacted by energetic use of straw, the **technical potential** of straw available for energy is much lower. Main uses of straw in agriculture are:

- Soil incorporation to increase the reproduction of organic matter

[5] Tum M., Gunther K.P.: Validating modelled NPP using statistical yield data. Biomass and Bioenergy, 2011, **35**: 4665-4674.

- Animal feed and bedding
- Mulch covering of soil as crop protection against weeds (e.g. in strawberries) or frost (e.g. vegetables, flower bulbs)

The amount of straw for animal production depends on the abundance and share of production systems in the regions. The use of surplus straw for energy generation, construction or fibre may lead to some competition with agricultural use but initially application of more effective equipment is expected to reduce the straw costs. Further details on the methodology of straw potential calculation can be found in Deliverable 1.2 The feedstock potential assessment for EU--27 + Switzerland in NUTS--3 http://bioboost.eu/results/public_results.php

The following part explains the relation of theoretic potential competing applications and the technically available, sustainable straw potential, the amounts of which are given in table 2.

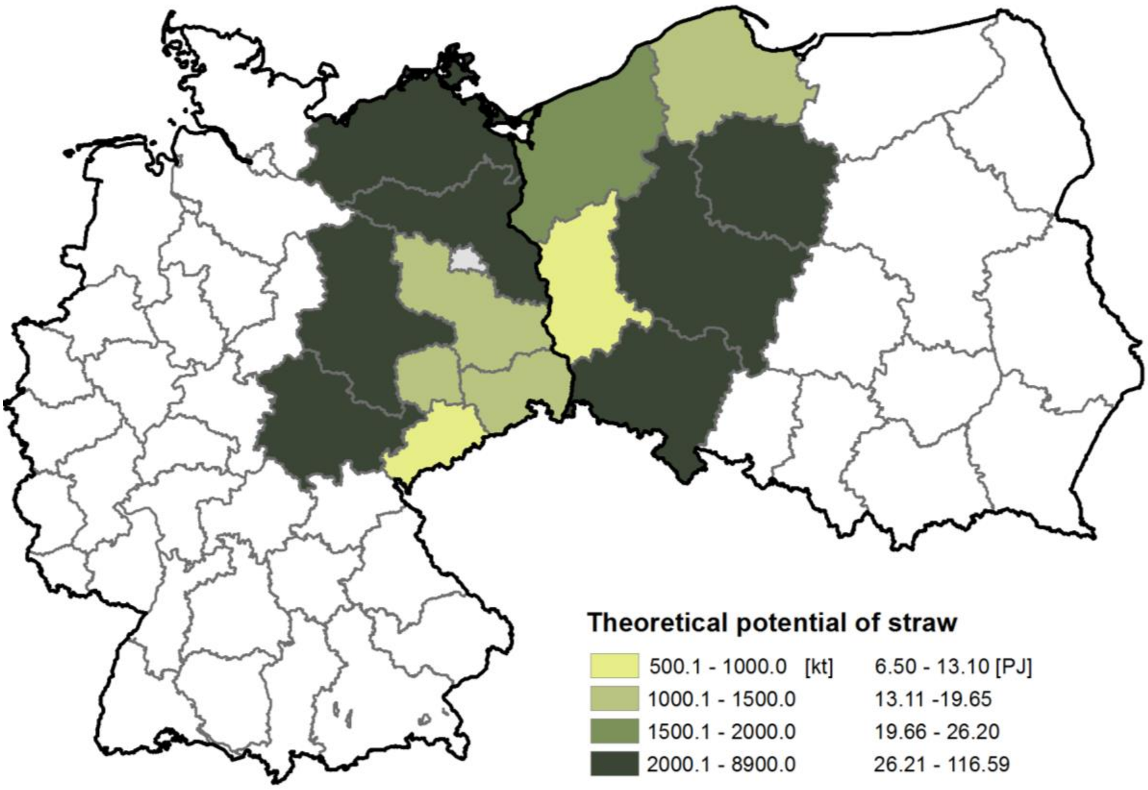


Figure 6. Theoretical potential of straw.

The relative share of the different cereal straws available in the area is presented in Figure 7. For the calculation of straw potential, the demand for animal rearing is very important (Figure 8).

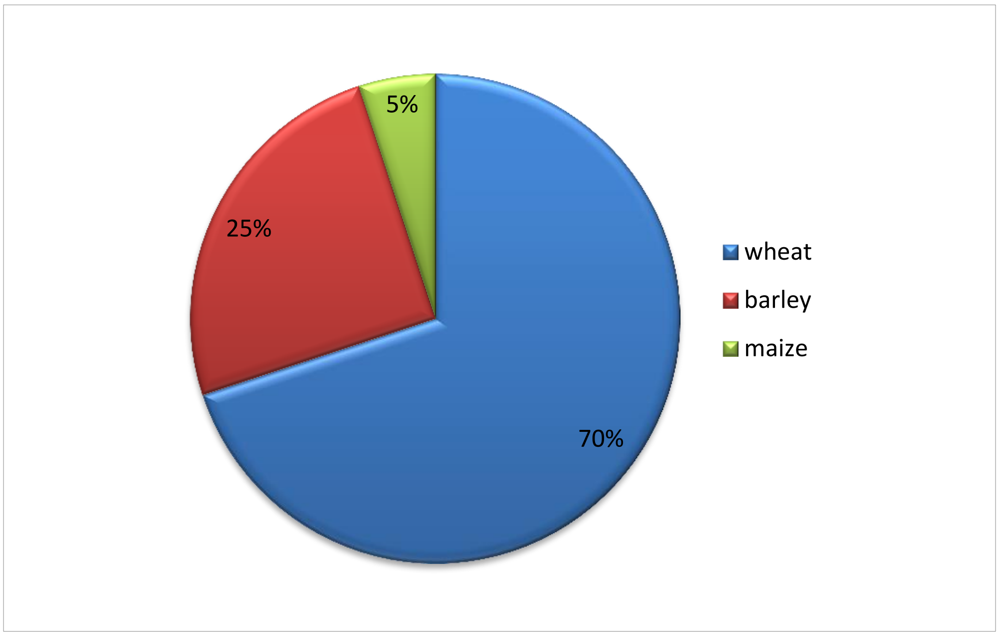


Figure 7: Share of each type of cereal on the sustainably available straw

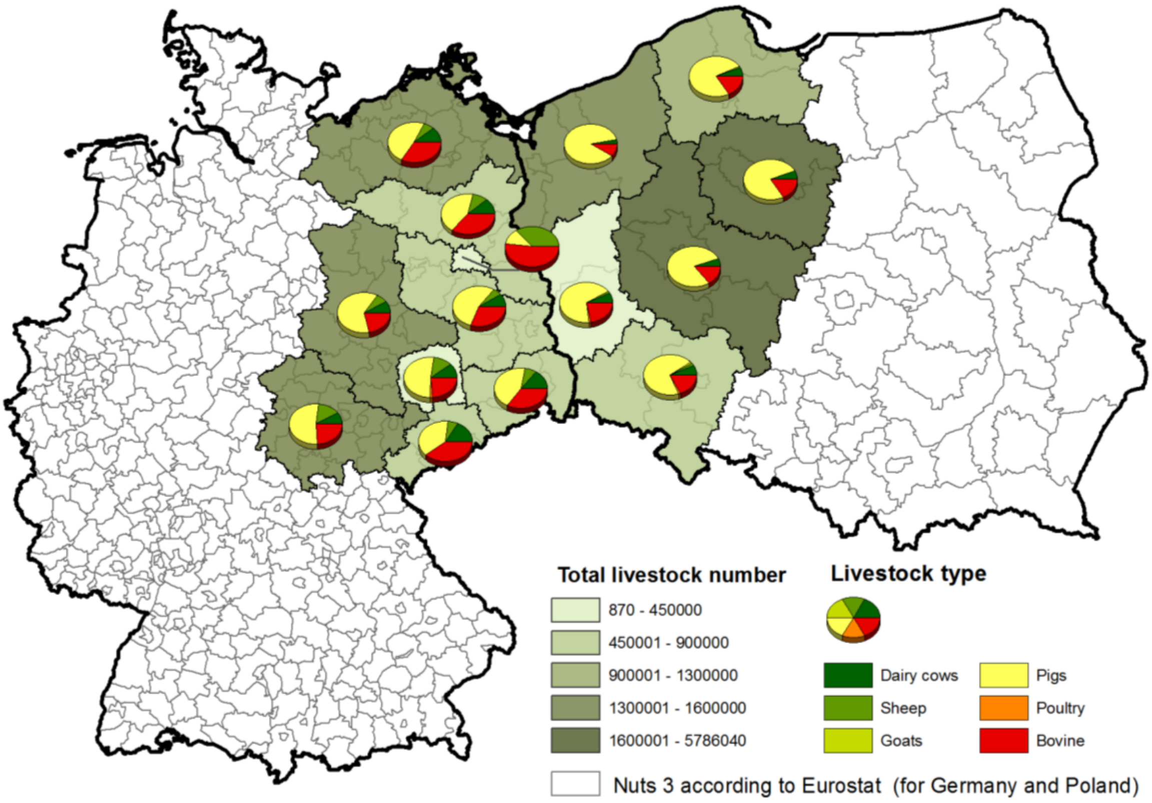


Figure 8. Livestock in case study area

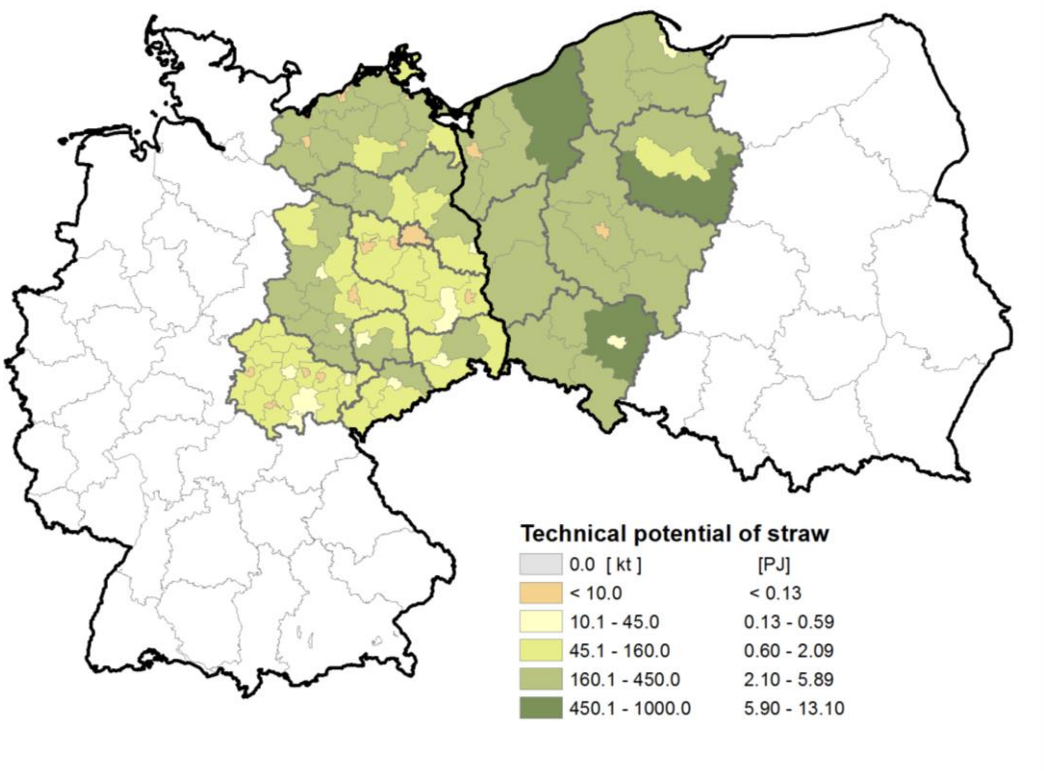


Figure 9. Technical potential of straw.

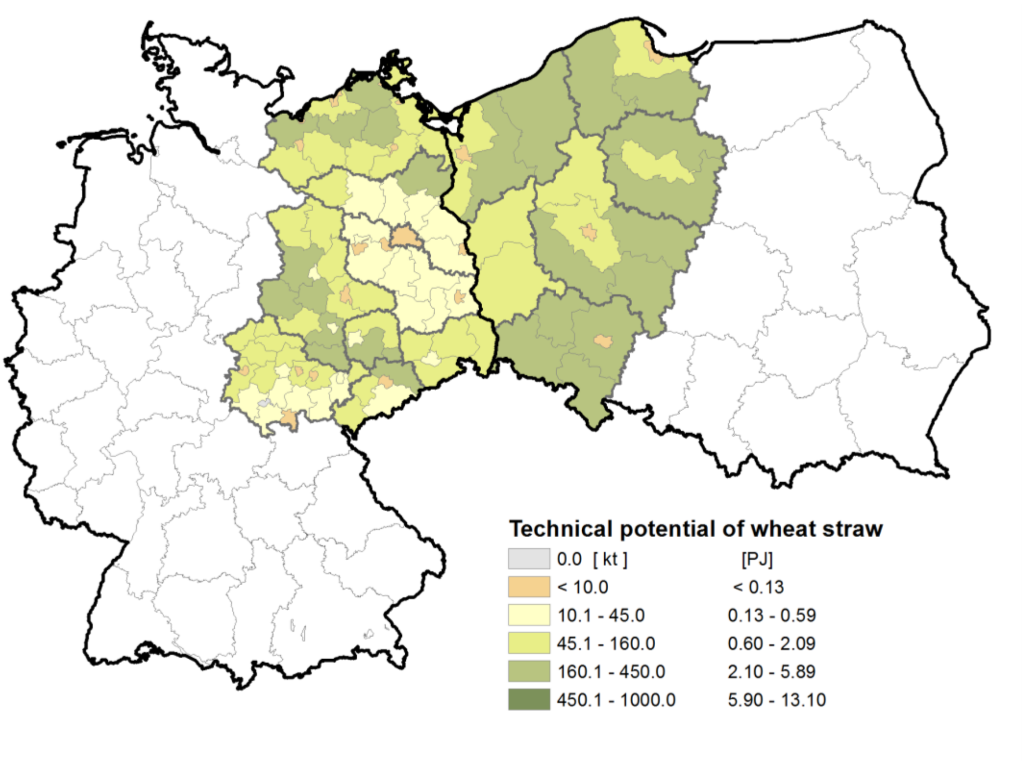


Figure 10. Technical potential of wheat straw.

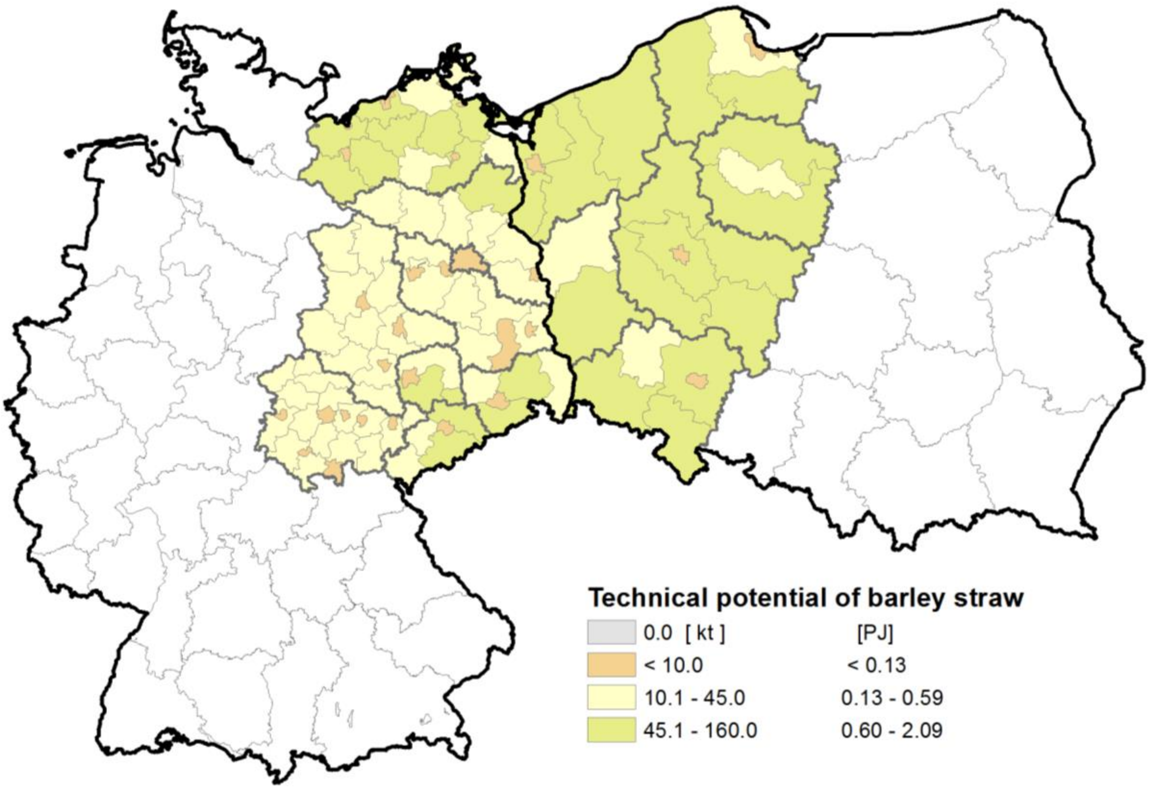


Figure 11. Technical potential of barley straw.

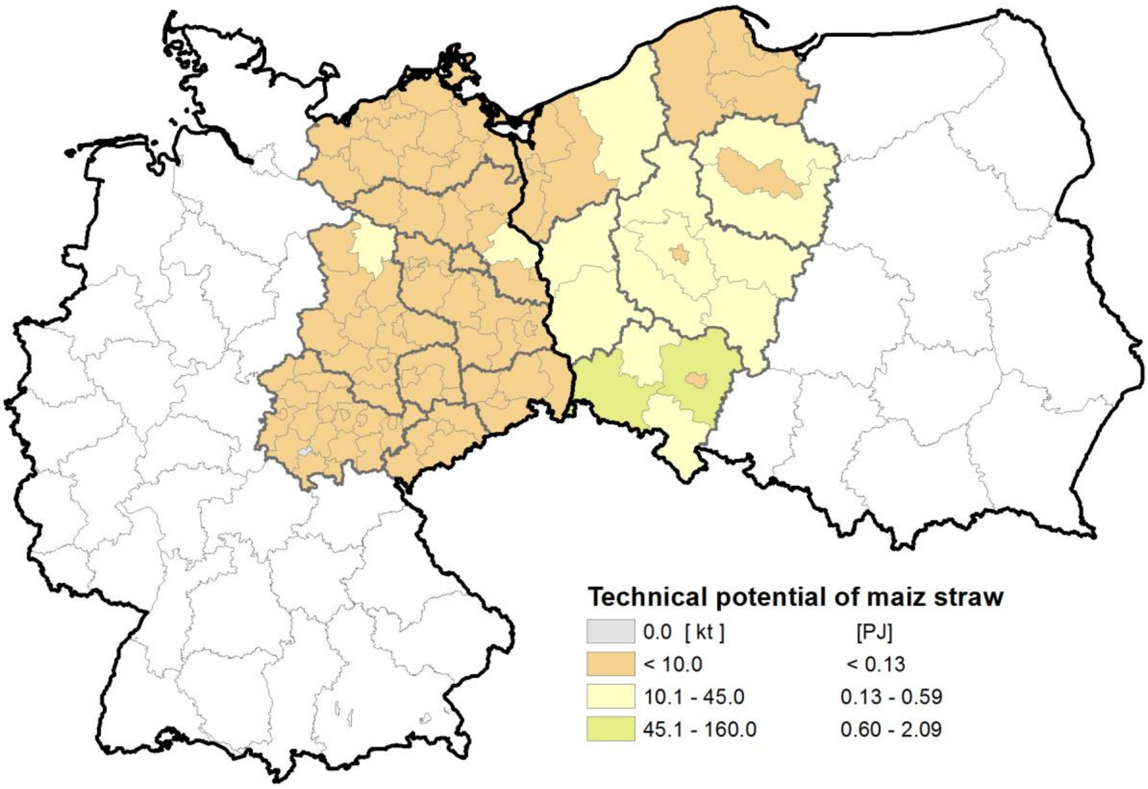


Figure 12. Technical potential of maize straw.

3.2. Forestry residues

Forestry residues are the next important biomass resource in terms of quantity and availability, which can be used as feedstock for energy purposes. As results on the forest residue potential were not available in the S2Biom project, the results presented below were determined on base of definitions and methodology proposed within EU-FP7 project BEE- Biomass Energy www.eu-bee.eu. Calculations were downscaled from country level to NUTS-3 for the case-study region.

The theoretical potential of primary forestry residues in each unit was calculated as a theoretical potential of logging residues and theoretical potential of stumps. The technical potential was assessed assuming the restrictions listed below:

- 50 % recovery rate of above ground forest residues; The recovery rates have been selected in line with the level chosen by European Environmental Agency and Asikainen et al.[6] but simplified to 0.5 per country
- 20 % as a recovery rate for stumps; Recovery rates for stumps have been chosen slightly lower compared to Asikainen et al. and a very coarse differentiation between countries was made with reference to silvicultural and harvesting practises and species distribution
- 30 % of the surplus complementary fellings are reserved for material use of wood
- 5 % of the current net annual increment is reserved for an increase of standing volume to facilitate an increased carbon storage and for biodiversity purposes including an increase of the dead wood component and to increase the share of mature forests especially in protected areas
- 5% unrecorded harvests from industrial roundwood in the current harvesting statistic were considered (thereby attributing more wood from the entire harvesting potential for material use).

The assessment is based on data from 2003 to 2007. In order to convert the modelled biomass into energy, an average moisture content of 35% was assumed, which is equivalent to 10.06 GJ/t. At harvesting the typical water content is around 45% (9 GJ/t). At 15% (air-dry) it is 15.48 GJ/t and 19 GJ/t for oven-dry matter.

With the approach chosen, the country and species-specific values of wood density were considered. On average, when recalculating the energy content per solid m³ for

[6] Asikainen A., Liiri H., Peltola S., Karjalainen T., Laitila J.: Forest energy potential in Europe (EU27). Working papers of the Finnish Forest Research Institute 69., 2008, http://www.metla.fi/julkaisut/workingpapers/2008/mwp069.htm.

the technical potential at EU level, this results in 7.25 GJ/m³ or 0.173 toe/m³. This conversion value is close to the 7.2 GJ/m³ that have been utilised in the EU-Wood study (BEE report "Executive Summary, Evaluation and Recommendations", 2010).

Spatial explicit method for NUTS-3. The yield was estimated for forest areas determined on base of Corine Land Cover (CLC) geo-data. From this map, deciduous, coniferous and mixed forests were extracted. For each NUTS-3 region, the average Net Primary Productivity (NPP) per class was determined based on the World Data Center for Remote Sensing of the Atmosphere (WDC-RSAT) data. The relative differences of net primary productivity have been used (as weighting factors) to redistribute the theoretical and technical values of potentials from country-level to the raster map.

Further details on the methodology of forestry potential calculation can be found in Deliverable 1.2 The feedstock potential assessment for EU--27 + Switzerland in NUTS--3:
http://bioboost.eu/results/public_results.php

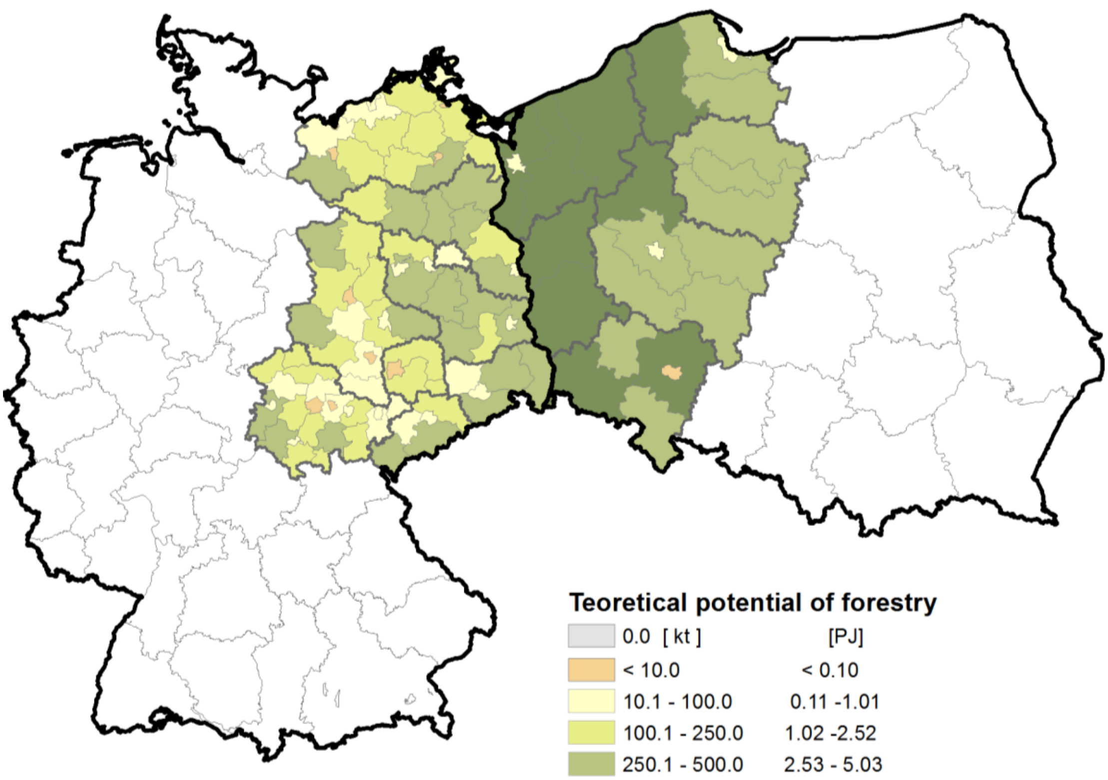


Figure 13.Theoretical forestry residues potentials

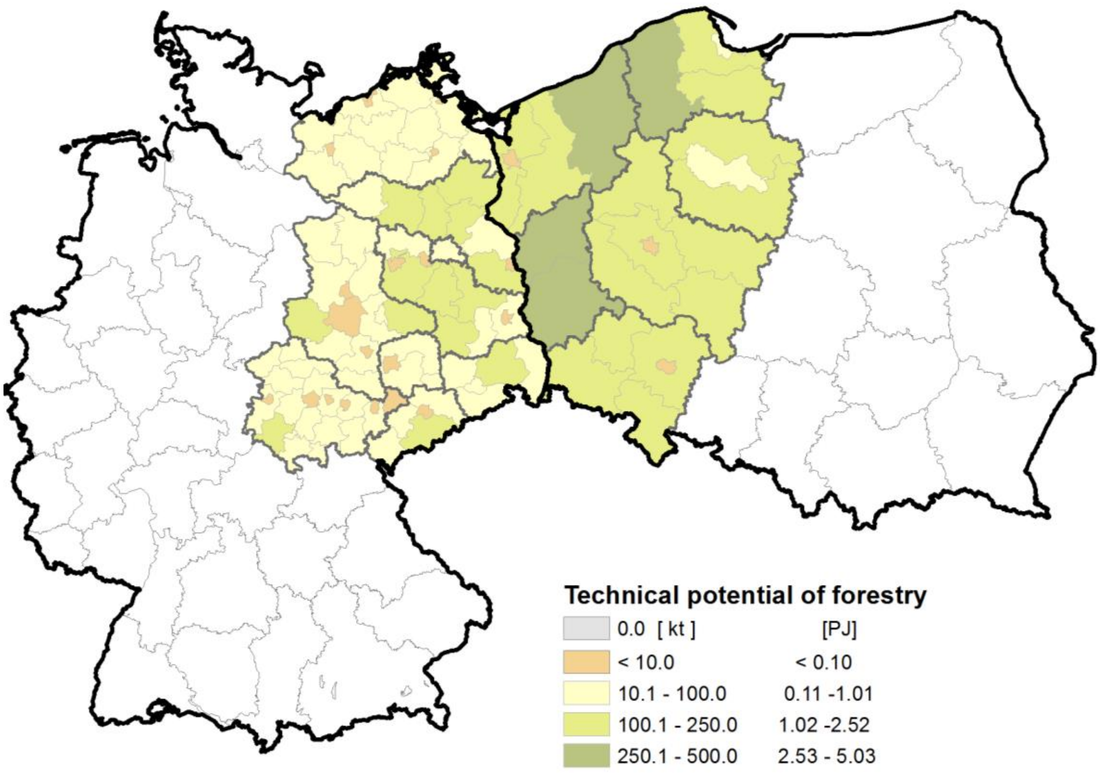


Figure 14. Technically available forestry residue potential

The table below gives an overview on the total technical potentials of straw and forestry residues in the NUTS2 regions of the case study area.

Table 2 Technical potential of straw and forestry residues in case study area

Region	Straw		Forest residues	
	kt	PJ	kt	PJ
DE3 - Berlin	0.75	0.01	25.73	0.26
DE4 - Brandenburg	1,772.94	23.05	1,625.75	16.26
DE8 - Mecklenburg-Vorpommern	2,480.04	32.24	706.42	7.06
DED - Sachsen	1,737.24	22.58	752.61	7.53
DEE - Sachsen-Anhalt	2,234.40	29.05	735.22	7.35
DEG - Thüringen	1,521.64	19.78	942.03	9.42
PL21 - Malopolskie	204.68	2.66	134.38	1.34
PL41 - Wielkopolskie	1,426.56	18.55	791.76	7.92
PL42 - Zachodniopomorskie	1,140.54	14.83	876.31	8.76
PL43 - Lubuskie	453.87	5.90	792.02	7.92
PL51 - Dolnoslaskie	1,587.68	20.64	691.34	6.91
PL61 - Kujawsko-Pomorskie	976.22	12.69	390.93	3.91
PL63 - Pomorskie	799.31	10.39	592.64	5.93
total DE	9,747.01	126.71	4,787.76	47.88
total PL	6,588.87	85.66	4,269.37	42.69
Total	**16,335.89**	**212.37**	**9,057.13**	**90.57**

4. Rational of the biofuel chains

The thermochemical biofuel pathways studied in this case study were developed in the FP7-project 'Biomass based energy intermediates boosting biofuel production' (BioBoost www.bioboost.eu). They are characterised by a two-step conversion process with concentration of bioenergy in decentral plants and upgrading to transportation fuel as usable bioenergy commodity in large, central plants. This requires also a two-step logistic chain of biomass feedstock transport from field side or forestry road to decentral plant and transport of the produced bioenergy carriers to the central upgrading plant. The rationale of this approach is:

- to keep the logistic effort low and have more added value in rural areas than with large, single-site plants
- to lower production costs per unit compared to small single-site plants due to scaling effects

The feedstock demand of the envisaged decentral catalytic- and fast-pyrolysis plants is in the order of several 100,000 tonnes per year. The produced intermediate bioenergy carriers biosyncrude (Fast Pyrolysis) and biooil (Catalytic Fast Pyrolysis) are characterised by an increased energy concentration (up to 300%) and improved handling performance (e.g. pumpable) as compared to the biomass, enabling efficient long distance railway transport to central upgrading plants. These may have GW-size or are integrated in refineries and profit of scale-of-unit-effects (production costs reduction per unit with increasing capacity) or synergies.

Concerning biomass feedstock, technically available and sustainable potentials are taken into account after the deduction of the demand of the primary sector (production of food, feed, pulp, …). The commodities cereal straw and forest fuels (logging residues, thinning wood, stumps) are studied in detail as feedstock of the reference pathways. Other studied biomasses included land management matter, waste wood and various residues of the alimentary industry.

The high feedstock demand of the decentral plants requires the utilisation of the most efficient technologies for feedstock procurement typically operated by dedicated subcontractors. These were identified in some advanced countries: The supply of forest fuel was developed and industrialized in Finland and Sweden. Forest management, residue forwarding, chipping, truck payload and forest fuel use are optimized and broadly implemented. For straw reference countries are Denmark, Great Britain and Spain with efficient agriculture, high density large square balers, automatic bale chasers and large straw consumers. Today, these systems are not necessarily operated in every country of the EC. This will change with the demand. For the determination of feedstock costs these most efficient technologies and

procurement strategies were used. For details on feedstock costs free field side or forestry road refer to BioBoost deliverable 1.1 'Feedstock costs', prepared by S. Kühner, SYNCOM, retrievable under:
http://www.bioboost.eu/uploads/files/bioboost_d1.1-syncom_feedstock_cost-vers_1.0-final.pdf

For the logistic system and associated costs from field side/forestry road to the plant refer to BioBoost deliverable 1.4 'Biomass logistics' prepared by S. Rotter and C. Rohrhofer, Fachhochschule Oberösterreich retrievable under:
http://www.bioboost.eu/uploads/files/bioboost_d1.4_fho_biomasslogistics_vers2.0-final.pdf

The assessment of economic and environmental effects in this case study is based on BioBoost deliverable 6.4 'Energy carrier chain assessment' prepared by I. Hernandez Mireles, A. van Horssen, T. van Harmelen and E. Hagen, TNO, retrievable at:
http://www.bioboost.eu/uploads/files/bioboost_d6.4_sustainability_assessment_v1.2-final.pdf

4.1. Straw - fast pyrolysis - gasification - synthetic transportation fuel

This pathway is based on the bioliq-technology developed by the KIT (Karlsruhe Institute for Technology). Detailed information is available under www.bioliq.de

Feedstock: Strawy biomass

Straw is a residue from the harvest of cereals as e.g. wheat, barley or rye. Depending on the soil demand for organic carbon and other agricultural uses, the surplus straw can be used as feedstock for bioenergy generation. Other options are herbaceous energy crops (like Miscanthus, Switch grass), dried land management matter (hay in the broader sense) and several dry waste materials. An efficient supply chain is based on large square bales of high density, collected in field-side stacks for truck transport. These bales have a density of about 200 kg/m^3 and enable to use the full payload of 120 m^3-large volume trucks.

First conversion step -fast pyrolysis

For fast pyrolysis (FP) straw is milled and pyrolysed at about 500°C in the absence of oxygen. The biomass vapours formed are cooled down rapidly and mixed with the milled char to a pump- and transportable ‘biosyncrude’, the energy carrier. The non-condensable gases are used to fire the pyrolysis reactor. 1,500 kg straw is converted to 1,000 kg biosyncrude, which contains 85% of the straw energy. The FP plants are expected to have a capacity of 200,000 to 660,000 tonnes straw per year which relates to 28 to 82 truck loads per day. In regions of good straw availability transport distances would be between 50 and 100 km. Biomass from landscape management, lignocellulosic energy crops (e.g. Miscanthus, Switchgrass) or waste wood are alternative feedstocks for this process. Use of these biomasses as co-feedstock would shorten the average transport distance. The decentralised FP plant produces between 145,000 and 435,000 tonnes biosyncrude per year. The energy carrier has a heating value of 18 to 20 GJ/t.

Biosyncrude energy carrier transport

With regard to transportability, a truck load of 24 tonnes of straw in large square bales has a volume of 120 m^3 and would be converted to about 15 m^3 of a pumpable energy carrier. A freight train of 40 railway tank wagons with a payload of 65 tonnes each could transport the energy carrier produced from 170 truck loads straw. This is a very cost- and environmental efficient transport mean to bring the bioenergy from several rural areas to a central, industrial site for upgrading. The transportation vessels require corrosion resistant properties.

Upgrading to transportation fuel

The good transportability of the biosyncrude enables long distance railway transport of the output of 5 to 10 straw pyrolysis plants to a large synfuel plant. These are expected to have a feedstock demand between 1.3 and 4 million tonnes of biosyncrude, which relates to a thermal fuel capacity between 800 MW to 2.5 GW. The energy carrier is gasified at high pressure and temperatures of higher than 1,200°C to hydrogen and carbon monoxide for the production of transportation fuels via Methanol-to-Gasoline- or Fischer-Tropsch-synthesis. Both fuels purely consist of hydrocarbons, which guarantee drop-in blending. The fuels are fully engine compatible and do not require changes in the distribution infrastructure, two points very important for consumer acceptance. Renewable power is a co-product, there are 2.5 MWh produced per tonne of transportation fuel which is after deduction of the internal consumption about 12 % by energy. The transport fuels have a GHG-avoidance potential of 81 % compared to fossil fuels.

Maturity of the pathway

The feedstock procurement is commercial, the conversion steps are established on demo-scale (TRL 7), the synthesis (Fischer-Tropsch or Methanol to Gasoline) are commercial available. At the developer KIT, the fast pyrolysis unit has 2 MW, the biosyncrude gasifier has 5 MW and the gasoline synthesis has 2MW.

Figure 15: The bioliq pilot plant at the KIT in Karlsruhe, Germany, has a straw pyrolysis unit of 500 kg/h (2 MW) with bioslurry preparation, an high pressure, entrained flow gasifier with a capacity of 1 t/h bioslurry (5 MW) with hot gas cleaning and fuel synthesis unit operating at 55 bar. Copyright: Karlsruhe Institute of Technology

The figures below show the fast pyrolysis reference pathway from straw to synfuel in terms of energy flows (Sankey-diagram) and logistic flows. It is compatible to herbaceous energy crops (like Miscanthus, Switch grass) and dried land management matter (hay in the broader sense). The data items were translated to the S2Biom-format in the following table.

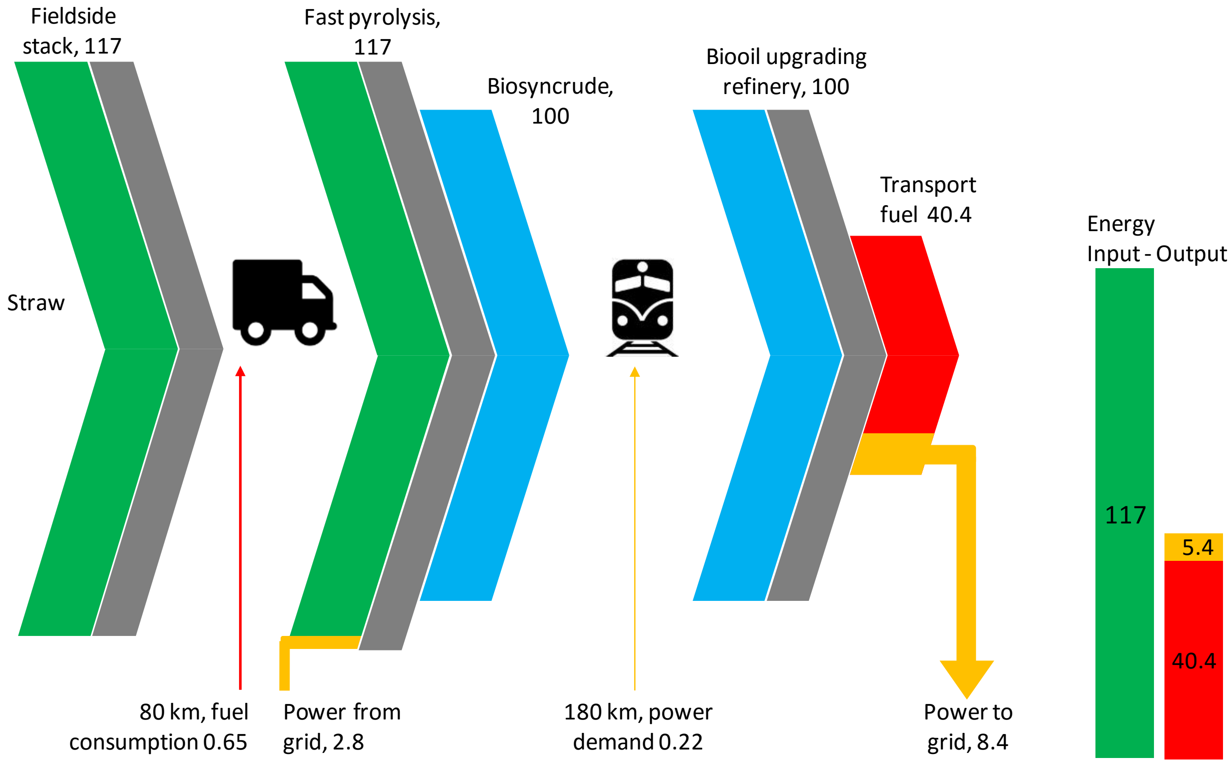
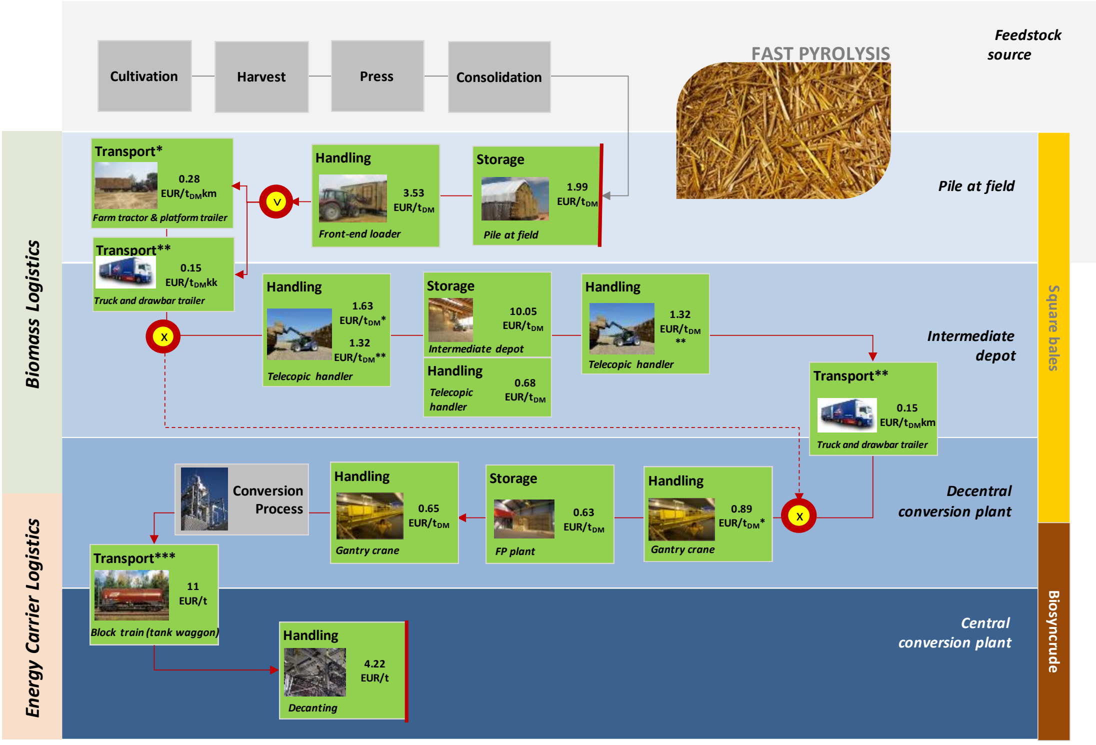


Figure 16 Sankey-diagram on energy flows of a design-size (100 MW) catalytic fast pyrolysis plant and respective upgrading capacity in a refinery (67.7 MW instead of design size 260 MW). Numbers indicate the energy flow in MW. Transport efforts are given for reference case. Colour code: Green-biomass; blue-FP-biosyncrude; red-transport fuel; orange-power (S. Kühner, SYNCOM)



* transports by farm tractor
** transports by truck
*** transports by rail
[1] Rail transport costs depend on transport relation (east/west) and distance classes (from 200 km to 2000 km); costs range from 11 to 60 EUR/t

Figure 17 The Fast Pyrolysis reference pathway as studied in the BioBoost-project. (S. Rotter, FHOÖ)

Table 3 The biomass value chain for Fast pyrolysis (BioBoost reference pathway).

What?	How?	Where?
Starts with: Straw in swath on a cereal field		
Straw baling	High density large square baler, 90x120x240 dim.	field
Bale collection and stacking	Bale chaser	at roadside landing
Storage	pile un/covered	at roadside landing
Handling - loading	Telehandler	at roadside landing
transportation	platform, drawbar truck	from roadside landing to decentral conversion plant
handling - unloading	Gantry crane	at decentral conversion plant
storage	covered in warehouse	at decentral conversion plant
handling	Gantry crane	at decentral conversion plant
decentral conversion process	Fast pyrolysis	at decentral conversion plant
Handling - loading	pumping	at decentral conversion plant
transport pyrolysis oil	tank wagon (railway transportation)	from decentral conversion plant to central conversion plant
handling - unloading	pumping	at central conversion plant
central conversion process	Gasification/synfuel	at central conversion plant

Forestry residues - catalytic fast pyrolysis - transportation fuels

This pathway is based on CatOil-technology developed by the CERTH (Centre for Research and Technology Hellas), Royal DSM and Neste. Detailed information is available under:
http://www.bioboost.eu/results/public_results.php

Feedstock: Forest residues

Forest residues are co-products of forest cultivation and wood harvest: Thinning wood occurs as whole tree or delimbed stems in the thinning of young stands. Final felling yields logs for the production of timber, wood pulp or boards; co-products are tree-tops, branches and off-spec logs (bent or rotten). In some countries stump excavation is allowed to prepare the ground for tree planting. Depending on the site conditions, soil fertility and eventual ash return a certain share of forest residues can be taken from the forest without threatening its productivity. This sustainable amount is collected and stored at the forest road for chipping into trucks or transport in whole for chipping at the plant. Depending on site and duration of storage, the water content of forestry residues is between 30 and 50 %. In 2015 the maximum allowable weight of forest trucks was between 40 and 76 tonnes in European countries. Optional feedstocks are other wood commodities (timber processing residues, waste wood, short rotation coppice) and other ligno-cellulosic residues.

First conversion step: Catalytic fast pyrolysis

The catalytic fast pyrolysis (CFP) starts with the drying and milling of forestry residues (e.g. thinning wood, tree-tops, branches). The biomass is pyrolysed at about 500°C in absence of oxygen in contact to a catalytic material. The catalyst splits off a high share of the oxygen which is contained in the biomass molecules (about 45 % by weight) as carbon dioxide, carbon monoxide or water. The pyrolysis vapours are rapidly cooled. The condensed biooil contains 50 % of the liquid biomass energy, is low in oxygen content (15 to 20 %) and has a heating value of about 30 GJ/t. CFP off-gases and the catalyst coke are combusted to supply the reaction heat for pyrolysis and produce power (0.83 MWh per tonne of biooil). Another co-product is crude acetic acid of which about 50 kg are produced per tonne of energy carrier. The decentralised CFP plants are erected in areas of high feedstock availability: They are expected to have a capacity of 160,000 to 520,000 tonnes forest residues per year which relates to 28 to 92 truck loads per day. In regions of good availability transport distances would be between 60 and 120 km. Straw, lignocellulosic energy crops (e.g. Miscanthus, Switchgrass) or waste wood are alternative feedstocks for this process. Use of these biomasses as co-feedstock would shorten the average transport distance. The decentral CFP plant produces between 45,000 and 147,000 tonnes biooil per year.

Biooil energy carrier transport

With regard to transportability, a truck load of 25 tonnes forest residue chips (14 to 17 tonnes wood dry matter, rest is water) is converted to 4 to 5 m³ of a pumpable energy carrier. A freight train of 40 railway tank wagons with a payload of 65 tonnes each could transport the energy carrier produced from 570 truck loads forest residues. This is a very cost- and environmental efficient transport mean to bring the bioenergy from several rural areas to a central refinery for upgrading by co-processing with crude oil. The energy carrier is moderately corrosive and compatible to standard crude oil transport and storage vessels.

Upgrading to transportation fuels

The good transportability of the energy carrier enables long distance railway transport for upgrading in refineries with capacities between 200,000 and 850,000 tonnes of biooil in European countries. The energy carrier is stabilized in two hydrotreatment steps consuming about 70 kg hydrogen per tonne of transport fuel. One co-product are light gases (180 kg per tonne fuel) another might be phenol(-ics) which have a higher market value for the chemical industry than for biofuel production. Due to changes in the European refining sector it is expected that the CP biooil may replace 2 % of fossil crude. This enables use of existing capacity for steam methane reforming and hydrotreatment for the deoxygenation of the biooil. The product is co-processed with the fossil streams and distilled to the conventional transportation fuels gasoline/kerosene/diesel according to the production slate of the refinery. All fuels purely consist of hydrocarbons which guarantee drop-in blending. The fuels are fully engine compatible and do not require changes in the distribution infrastructure, two points very important for consumer acceptance. The fuels have a GHG-avoidance potential of 81 % compared to fossil fuels.

The figures below show the catalytic fast pyrolysis reference pathway in terms of energy flows (Sankey-diagram) and logistic flows; its steps were translated to the S2Biom biomass value chain format in the following table.

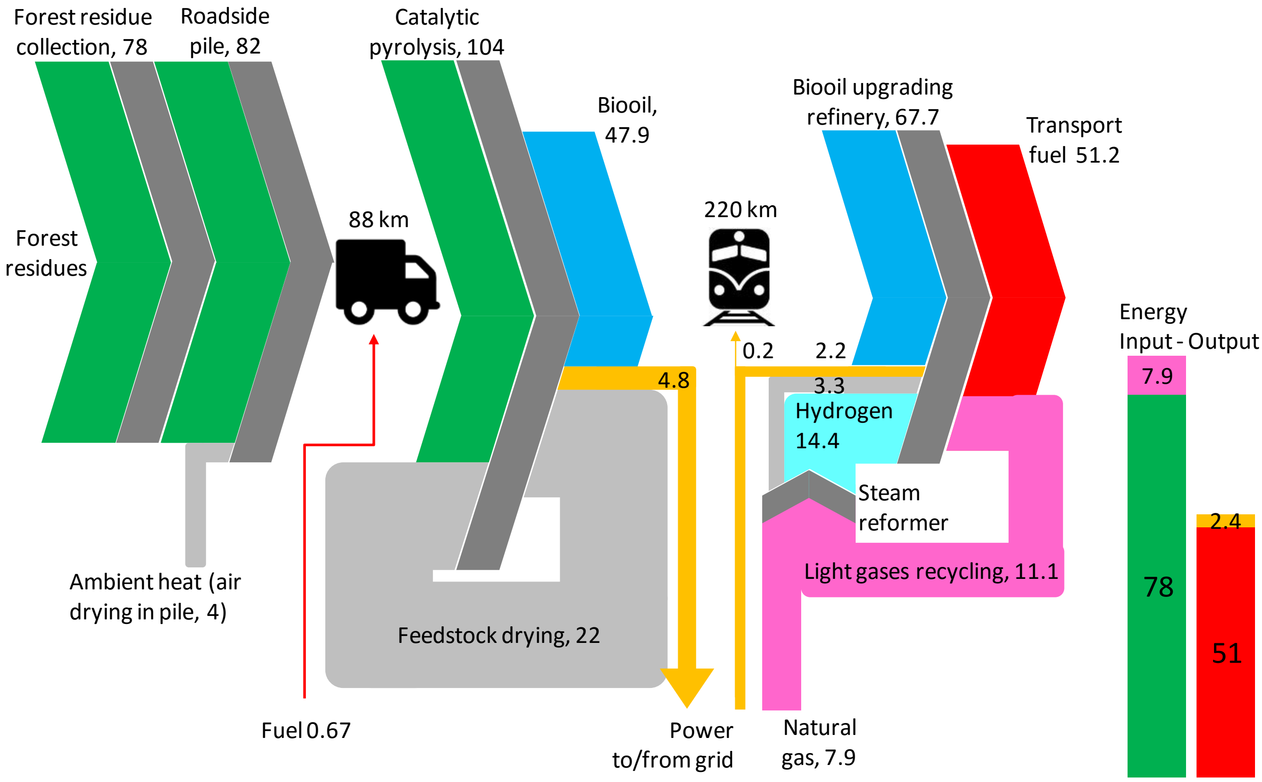
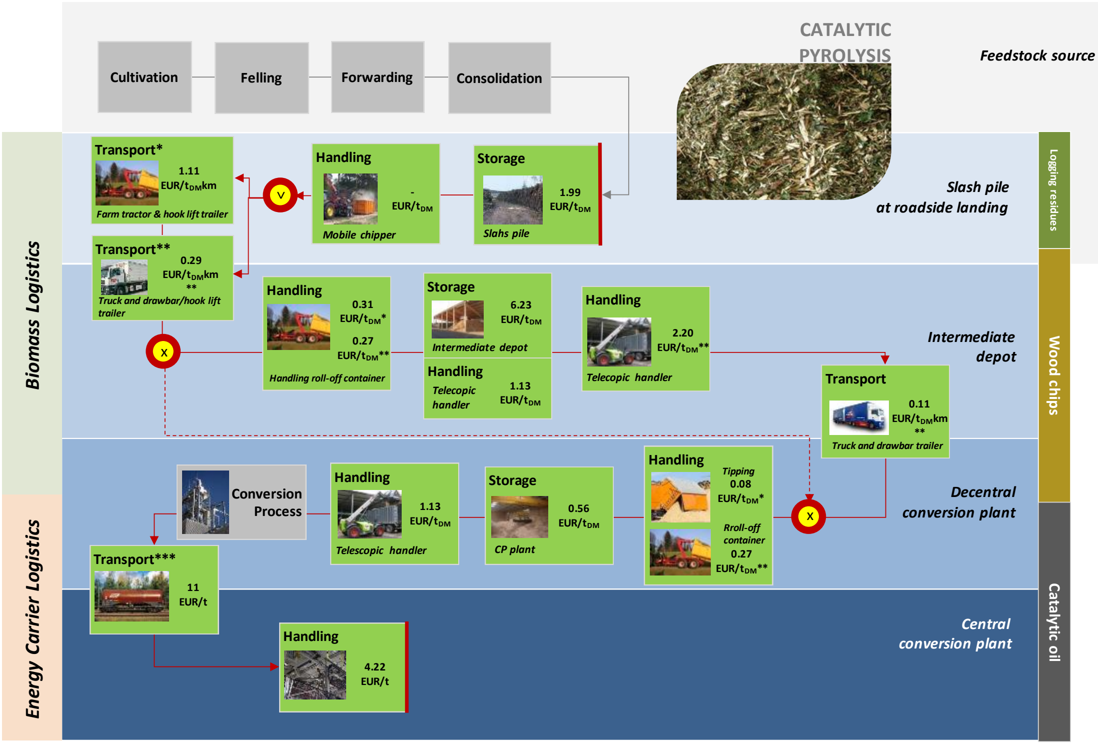


Figure 18: Sankey-diagram on energy flows of a design-size (100 MW) catalytic fast pyrolysis plant and respective upgrading capacity in a refinery (67.7 MW instead of design size 260 MW). Numbers indicate the energy flow in MW. Transport efforts are given for reference case. Colour code: Green-biomass; blue-FP-biosyncrude; red-transport fuel; orange-power, pink-natural/combustible gas (S. Kühner, SYNCOM)



* transports by farm tractor
** transports by trucks
*** transports by rail
[1] Rail transport costs depend on transport relation (east/west) and distance classes (from 200 km to 2000 km); costs range from 11 to 60 EUR/t

Figure 19. The description of a biomass value chain (reference pathway) for catalytic fast pyrolysis in the BioBoost-project (S. Rotter, FHOÖ).

Table 4 The biomass value chain catalytic fast pyrolysis. Shaded in grey is an optional intermediate storage in a biomass center.

What?	How?	Where?
Starts with: Thinning wood or logging residues in forest		
Forest residue forwarding	Forwarder	Forest
storage logging residues	pile un/covered	at roadside landing
chipping	truck-mounted chipper	at roadside landing
transportation	Hook-lift containers, truck	from roadside landing to intermediate depot
handling - unloading	tipping	at intermediate depot
handling	telescopic handler	at intermediate depot
storage	covered in warehouse	at intermediate depot
Handling - loading	telescopic handler	at intermediate depot
transportation	truck and drawbar trailer	from intermediate depot to decentral conversion plant
handling	tipping	at decentral conversion plant
storage	covered in warehouse	at decentral conversion plant
handling	telescopic handler and screw conveyor	at decentral conversion plant
decentral conversion process	catalytic fast pyrolysis	at decentral conversion plant
Handling - loading	pumping	at decentral conversion plant
transport pyrolysis oil	tank wagon (railway transportation)	from decentral conversion plant to central conversion plant
handling - unloading	pumping	at central conversion plant
central conversion process	Deoxygenation/transp.fuel	at central conversion plant

This procurement chain is compatible to forest residues from thinning and logging as well as for woody biomass from land management and roadside clearing.

5. Description of the optimisation approach

A holistic logistic approach employing a multi-stage supply network was developed by the University of Applied Science Upper Austria (FHOÖ) in the BioBoost project. It is used to model and optimise de-central energy carrier production and central processing in trans-regional (up to EU-wide) supply chains as shown in the figure below.

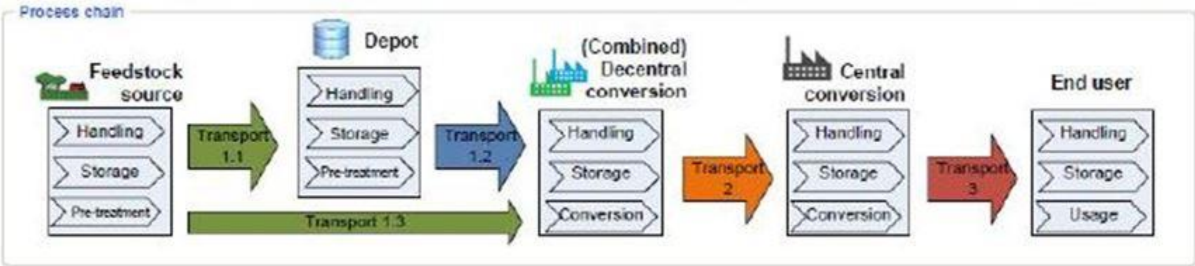


Figure 20. General description of the BioBoost process with depots, decentral conversion and central conversion (Erik Pitzer, Gabriel Kronberger, FHOÖ, 2013).[7]

Simulation-based optimization was used to construct an optimisation scenario for feedstock usage, plant location selection, and transport route selection. It is based on a detailed description of the conversion and transport processes and on sophisticated evolutionary algorithms for assigning values to the free variables of this simulation model, which are feedstock sourcing area, feedstock sourcing ratio, plant location, plant capacity and energy carrier supply. These scenarios are evaluated using the holistic simulation model. Using the simulation result as input to evolutionary algorithms, optimized scenarios can be constructed.

Here, a mixed-integer optimization problem is being solved for finding optimal biomass networks with respect to both economic as well as ecologic objectives. Discrete variables describe placement decisions or routing strategies, while continuous variables are needed for modelling numerical values such as biomass utilizations and plant capacities. The whole process of simulating a given logistic scenario gives a set of regional values, most importantly total cost including feedstock, handling, storage, transportation, conversion, waste disposal, construction and various estimates concerning environmental aspects for final life-cycle assessment. These final figures are then combined into a single quality value that describes the overall desirability of a specific scenario.

[7] Sources: Bioboost, 2013; Pitzer & Rotter, 2012; Kronberger, G. & E. Pitzer, 2015; Rotter & Rohrhofer, 2012 & 2014;

The program has been developed based on the open-source software *HeuristicLab*, which also provides a user-friendly GUI. Through specifically designed interfaces for defining input data, such as feedstock availabilities, feedstock cost, the simulator yields information such as total transport cost and emissions, or plant construction cost.

Different types of evolutionary algorithms were used for solving this optimization problem. Evolutionary algorithms are a kind of meta-heuristic algorithm which can be applied to a large variety of different optimization problems. Meta-heuristic algorithms can be used for optimization problems when it is not necessary to solve the problem exactly and it is sufficient to find a good solution as is here the case. Of the many available types of evolutionary algorithms Evolution Strategies and Genetic Algorithms were adapted to the requirements of the BioBoost simulation model. Evolutionary algorithms start from a set of initial configurations of the problem (usually these are initialized randomly) and then iteratively generate new configurations by combining elements from a set of active configurations. The process is designed in a way to improve the quality of solutions over time. This is accomplished in evolutionary algorithms by exerting selection pressure on the configurations. Either, better configurations are selected from the active set with a higher probability (GA), or a surplus of new configurations is generated and only the best of them are kept (ES). First, the algorithm implemented in HeuristicLab produces solution candidates for the simulation model; then the simulation yields a total cost that is fed back to the optimizer. The optimizer then uses this information to generate improved configurations. Over time the quality of the solutions improves and the process continues until an acceptable solution is finally found.

Transport distance matrix

The geographical fundament of the scenario is the feedstock potentials in the NUTS 3 regions and a transport distance matrix pre-calculated for the whole network. For the determination of transport costs, the distances between feedstock source (e.g. field) and de-central conversion plant is required. Average route lengths were estimated on base of the European road network using Open Street Map data. If feedstock and conversion plant are in the same region, an average route length was estimated by calculating routes from 20 random points in the region to the centroid, where the conversion plant was assumed to be. If transport was from one region to another, route lengths between 20 random selected points in each region were calculated and averaged. The large difference in the size of the NUTS 3 regions led to a distorted matrix as intra-regional transport was in some cases several 100 km long, which impacted the optimisation. This problem was solved by splitting large NUTS regions to sub-regions of maximum 7500 km². The feedstock potential was assumed to be evenly distributed in these cases.

Biomass feedstock price

The optimisation model operates with feedstock prices, which depend on the degree of utilization (sourcing ratio) as the price of a commodity depends on offer and demand in a free market. Facilities with a feedstock demand in the range of tens to hundreds of thousand tonnes biomass are expected to change established offer/demand ratios (and thus the price) considerably. For feedstock sourcing between 0 and 50 % (x-axis) a single price (y-axis) is assumed, which increases with higher utilization rates as shown in the figure below for the European average.

It has to be underlined that the feedstock amount at 100% sourcing is the sustainable amount of ready available residue biomass. The demand of e.g. straw for agricultural applications (fodder, bedding,…) or timber in the forestry sector (saw logs, pulp mills, board production) was deducted from the theoretical potential to exclude competition. Feedstock-competing sectors are expected to profit initially from an increased demand due to establishment of more efficient procurement technology until prices generally increase at higher sourcing ratios as observed on the Swedish forest fuel market.

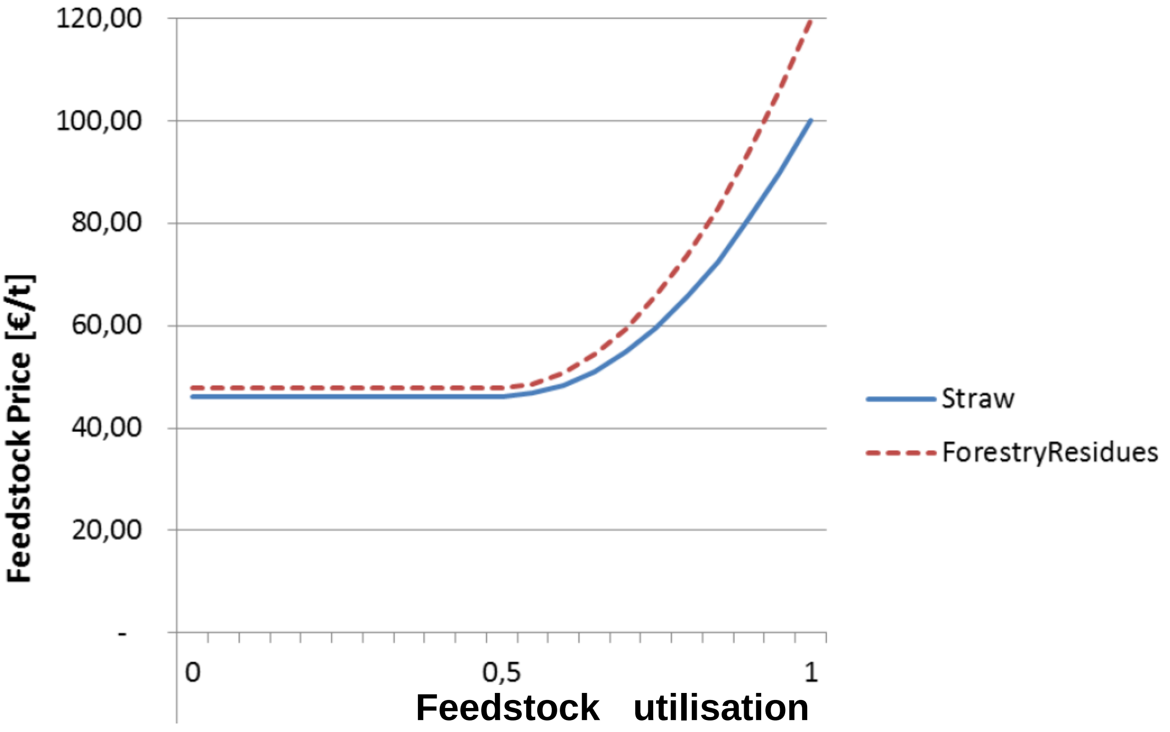


Figure 21: The feedstock prices (y-axis) depend on degree of utilization (x-axis). Increasing prices were assumed, if more than 50% of the available residue and waste feedstock is marketed.

Overview on scenario parameters

The parameters for the calculation of the scenarios were collected in the BioBoost-consortium and harmonized for techno-economic assessment by TNO. The production costs per unit drop with increasing capacity, as e.g. less steel is required per m³ of reactor volume or the loan of a worker does not depend on the size of the operated wheel-loader. For sake of simplicity, this scale of unit-effect was restricted to construction costs. The table below gives an overview on cost items, the range of plant size. The scale of unit-effect of production cost are shown in the following figure.

Table 5: Overview on technical parameters of the plants of the two conversion pathways

	Catalytic Pyrolysis	Refinery upgrading	Fast Pyrolysis	Synfuel plant
Design capacity [t/a feedstock]	179,856	249,690	219,123	1,345,493
Conversion efficiency [t product/t feedstock]	0.26	0.69	0.68	0.16
Construction costs [EUR/t*20a]	12,243,937	30,858,231	11,003,716	139,037,373
Operation costs [EUR/a]	9,545,962	38,295,258	7,278,442	107,841,770
Construction scaling exponent	0.7	0.7	0.7	0.7
Operation scaling exponent	1	1	1	1
Utilisation factor	0.91	0.91	0.91	0.91
Storage costs [EUR/t]	2.55		2.60	
Catalyst costs [EUR/t]	4.13			
Exemplary feedstock costs [EUR/t]	70	750	60	220
Electricity costs [EUR/t feedstock]		37	8.6	
Hydrogen costs [EUR/t feedstock]		93		
Waste water costs [EUR/t feedstock]		0.04		0.15
Cooling water costs [EUR/t feedstock]			0.01	
Electricity revenues [EUR/t feedstock]	18.4			33.9
Light gases revenues [EUR/t feedstock]		44.8		
Linear production costs [EUR/t product]	429	1,491	155	1,663
Scalable production costs [EUR/t product]	262	179	74	645

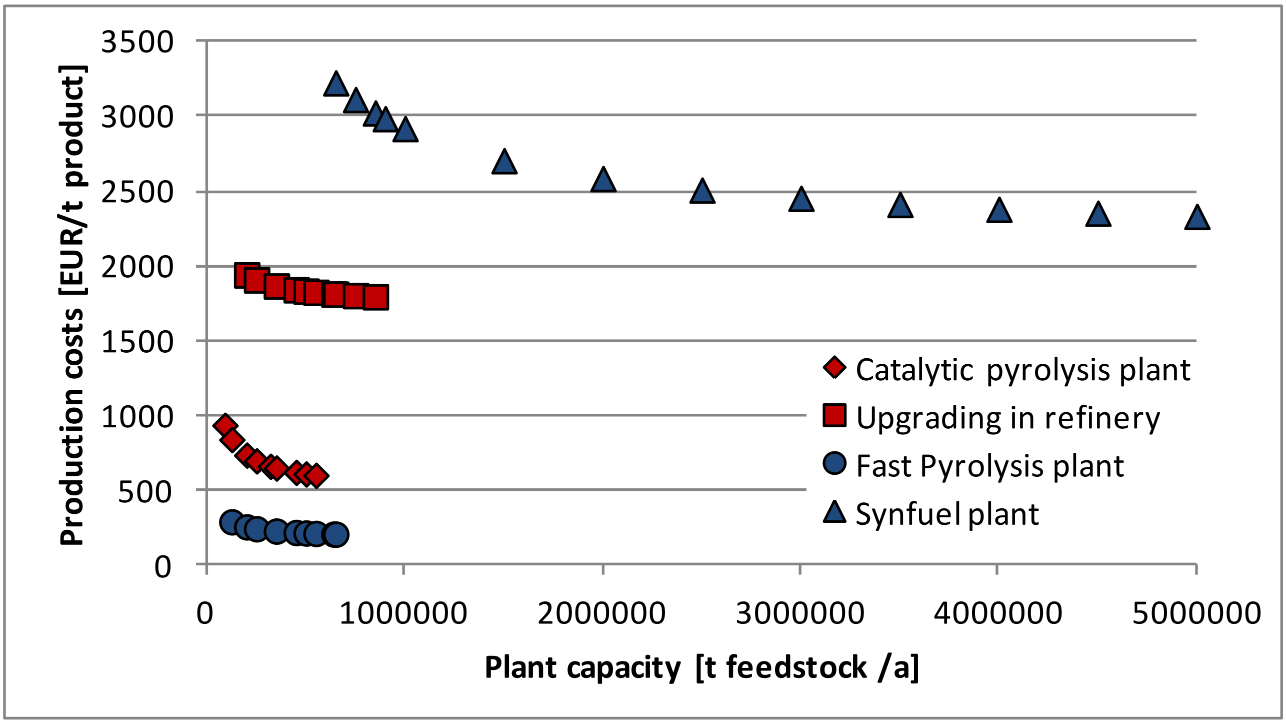


Figure 22: Range of plant capacity in terms of tonnes feedstock conversion capacity per year and respective dependence of production costs per unit of product.

6. Optimisation of fuel production in NE Germany and NW Poland

6.1. Biofuel production with the Catalytic Pyrolysis value chain

The study area has a total sustainably available potential of about 9 million tonnes forestry residues which may be converted to a total of 2.3 million tonnes of CP-biooil per year. This amount could be upgraded to 1.6 million tonnes transportation fuel. However, the concepts of the CP-pathway foresees upgrading in existing refineries, which reduce investments to new units to the minimum and saves costs by using existing structures and skilled personnel. It was assumed that 2% of the crude oil processing capacity could be substituted with CP-biooil with the established infrastructure. The conversion of larger amounts would either require a stand-alone plant or further investments in e.g. hydrogen production capacity. Four refineries are situated in the study area. According to published crude oil processing capacities these were assumed to have a biooil upgrading capacity of Plock – 252,000 t/a; Leuna – 207,000 t/a; Gdansk and Schwedt – both 192,000 t/a. Using the total biooil upgrading capacity of 843 kilotonnes per year would yield about 531 kilotonnes of transportation fuel. In the optimisations the 4 refineries produce about this amount of fuel which means that about 36% of the forest residues in the study area are converted to transportation fuel. The production costs in the plants vary in the 6 replicate optimisation runs between 1626 and 1743 EUR/t transportation fuel. The average production costs are 1661 EUR/t over the 4 plants in the best run, which is shown in the figures below and described in the following.

The integration of the CP-fuel in the local transport fuel market is straight forward: The upgrading in the refinery leads to a biocrude which is further processed together with fossil crude in the refinery. So the product of the CP-pathway is a drop-in biofuel which does not require separate pumps at the filling stations nor new fuel standards. The customer does not experience impacts on engine performance or increased consumption as with other biofuels. Concerning market shares, the population of about 29 million in the study area has a transport fuel demand of about 15.7 million tonnes oil equivalent, calculated on base of the national average consumption of 0.626 and 0.429 tonnes per person for Germany and Poland. Assuming that the produced 531,000 tonnes CP-fuel would be used in the study area gives a share of 3.4% in the transport fuel market. For the year 2020, the European Fuel Quality Directive (FQD, 2009/30/EC) sets a target of 6 % green house gas reduction by substitution of fossil transport fuel with biofuel. The CP-based fuel is expected to have a GHG-avoidance exceeding 80 %. Assuming 85 % avoidance the 3.5 % CP-fuel blend would have a GHG-avoidance of 3% in the study area. So halve of the FQD target could be achieved with regionally produced biofuel from locally harvested forest residues on the Catalytic Pyrolysis pathway.

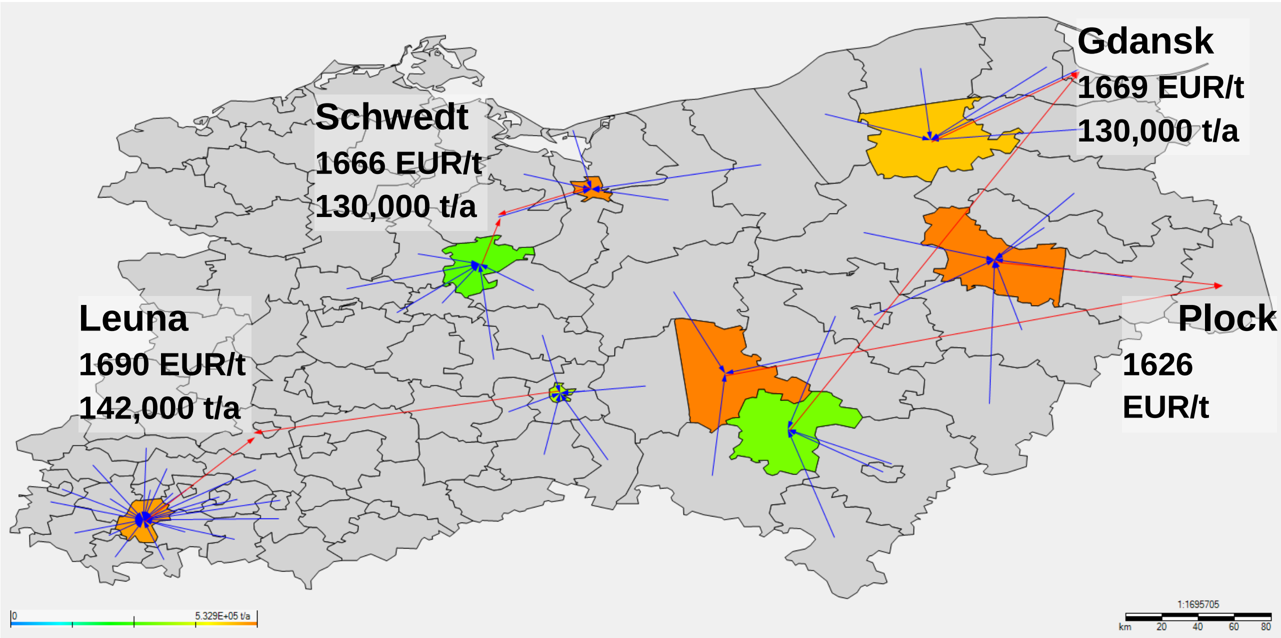


Figure 23: Regions with CP-plants and their size in tonnes forestry residues conversion capacity per year (green-290,000 t/a; orange-533,000 t/a). Forest residue procurement is indicated by the blue arrows, red arrows indicate biooil transport for upgrading at existing refineries. Total transport fuel production costs and amounts are given for the refineries as yielded in this best of 6 parallel optimisation runs.

The figure above shows that the Catalytic Pyrolysis plants varied in production capacity between 290,000 (green) and 533,000 t/a (orange). The biooil production cost were between 713 and 793 EUR/t, large plants are more economic than smaller and Polish plants are more economic than German, mostly due to lower labour costs in the feedstock supply chain. The same two principles are true for the biooil upgrading in the refineries, the larger the better and operation with feedstock/biooil from Poland is more economic than with German. Generally, upgrading costs to transportation fuel for a given amount are similar at the four refineries in the study area. At a biooil amount below 210,000 t/a, (which is the capacity of the smallest refineries in the set) the difference between German and Polish sites is negligible, which would favour the nearest refinery. At larger amounts the scale of unit-effect led to a difference of about 17 EUR/t in fuel production costs between the largest refinery (Plock) and the smallest (Schwedt and Gdansk) in the study area. This is less than the variation in the biooil transport costs observed in the 6 parallel optimisation runs initially described. But there is a second reason, why the Plock-refinery typically performs best: Plock can be supplied by two CP-plants of maximum size, which results in low biooil production costs as shown in the production cost bar chart below. This effect accounts to 30 to 50 EUR per tonne of transportation fuel and is a modelling artefact. In reality, a CP-plant might sell its oil to more than one customer but implementation of this feature in the model would have cost too much calculation time.

In the best run, the ratio of forest residue utilisation was 36 % as described above. However, in the catchment areas of the CP-plants, it was typically between 45 and 60 %, while it was 0 in the rest of the area, as shown in the figure below. The average transport distance of forest residues to catalytic pyrolysis plants was 88 km, the logistic costs varied between 20 and 23 EUR/t.

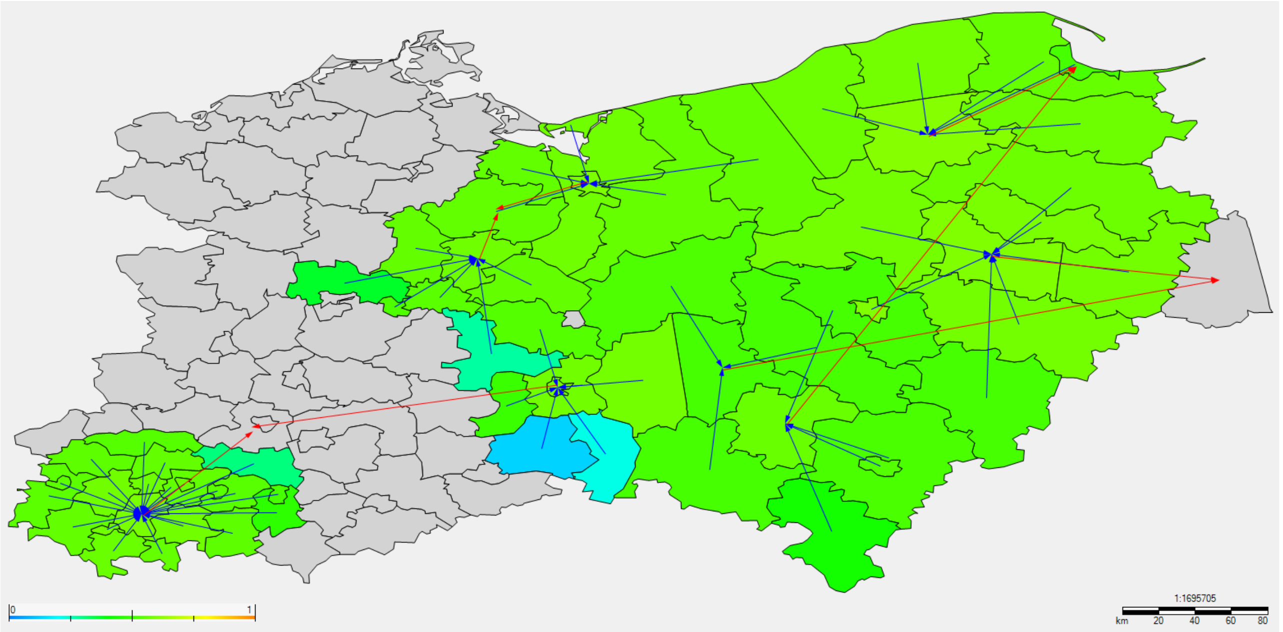


Figure 24: Regional forest residue utilisation in best run. Blue shading: 5-20%; green: 40-60%, red: 100% utilisation; blue arrows: forest residue transport to CP-plant; red arrow: biooil transport to refinery.

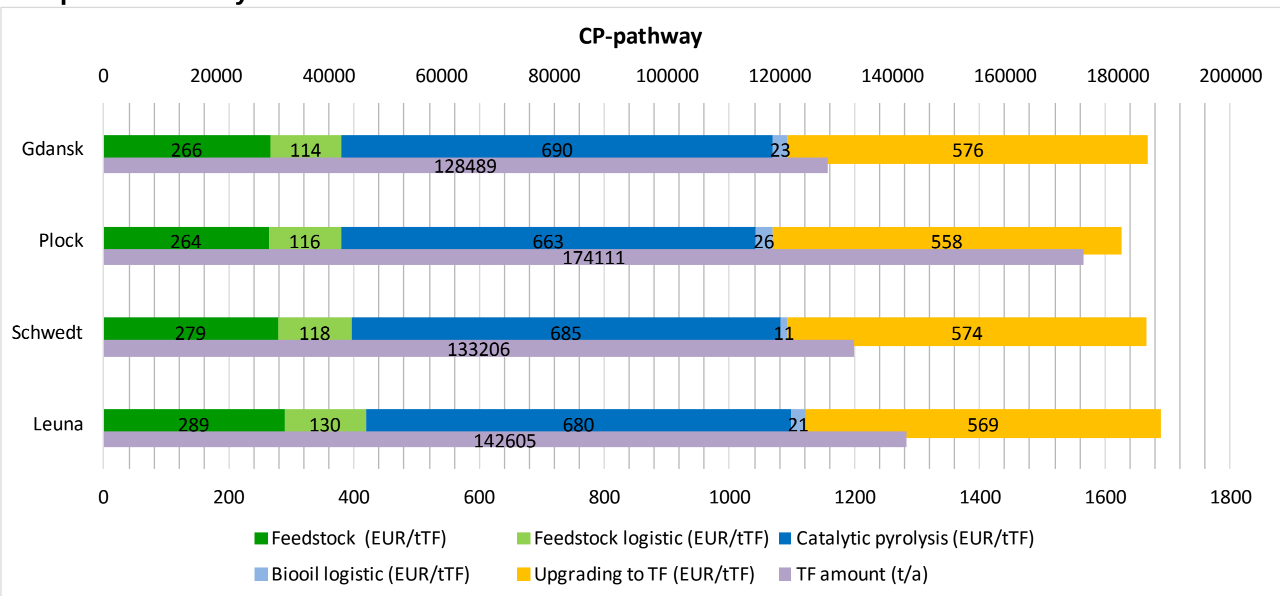


Figure 25: Composition of fuel production costs and amount of Catalytic Pyrolysis-based transport fuel in the four refineries of the case study area.

The figure on value added in the regions due to the implementation of the CP-value chain shown below has basically 3 categories: The regions where the feedstock is sourced profit by up to 9 million EUR per year, depending on size and forest residue availability (shaded in blue). At the sites of decentral CP-plants between 40 and 60 million EUR per year are generated, while refinery regions receive an additional 80 to 110 million EUR/a. The total added value in the study area amounts to 960 million EUR per year.

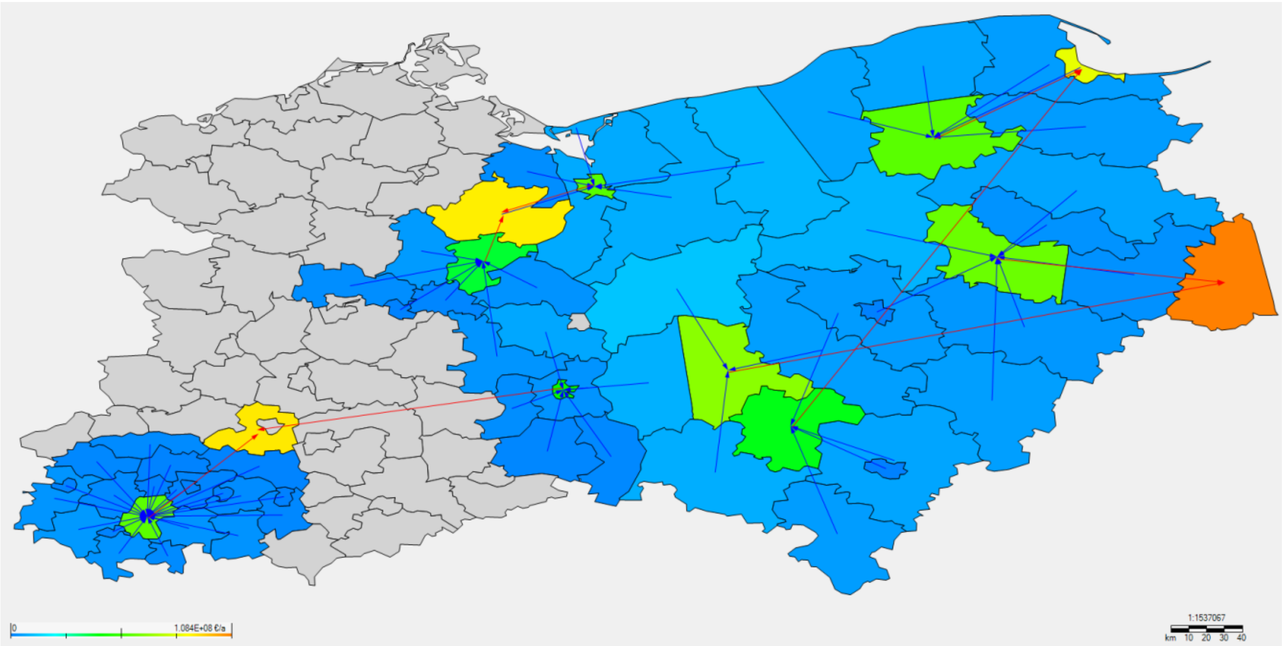


Figure 26: Added value in the regions of the study area. Blue shading: Up to 11 MEUR/a; green: 40 to 60 MEUR/a; yellow: 80 – 90 MEUR/a; red: 110 MEUR/a

Sensitivity analysis: Direct feedstock supply to CP at refinery

The above described indirect value chain foresees biomass conversion at regional CP plants and biooil transport for upgrading at a central refinery. An often studied alternative is the direct supply of forest residues to a stand-alone plant or in case of this value chain a CP plant at the refinery. This doubles the feedstock transport costs to 64 EUR/t as shown in the figure below. The forest residue truck transport amounts to 552 million t*km. This is an average transport distance of 178 km per tonne of forestry residues or -referred to final product- 1052 t*km per tonne transport fuel doubled as compared to the staged value chain. The biooil transport by train from the CP-plant in the feedstock rich areas to the refinery requires 320 km per tonne transport fuel but total efforts in the staged decentral/central-approach are 22% lower. The total fuel production costs increase by about 100 EUR/t to 1743 to 1789 EUR/t. The biooil transport costs are saved (20 EUR/t TF with decentral CP) but the feedstock transport costs increase to an average of 228 EUR per tonne of transport fuel, which is 100 EUR more than in case of the regional biomass conversion .

Table 6: Comparison of parameters of the staged process with biooil transport to the sensitivity study of Catalytic Pyrolysis on-site of the refinery.

Item	Remote CP, biooil transport	CP at refinery
Forest residue transport distance [km]	88	178
Biooil transport distance [km]	220	0
Total logistic costs [EUR/t transport fuel]	140	228
Total production costs [EUR/t]	1661	1761

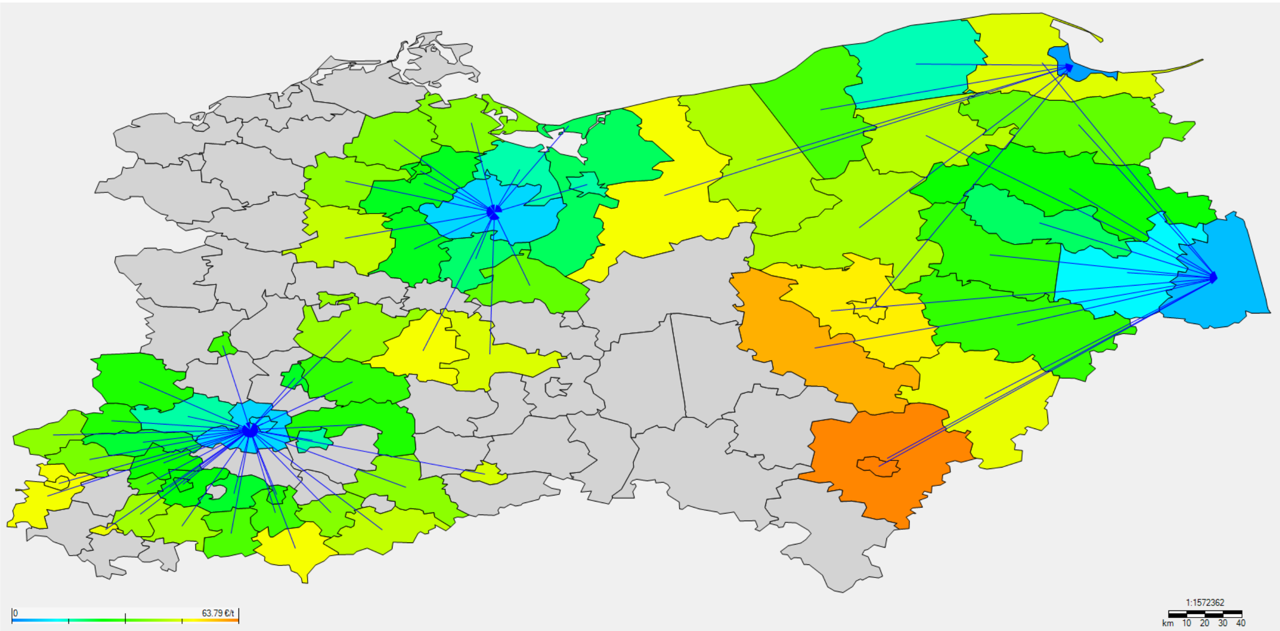


Figure 27: Forest residue transport costs in a comparable 'stand alone'-concept. Forest residues are supplied to CPs located at the refinery sites. The maximum transport cost (red) is at 64 EUR/t forest residues, minimum is 5 to 10 EUR/t.

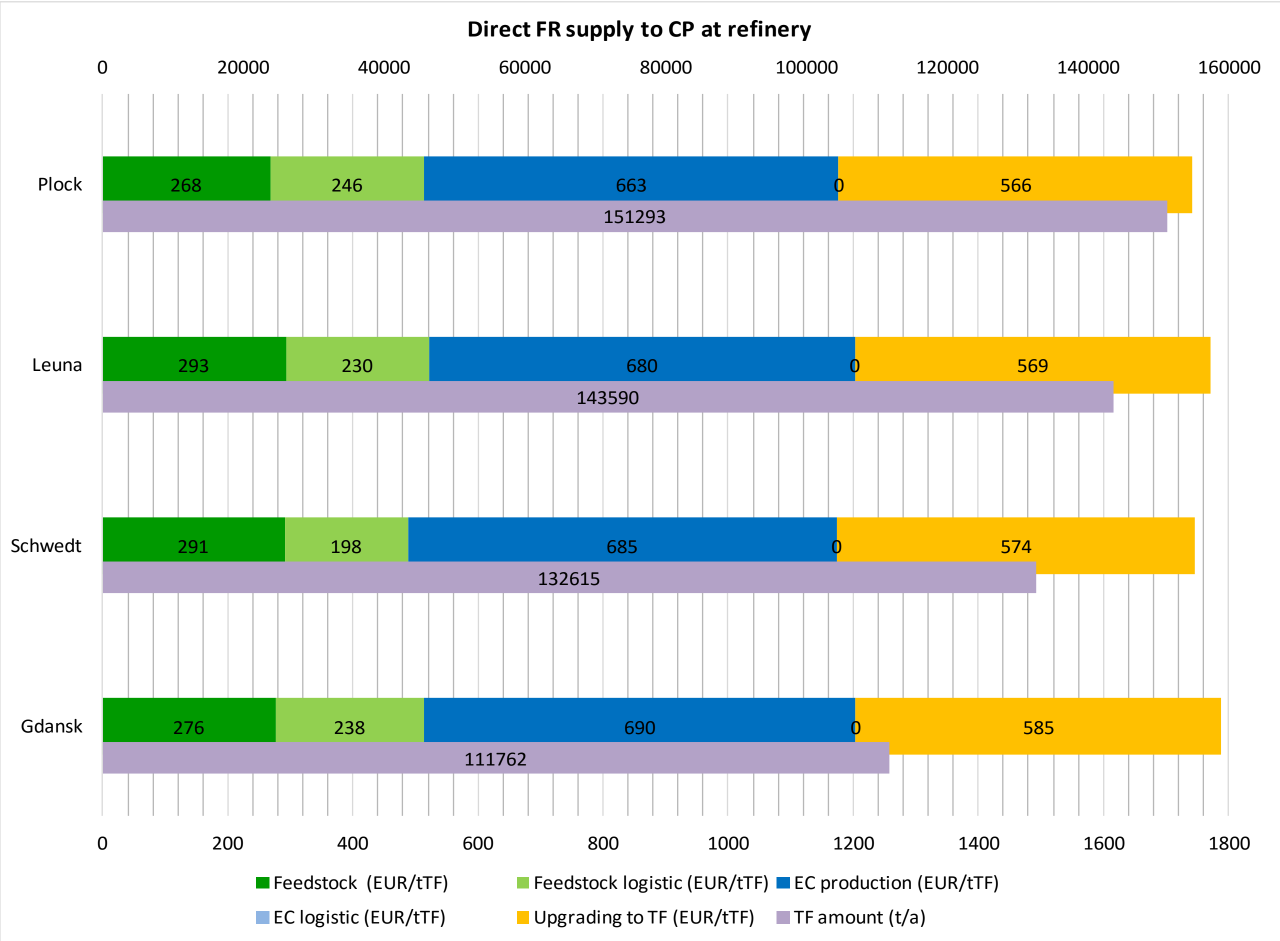


Figure 28: Composition of production costs in a scenario of catalytic pyrolysis on site of the refinery.

Market implementation of the CP-biofuel pathway

The first catalytic pyrolysis plant(s) of the pathway would be built where the production costs are lowest. These are determined by the plant size (scale of unit-effect) and the feedstock costs. The latter are composed of the price of forest residues free forest road and the transport costs to the CP-plant, which depend on the amount of biomass per area, the road network and the transport costs per tkm (tonnes x km). The forest residue densities are comparable, Poland has lower labour costs and corresponding price of forestry residues and transport costs, Germany the better road network. Altogether, the biooil production costs in large CP-plants (540,000 t/a feedstock) are with 645 EUR/t about 40 to 50 EUR/t lower in Poland than in Germany. In contrast, a small plant of 90,000 t/a forest residue conversion capacity would have 110 to 120 EUR/t higher biooil production costs due to the scale of unit-effect (see fig. 22).

The figure below shows where the first plants of the Catalytic Pyrolysis-pathway would be situated in the study area. There are three Catalytic Pyrolysis plants of about 535,000 t/a feedstock capacity (maximum size), the two Eastern supply the Plock-refinery, the Western Schwedt. The forestry residue density in the eastern sourcing areas are in average 0.32 and 0.24 t/km²*a for the Slupski and Wloclawski plant. This is relatively low compared to the 0.57 t/km²*a in the catchment area of the Gorzowski-plant, which seems to propose shorter transport distance from forest to plant. However, average transport distances are with 92 km only slightly better than the 95 km of the Slupski-plant, which means the transport network is there far better than in the Gorzowski-region. The Wloclawski plant has 111 km average transport distance. Concerning the feedstock transport costs there are 19 and 21.6 EUR/t for the eastern plants and 19.5 for the Gorzowski-plant. Costs for conversion of forest residues to biooil are 714, 719 and 725 EUR/t for the plants in Slupski, Gorzowski and Wloclawski-region. The costs for railway transport to the Plock-refinery are 12 and 16 EUR/t biooil for the Wloclawski and Slupski-plants. Biooil transport costs from the Gorzowski-plant to the Schwedt refinery are 13.5 EUR/t but would be around 25 EUR/t for the transport to Plock. Would the Slupski-biooil be supplied to the Gdansk-refinery, transport costs were just 9.4 EUR/t. Concerning the biooil costs free Plock-refinery, the closer-by Wloclawski-plant outcompetes the Gorzowski-plant, which has lower production costs. The CP-based transportation fuel production costs were calculated to be 1,621 EUR per tonne in Plock and 1,663 EUR/t in Schwedt. If the biooil would be provided to the nearest refinery, the chain Slupski-CP for upgrading in Gdansk had with 1,650 EUR/t the lowest production costs. In the figure shown below upgrading at the Plock-refinery performs best because this largest refinery in the study area has the highest upgrading-capacity and has reasonable biooil transport costs. The expected greenhouse gas avoidance of all pathways is about 80% as compared to fossil fuel.

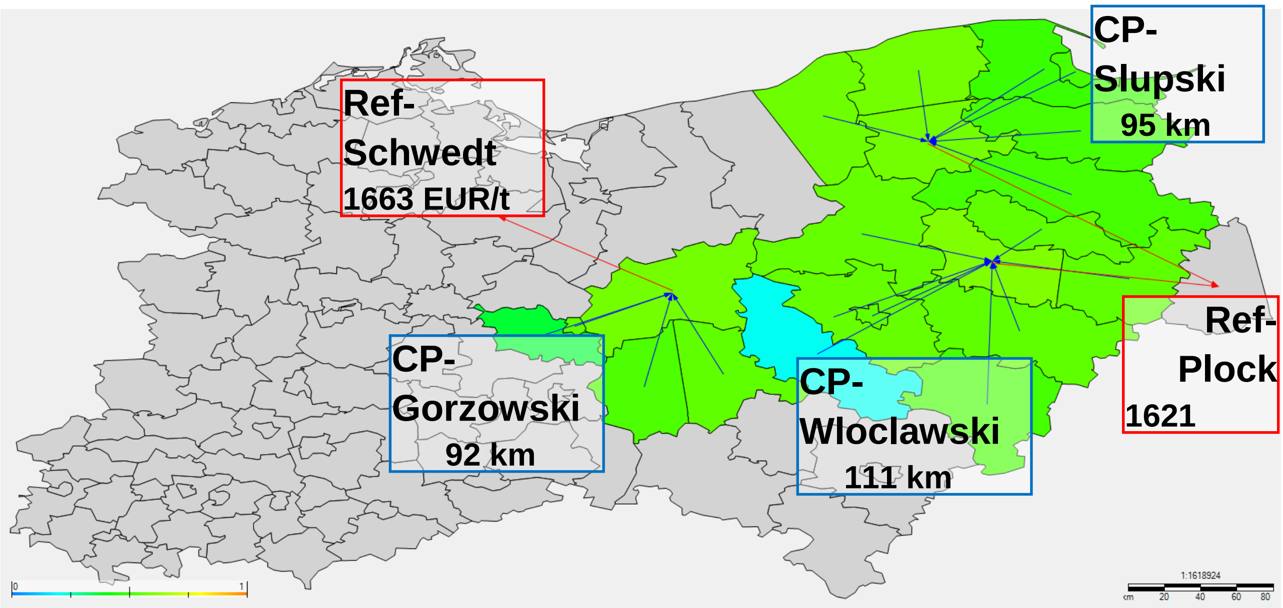


Figure 29: CP-plants in Slupski and Poznan and biooil upgrading in the Plock-refinery is the most cost-effective implementation of the Catalytic Pyrolysis to transport fuel-pathway in the study area. An even better site for a CP-plant is in the Gorzowski area, upgrading of its oil would be most cost-effective in the Schwedt-refinery near-by. Green shading: 40-60% forestry residue utilisation; Blue arrows: forest residue transport to CP-plant; Red arrow: biooil transport to refinery.

In comparison to other regions in Europe, the catalytic pyrolysis in the study area is relatively competitive. Running all refineries in the study area at full upgrading capacity would consume only about 1/3 of the available forest residue potential in the most profitable areas. If there is a demand for more CP-fuel either dedicated facilities might be constructed in the area or CP-biooil might be supplied to refineries elsewhere. These might be located in Rotterdam, the Netherlands, which are a centre of the European refining industry, offering an upgrading capacity of over 800,000 t/a biooil. It can't be fuelled from local sources as Dutch forest residues are far too low in amount and scattered: Some 70,000 t/a biooil would be produced for 1,014 EUR/t, which would result in transport fuel production costs of 2,133 EUR/t, which would not be competitive.

However, inclusion of the Rotterdam-refineries with the intention to upgrade surplus amounts of biooil changes the modelling outcome in an unexpected way: In the 6 parallel runs, forestry residue are sourced as expected from the whole study area and the average utilization increases from 37 to 50-60 %. The CP-plants are larger and mostly at maximum capacity (shown in the figure below). Unexpected was that over 60 % of the biooil is supplied to Rotterdam leaving Plock and often Schwedt as the only remaining regional refineries, supplied by close-by CP-plants. The total transport fuel production exceeds 800,000 t/a. Some results of the best run are shown in the figure below. Logistic costs for biooil supply from the 7 catalytic pyrolysis-plants to Rotterdam amounts to 42.4 EUR/t in average, 14 EUR/t for Plock and 9 EUR/t to the Schwedt-refinery. Fuel production is most economic in Plock (1624 EUR/t), Schwedt produces at 1,653 and Rotterdam at 1,670 EUR/t. Rotterdam has the 4-fold production capacity of the Schwedt-refinery leading to savings of 150 EUR per tonne transport fuel in upgrading costs compared to higher logistic costs in the order of 25 to 45 EUR/t transport fuel. In this optimisation Rotterdam is supplied by the more expensive German CP-plants while Schwedt receives its biooil from Polish CP-plants with only two smaller deliveries of German forest residues to the CP-plant in Szczecin. If Schwedt would be supplied e.g. from the relative expensive CP-plants in Potsdam and Prignitz (North Western plants) and Rotterdam from Polish plants, production costs in Schwedt would be 1,738 EUR/t and 1,635 EUR/t in Rotterdam.

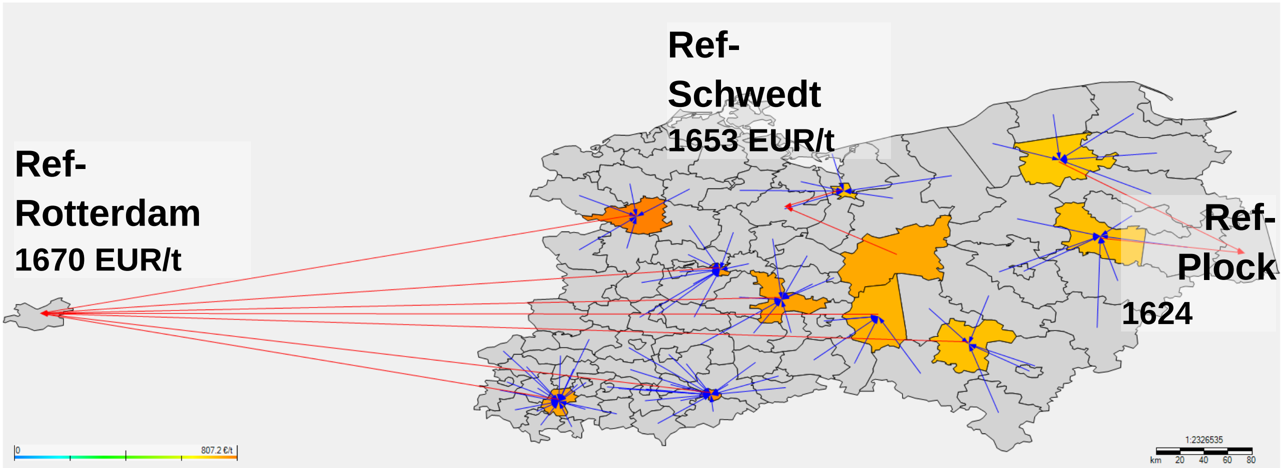


Figure 30: Increase of transport fuel production from Catalytic Pyrolysis by supply of biooil for upgrading to Rotterdam. Regions with CP-plants are coloured according to biooil production costs (yellow-714 EUR/t; red-807 EUR/t). Forest residue procurement is indicated by the blue arrows, red arrows indicate biooil transport for upgrading at existing refineries. Total transport fuel production costs and amounts are given for the refineries as yielded in this best of 6 parallel optimisation runs.

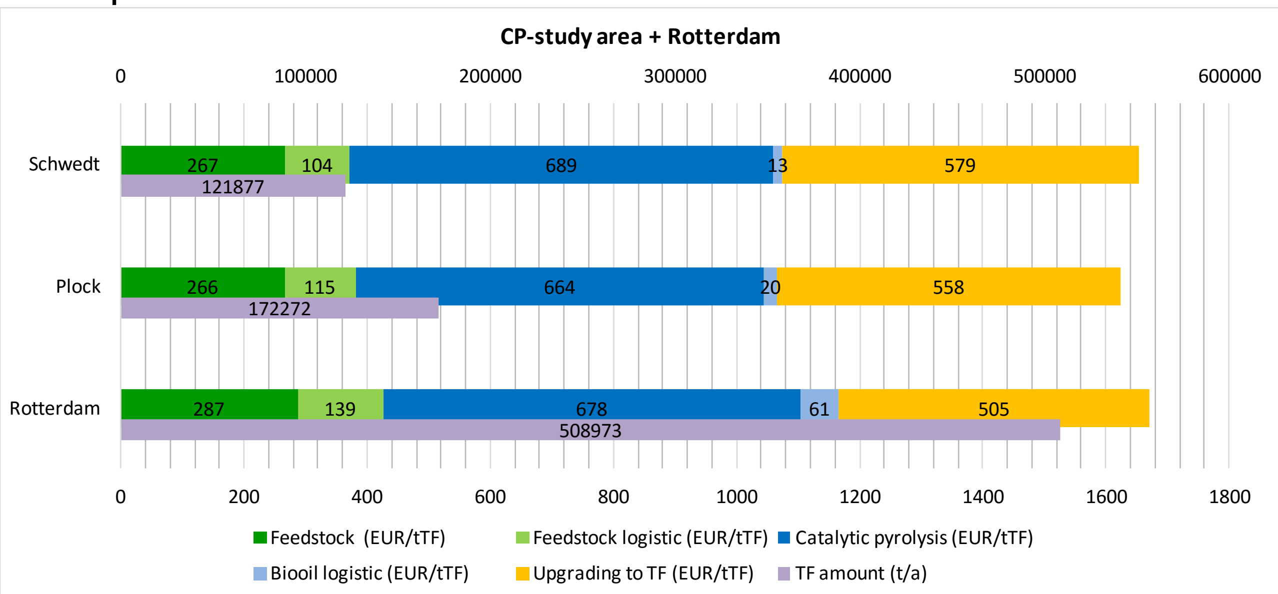


Figure 31: Composition of production costs and amount of Catalytic Pyrolysis-based transport fuel in a scenario foreseeing increase of fuel production by biooil export to Rotterdam.

The value added of the CP-value chain shown below has basically 3 categories: The regions where the feedstock is sourced profit by up to 9 million EUR per year, depending on size and forestry residue availability (shaded in blue). At the sites of the eleven decentral CP-plants between 35 and 65 million EUR per year are generated, while the two smaller refineries receive an additional 82 and 107 million EUR/a, Rotterdam is at 290 million EUR/a. The total added value in the study area is 1040 million EUR per year, 80 million more than in the reference scenario.

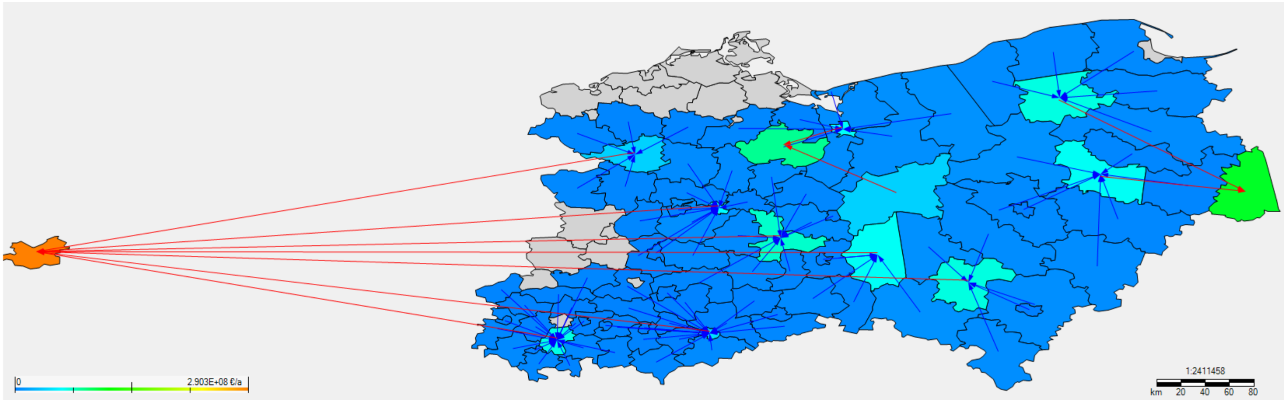


Figure 32: Added value in the regions of the study area. Heavy blue shading: 0.2 to 9 million EUR/a; light blue: 35 - 65 MEUR/a; green: 82 to 107 MEUR/a; red: 290 MEUR/a

Table 7: Overview on key results of the main scenarios of the CP-value chain.

Scenario	Upgrading in 4 reg. refineries	First plants	2 reg. refineries + Rotterdam
Average production costs [EUR/t]	1661	1635	1658
Average production costs [EUR/L]	1.40	1.38	1.40
Local added value [million EUR/a]	960	444	1040
Av. feedstock procurement ratio [%]	37	17	52
Fuel amount [t/a]	531,000	263,000	803,000
Blend in transport fuel [%]	3.4%	1.7%	5.1%
GHG-avoidance [%]	81	81	81
Contribution to 6% GHG-avoidance target [%]	50	0	1
GHG-avoidance costs [EUR/t]	505	495	504

A variation of this scenario might be, that Rotterdam is supplied also from other regions as e.g. the Baltics, where biooil production potentials exceed the upgrading capacity. Then, all 4 local refineries would be preferentially served, which reduces the supply to Rotterdam to 50% and keep the local added value high. An according rearrangement of the above described optimisation run is shown below as an example. Overall it has higher production costs because it is not possible to add '50% external supply' to the Rotterdam plant in the optimisation model. Provided, that this comes e.g. from the Baltic States one can assume production costs as shown below.

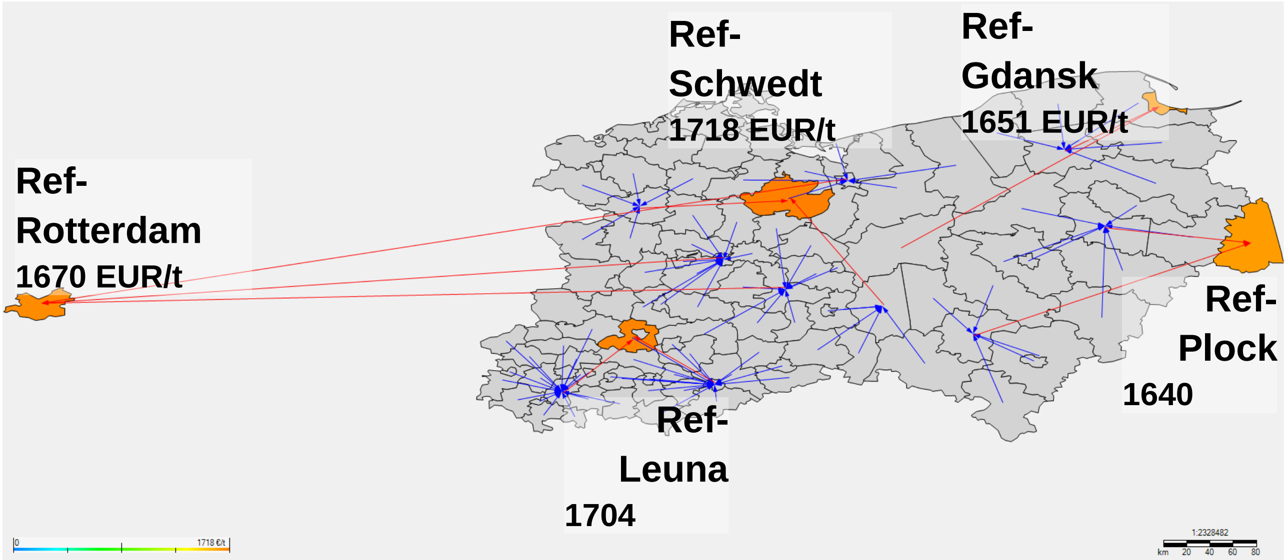


Figure 33: Fuel production from Catalytic Pyrolysis and supply of surplus biooil for upgrading to Rotterdam. Regions with CP-plants are coloured according to biooil production costs (yellow-714 EUR/t; red-807 EUR/t). Forest residue procurement is indicated by the blue arrows, red arrows indicate biooil transport for upgrading at existing refineries. Total transport fuel production costs and amounts are given for the refineries.

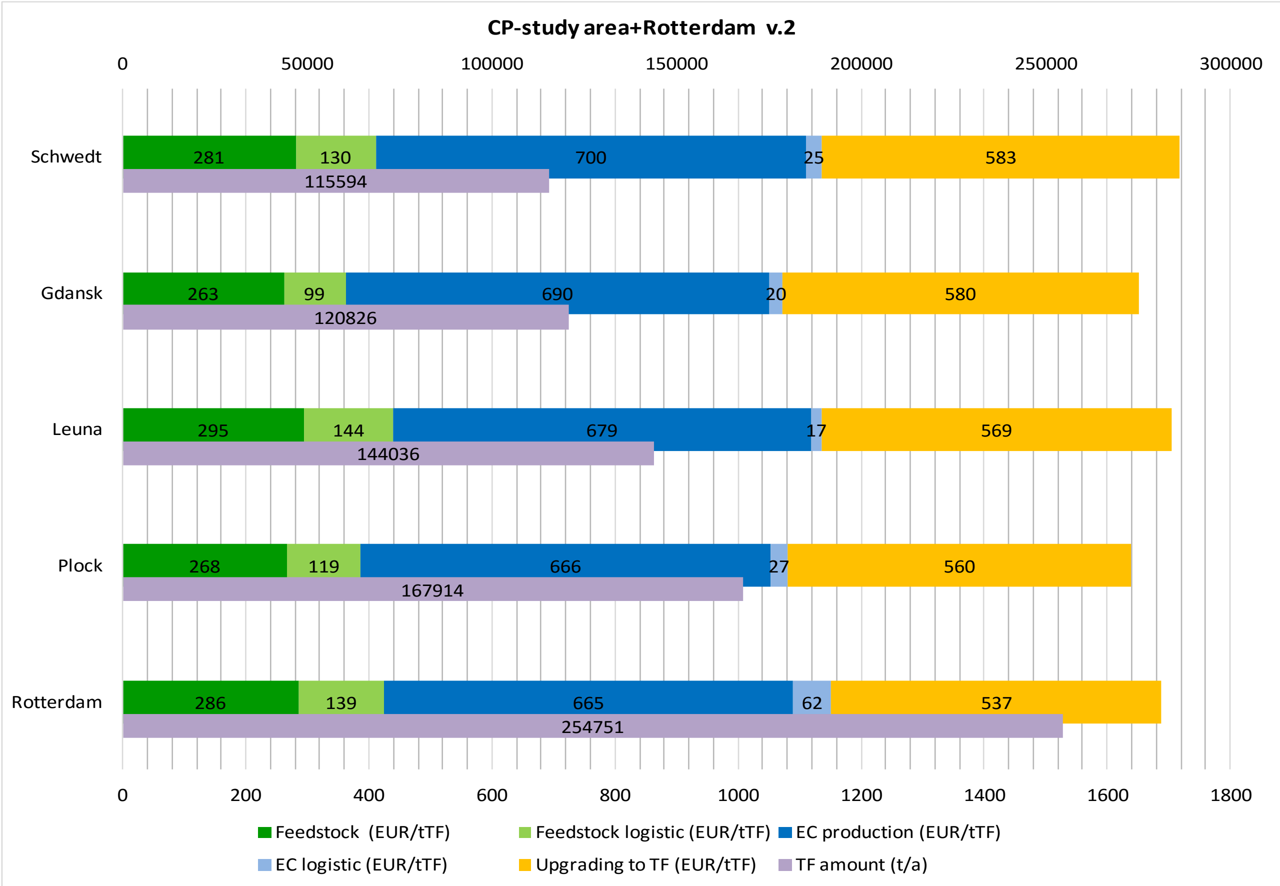


Figure 34: Composition of production costs and amount of Catalytic Pyrolysis-based transport fuel in a scenario foreseeing increase of fuel production by export of surplus biooil to Rotterdam.

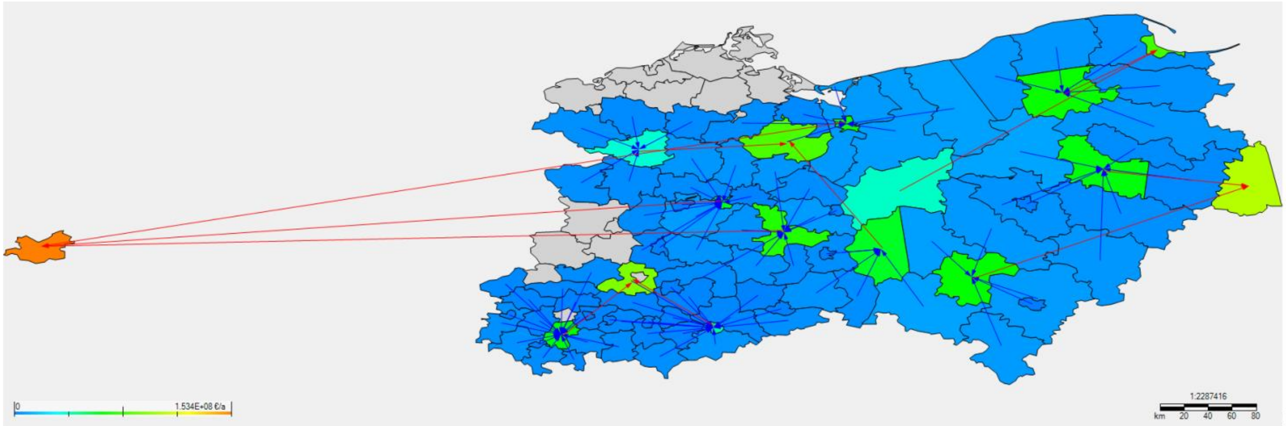


Figure 35: Added value in the regions of the study area. Heavy blue shading: 1 to 10 million EUR/a; cyan: 35 MEUR/a; green: 60 to 110 MEUR/a; orange: 153 MEUR/a

The value added of this more study-area focused increase of CP transport fuel production shown above has basically 3 categories: The regions where the feedstock is sourced profit by up to 9 million EUR per year, depending on size and forestry residue availability (shaded in blue). At the sites of the eleven decentral CP-plants between 35 and 65 million EUR per year are generated, while the four smaller refineries receive an additional 80 and 105 million EUR/a, Rotterdam is at 150 million EUR/a. The total added value in the study area amounts to 1200 million EUR per year, which is about 250 million more than in the reference case.

6.2. Biofuel production with the Fast Pyrolysis value chain

In contrast to the CP-value chain which profits of existing infrastructure for upgrading in refineries, the plants of the Fast Pyrolysis pathway are stand-alone. Biosyncrude is produced in Fast Pyrolysis plants situated in feedstock-rich areas and transported by rail to central synfuel plants. These tend to be at logistic nodes for reason of low transport costs, with the side effect of short supply distance to the consumer. Compared to the CP-process described above, the capacity of the central synfuel plant is with a design size of 1 GW four times higher. The figure below shows an optimised network of FP- and synfuel-plants in the study area. Straw transport to FP-plants is indicated with blue arrows, the produced biosyncrude is transported to synfuel plants at regions indicated by red arrows. The shading shows the relative density of available straw (technical potential after deduction of agricultural demands), expressed in tonnes straw per hectare of total land surface and year (not field surface!). Straw density peaks in the Börde-region in the south-west of the study area with nearly 2 t/ha*a (red), followed by 1.6 t/ha in Mecklenburg in the north-west (yellow). Highest density in the Polish part is around 1 t/ha in Lower Silesia (green). Many of the 16 decentral plants are situated in these areas of high straw availability.

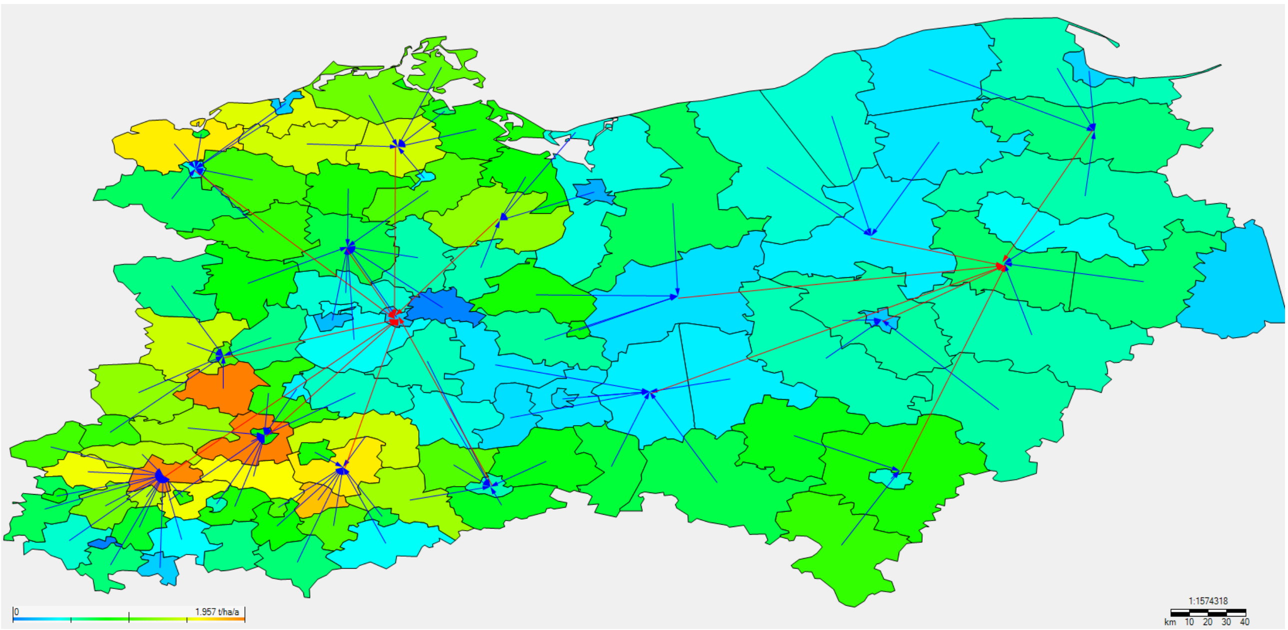


Figure 36: Straw transport (blue arrow) to Fast Pyrolysis plants and biosyncrude transport (red arrow) to central synfuel plants in the study area. The shading shows the straw density in tonnes per hectare total surface area and year. Red shading: 2 t/ha*a; yellow: 1.5 t/ha*a; bright green: 1 t/ha*a; light blue: 0.3 t/ha*a.

The straw price free field side stack varies with the amount of straw per hectare and the field size, labour costs play a minor role. In the German part of the study area the large field size (sometimes exceeding 100 ha per field, estimated averages between 15 and 35 ha) and high straw amounts per hectare field size (4.3 to 5.3 t/ha) lead to straw prices around 46 EUR/t. In the Polish part fields are smaller (averages between 1.1 and 4.3 ha) and less productive (3.1 to 4 t/ha field size) leading to straw prices between 47 and 49 EUR/t at sourcing ratios up to 50% of the available amount. In the best of 10 runs the price free FP-plant varied between 60 and 68 EUR/t (shown below), which is relatively little. It is influenced by the sourcing ratio-dependent straw price, transport distance and costs per tonne-km. The average transport distance from field side stack to the FP-plant is 80 km. The maximum distance is 183 km, the distance for transport to a FP-plant in the same region is 7 to 53 km (shown below). The average straw sourcing ratio is 60%, 9.7 of the available 16.2 million tonnes are transported to the FP-plants.

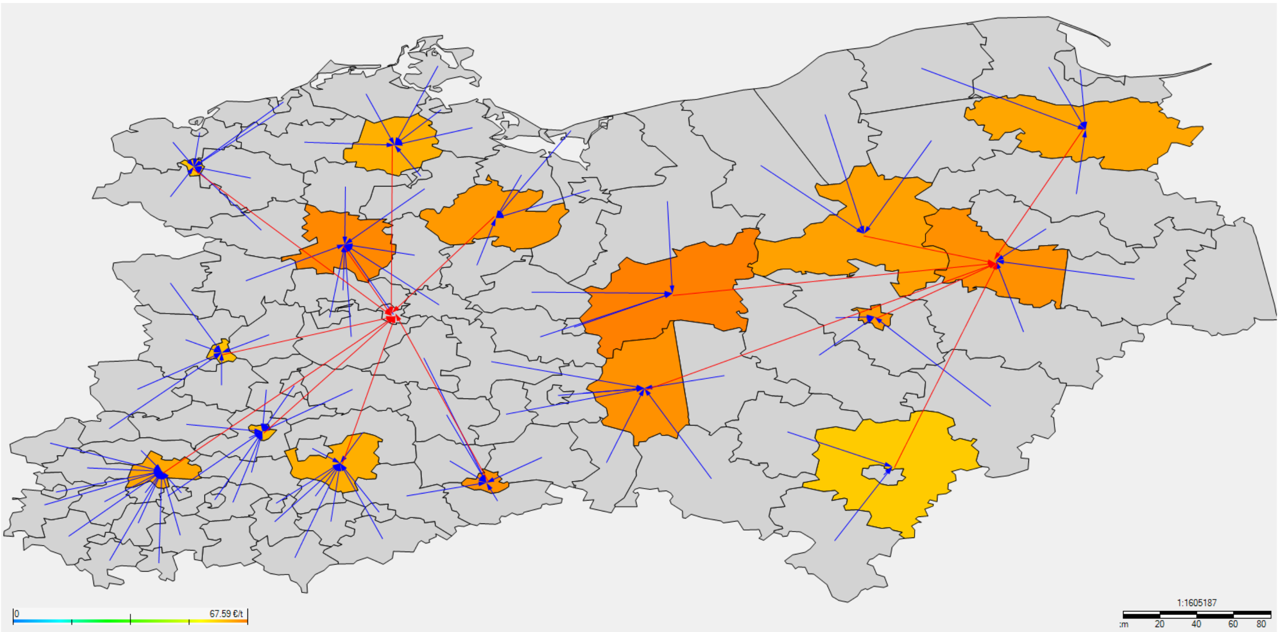


Figure 37: Straw price free FP-plant. Beige: 60 EUR/t; heavy orange: 68 EUR/t.

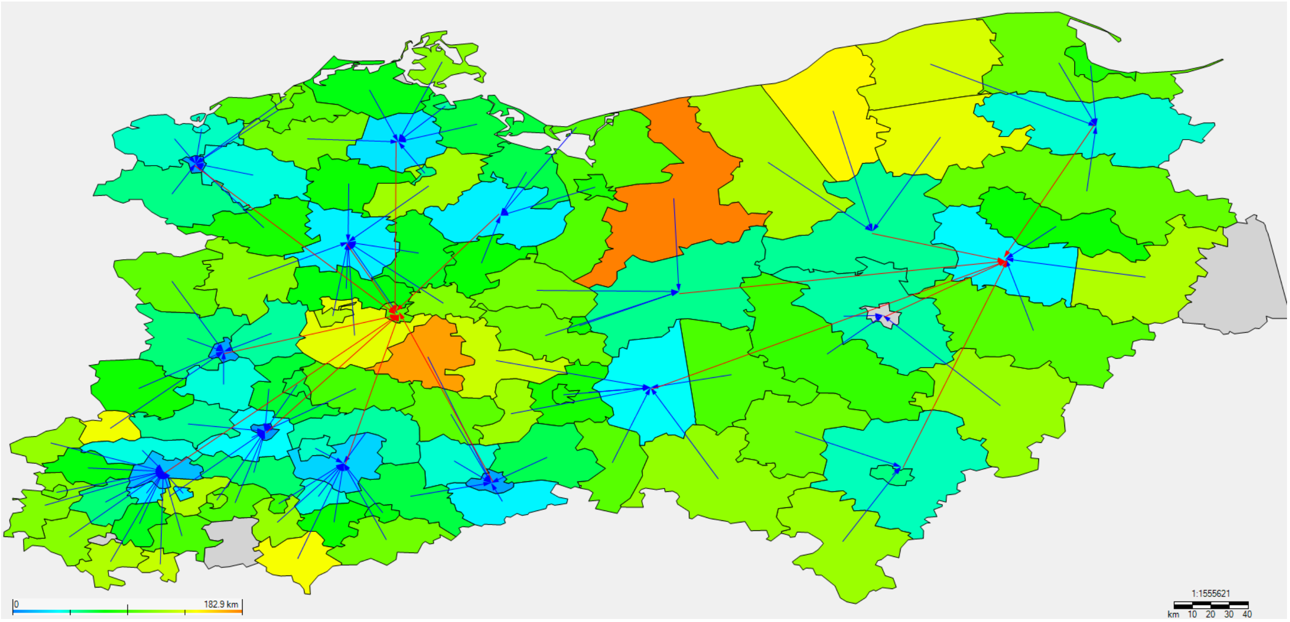


Figure 38: Distance of straw transport (blue arrow). Red: 183 km; yellow: 140 km; green: 100 km; blue: 35 km.

The Fast Pyrolysis plants in this best optimisation run are all relatively large (shown below). With 510,000 to 660,000 t/a feedstock conversion capacity, they are 2.3 to 3 times larger than the design size. Accordingly, the biosyncrude production costs are with 221 to 235 EUR/t quite similar. The 16 FP-plants supply the biosyncrude (red arrows) to two central gasification plants which produce the synfuel. The average biosyncrude transport distance is about 180 km.

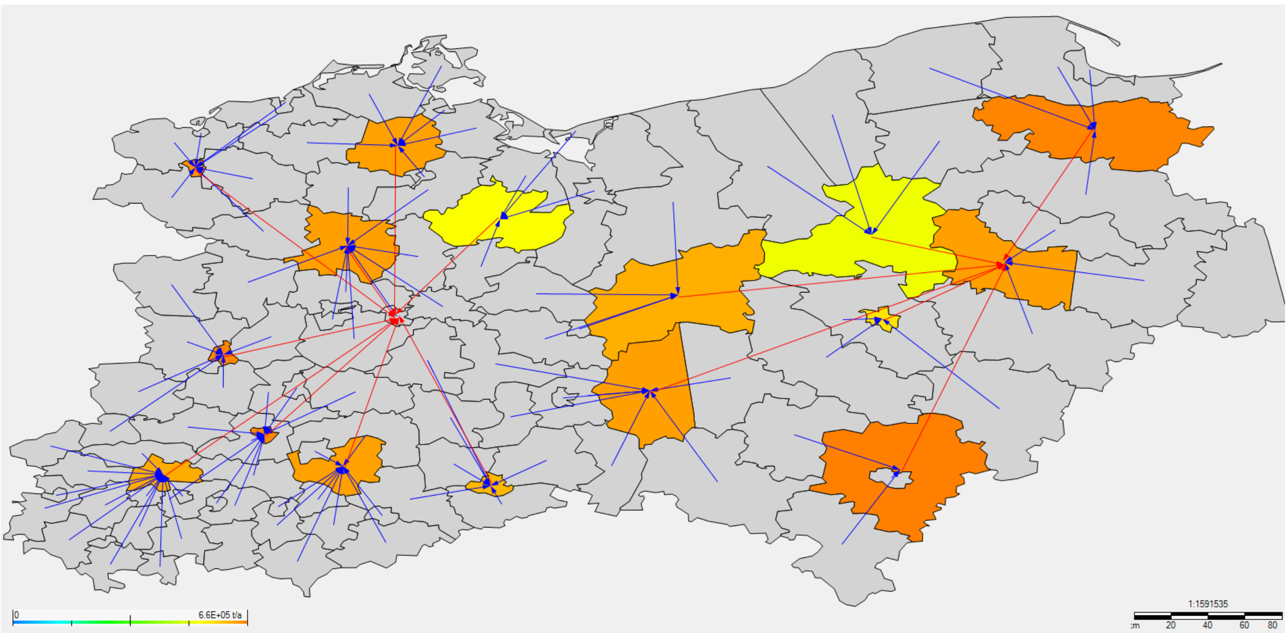


Figure 39: FP-plant straw conversion capacity. Yellow shading: 550,000 t/a; red: 660,000 t/a.

The central synfuel plants are situated in Potsdam and in the Wloclawski-region as shown in the figure below. The Potsdam facility is with 3.67 Mt/a somewhat larger and converts the syncrude of the German FP-plants to 550,000 t/a synfuel at a price of 2362 EUR/t. The plant in the Polish Wloclawski-region has a capacity of 2.87 Mt/a and produces 420,000 t/a synfuel at 2407 EUR/t.

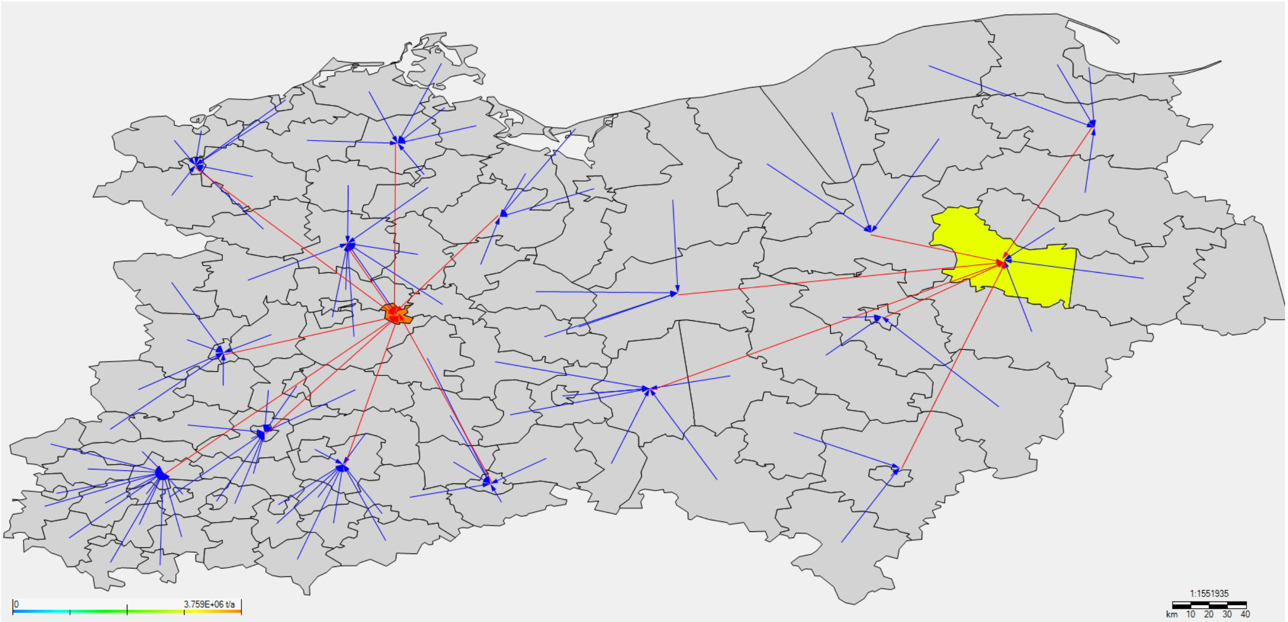


Figure 40: Biosyncrude conversion capacity of the central synfuel plants. Yellow: 2.87 million tonnes per year; red: 3.67 million tonnes per year.

The regional added value can be differentiated in 3 classes: The regions with the synfuel plant (Potsdam and Wloclawski) have with 526 to 587 million EUR/a the highest added value. In the next class are the 15 regions with a biosyncrude plant, receiving 47 to 74 million EUR/a. Regions supplying straw are in the third category of up to 19 million EUR/a added value, the average is 5.1 MEUR/a, as shown in the figure below.

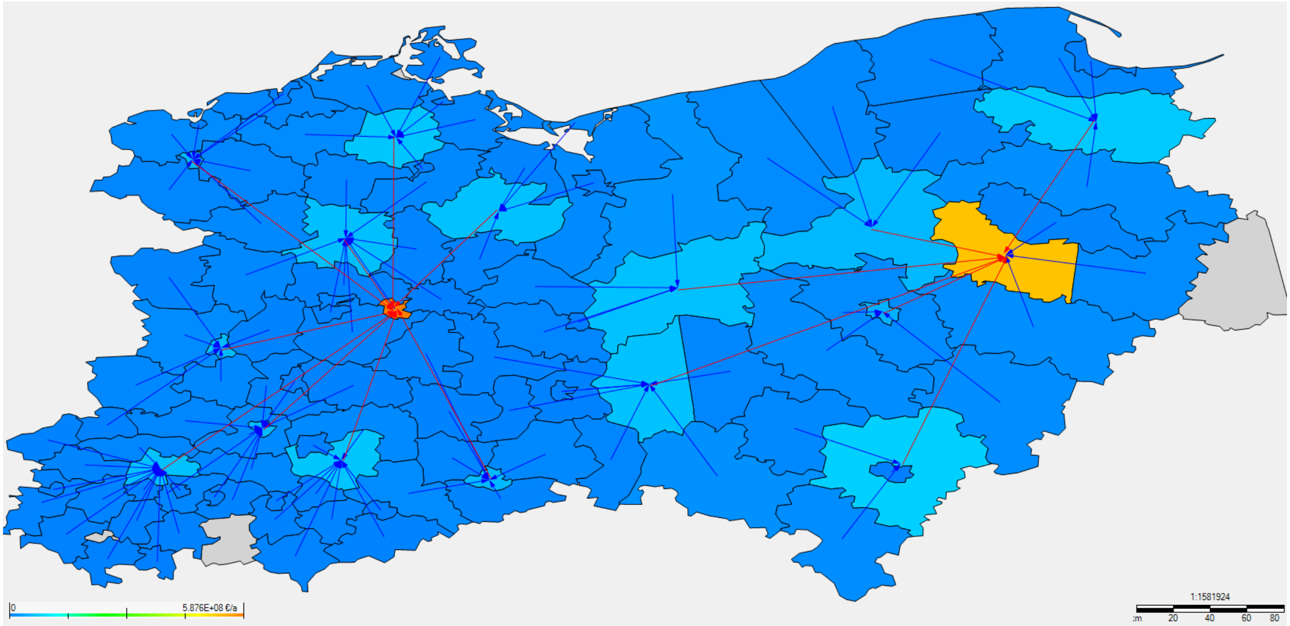


Figure 41: Local added value generated on the FP-synfuel value chain. Red: Potsdam synfuel plant, 587 MEUR/a; orange: Wloclawski FP and synfuel plant, 526 MEUR/a; light blue: FP-plants 47 to 74 MEUR/a; heavy blue: straw supplying regions, up to 19 MEUR/a

The total production costs of the straw – fast pyrolysis – synfuel value chain are calculated to be around 2400 EUR/t for the two plants of the study area. The contribution of the individual cost items to the total costs is specified in the figure below. While the feedstock sourcing costs are 37 EUR/t transport fuel lower in the Potsdam-plant, the straw transport costs are 28 EUR/t higher compared to the plant in the Wloclawski-region. Due to the similar production capacity the costs for decentral conversion of straw to biosyncrude are very similar as are the transport costs to the central synfuel plant. Gasification of biosyncrude for production of synthetic transportation fuel is a process with a strong scaling effect. Therefore, the larger plant in Potsdam has 44 EUR/t lower conversion costs.

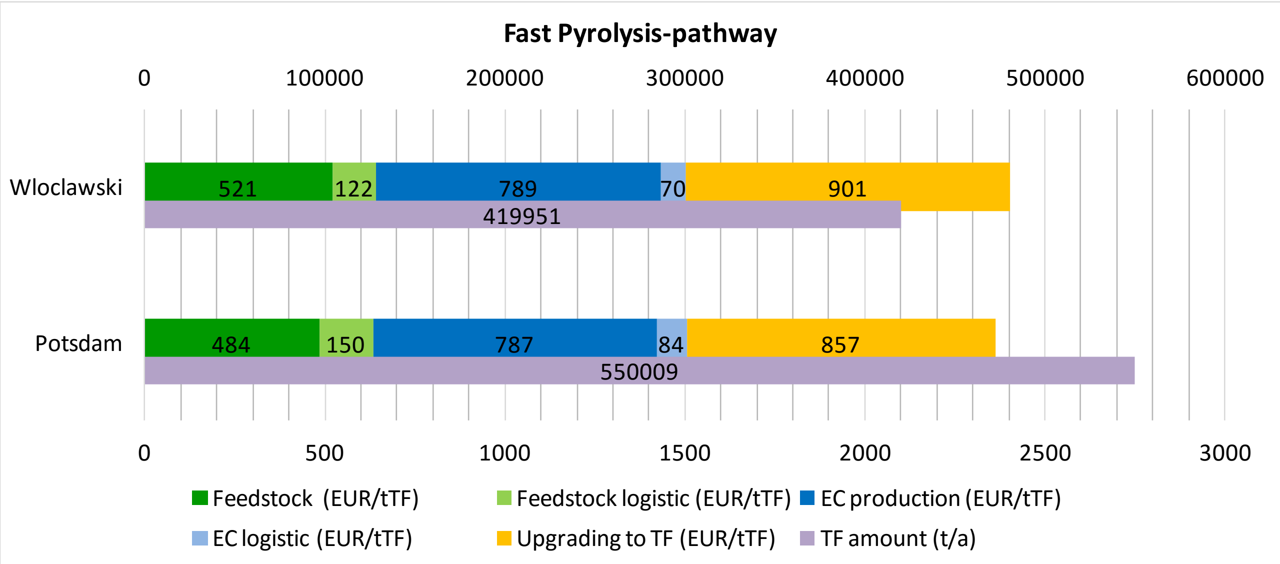


Figure 42: Composition of production cost of straw - Fast Pyrolysis-based synthetic transportation fuel in the study area.

The two synfuel plants in Wloclawski and Poland produce a total of 970,000 t transport fuel per year with a greenhouse gas avoidance potential of 80%. If used exclusively for fuel blending in the study area it would have a share of 6.4% by mass and contribute 85% to achieving the GHG-avoidance target of 6%.

Market implementation of the FP-process in the study area

The first plant of the Fast Pyrolysis process for production of synthetic transport fuels from straw would be build where the production costs are lowest. In the Polish part of the study area the straw prices are higher due to lower amounts per area and smaller field sizes but the lower loans reduce transport costs. The following figure shows regions with similarly low biosyncrude production costs between 221 and 223 EUR/t, making them candidates for the first plants of the Fast Pyrolysis value chain. These plants all have a straw converter capacity of 660,000 t/a, which is the largest size foreseen in the optimisation model. The transport distances vary between 58 and 91 km, with an average of 70 km over all six sites. The plant for the upgrading of biosyncrude to synfuel is stand alone and it would be most economic to construct it at the site of the first straw converter, saving costs for transport of the about 410,000 t/a biosyncrude. However, this amount is below the minimum capacity of the gasification plant foreseen in the optimisation model. As these plants have a strong scaling effect (see figure 22), this low size increases the production costs significantly: The first synthetic transportation fuel production at one of these regions would have costs between 2699 and 2733 EUR/t. The composition of total synfuel production costs is shown below.

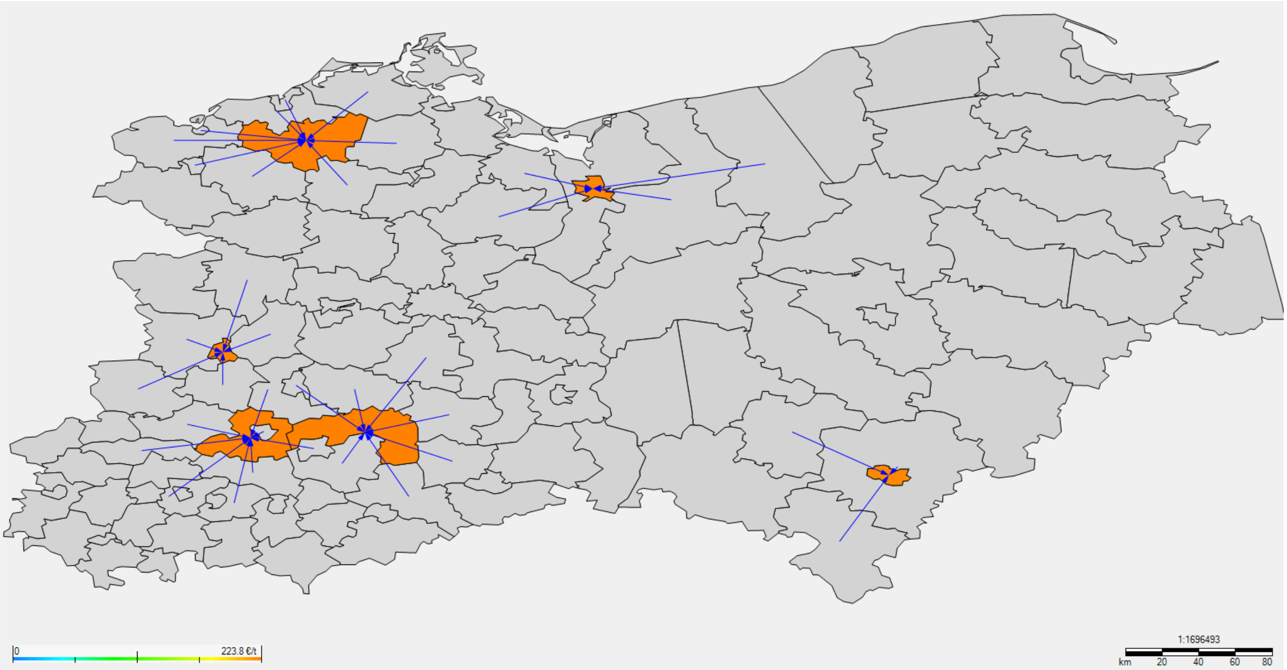


Figure 43: Regions of comparable competitiveness for the first plants of the Fast Pyrolysis value chain from straw to synfuel. Blue arrows indicate straw transport, shading indicates biosyncrude production costs between 221 and 223 EUR/t.

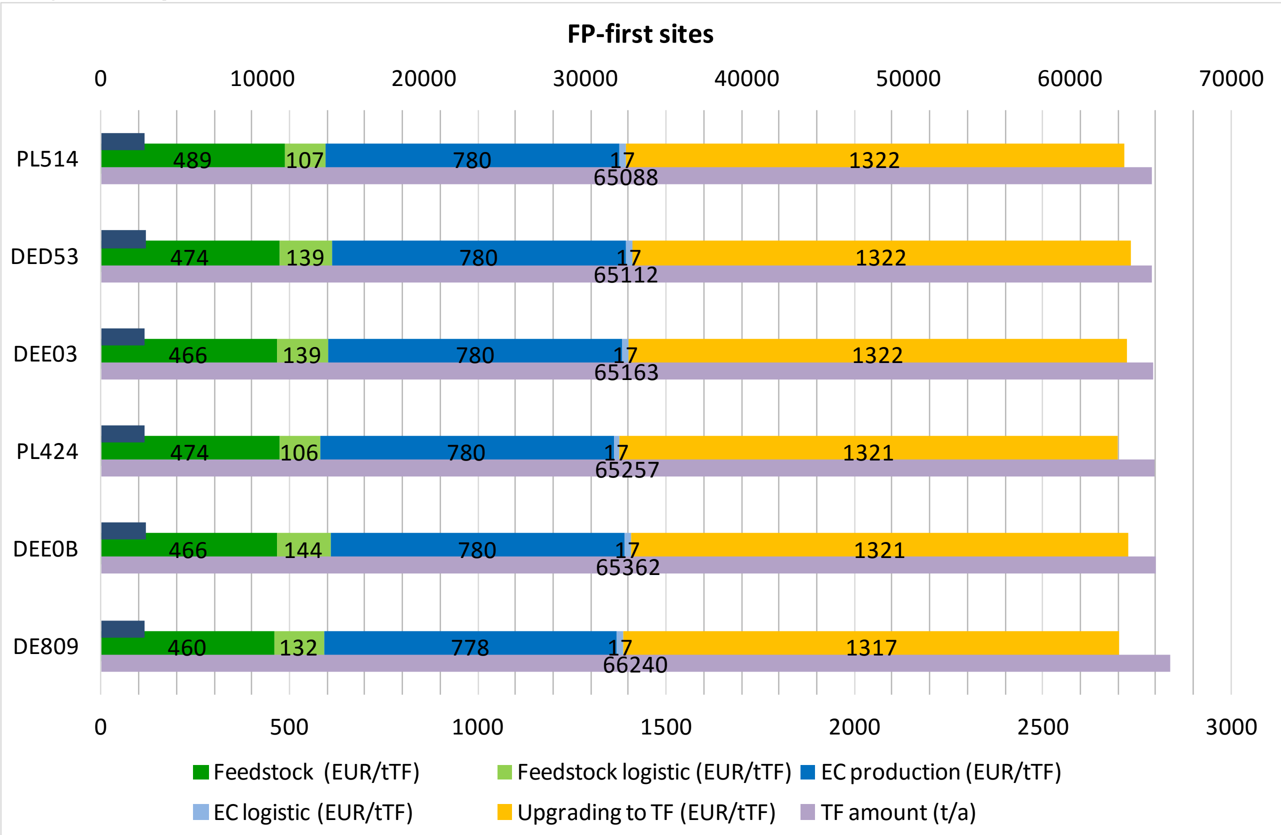


Figure 44 Composition of synfuel production cost of straw - fast pyrolysis - synthetic transportation fuel value chain in the study area.

Sensitivity analysis: Direct supply of straw, pyrolysis and gasification plant at same site

The rationale behind the fast pyrolysis straw pretreatment and the rail-transport from several decentral plants to a central synfuel plant is to profit of scale-effects in upgrading and reduce the transport efforts at the same time. The chapter above on first FP/synfuel plants has shown that total fuel production costs are relatively high (+300 EUR/t) if the upgrading capacity is restricted to one maximum size straw converter. In the following the effects of direct supply of straw to the region of a full size central plant is shown. It is assumed that the maximum size FP-plants with a straw conversion capacity of 660,000 t/a can't be build bigger and that up to 9 max-size FP-plants are constructed at the site of the central upgrading unit. In that case about 10 million tonnes straw would be transported in the optimisation shown below to two regions, Szczecin and Halle. The average transport distance would be 209 km, the maximum distance is 450 km. The following figure shows the transported amounts of straw. In the total synfuel production costs the straw transport costs would roughly double from 120 to 150 EUR/t to about 265 EUR/t fuel compared to the reference case. In contrast the biosyncrude transport costs would not arise, saving 60 EUR/t synfuel. The total production costs would increase from about 2380 EUR/t to 2450 EUR/t. So the staged approach with regional pretreatment of straw and efficient rail transport of pyrolysis oil to a central synfuel plant comes with relatively short straw transport distance, lower total production costs and a better regional distribution of added value and employment.

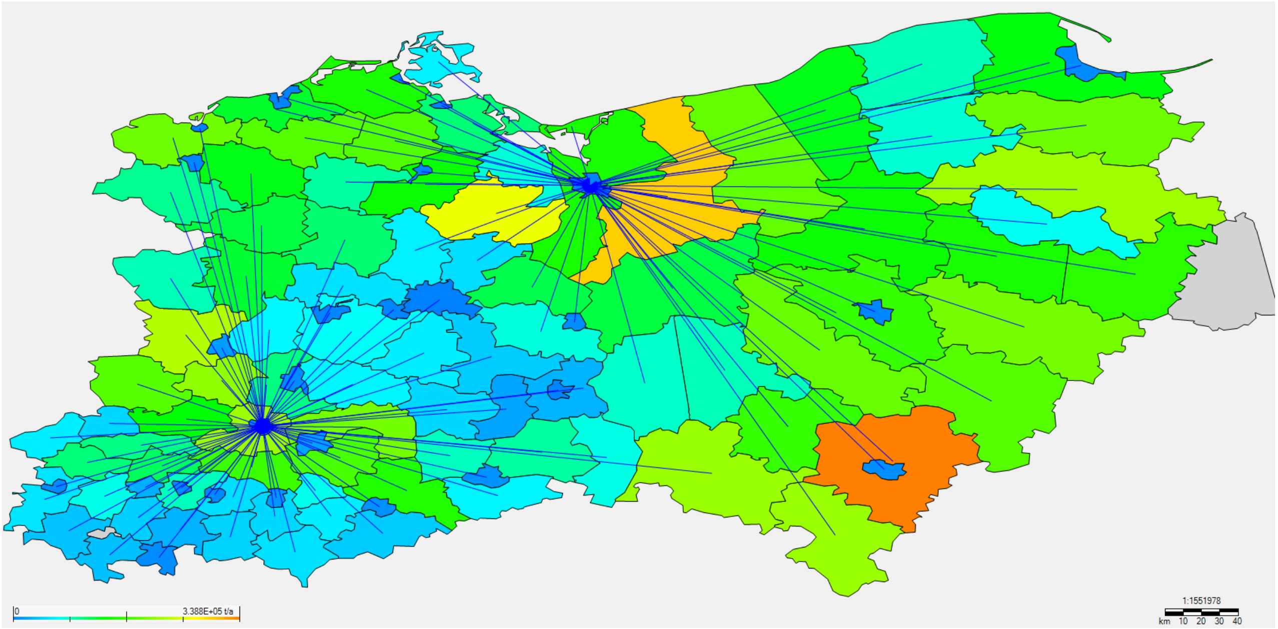


Figure 45: Straw amounts transported from the regions to the central pyrolysis and upgrading plants in sensitivity study. Blue: up to 75,000 t/a; green: 75,000 to 200,000 t/a; yellow: 200,000 to 300,000 t/a; red: 340,000 t/a.

Further results for these pathways in EU-28 can be retrieved under www.bioboost.eu.

6.3. Discussion of results of value chain optimisation

The table below shows the key results of the evaluation of the CP- and FP-based value chains for the conversion of forestry residues and straw to drop-in biofuels in the study area.

Table 8: Overview on optimisation results for the two advanced biofuel production pathways in the study area. Avoidance costs were calculated as difference to the price of fossil fuels (0.26 EUR/l gasoline and 0.27 EUR/l diesel based on CIF-NWE rates of 16.03.2016)

Pathway	Forest residues-CP-transport fuel			Straw-FP-synfuel	
Scenario	Upgrading in 4 reg. refineries	First plants	2 reg. refineries + Rotterdam	full use	first plants
Average production costs [EUR/t]	1661	1635	1658	2381	2699
Average production costs [EUR/L]	1.40	1.38	1.40	1.80	2.04
Local added value [million EUR/a]	960	444	1040	2490	176
Av. feedstock procurement ratio [%]	37	17	52	60	4
Fuel amount [t/a]	531,000	263,000	803,000	970,000	65,300
Blend in transport fuel [%]	3.4%	1.7%	5.1%	6.2%	0.4%
GHG-avoidance [%]	81	81	81	80	80
Contribution to 6% GHG-avoidance target [%]	50	0	1	1	0
GHG-avoidance costs [EUR/t]	505	495	504	630	728

The production costs of the studied advanced biofuel pathways are with 1.38 to 1.8 EUR per litre far above the actual prices of fossil fuels being at about 0.27 EUR/l at 42.40 USD per Barrel and a 1.13 USD per EUR. However, the European Directives on renewable energy (RED 2009/28/EC), fuel quality (FQD 2009/30/EC) and sustainability (ILUC 2015/1513 EC) set a target of 10% bioenergy share in transport and a related reduction of GHG-emissions of 6% by 2020. These targets can not be achieved with the established starch-, sugar- or oil-crop based biofuel production pathways for two reasons:

- They have a GHG-avoidance between 50 and 60% requiring blends of 10 to 12% biofuel in fossil fuel to achieve the 6% GHG-reduction target.
- Such high average blend ratios are in conflict with the oxygenate blend walls of the commonly available fuels E5 and E10 gasoline and B7 diesel. Fuels with a higher avoidance potential like E85, E100, B100, bio-CNG or renewable power for all-electric vehicles are relative niche markets.

A way out are drop-in fuels which could be blended at (almost) any ratio due to their hydrocarbon nature. A commercial example is Neste's NEXBTL based on hydrogenated fatty acids of which about 1.2 million tonnes per year were produced in Europe in 2015. The fuels of the CP- and FP-value chains of this study would also be drop-in fuels. The joint JRC-EUCAR-Concawe biofuel-report[8] calculated a 4.3% GHG-avoidance for the reference scenario based on assumptions on the vehicle fleet, consumption and fuel production. This would leave a gap of 1.7% which could

[8] JEC (2014): EU renewable energy targets in 2020: Revised analysis of scenarios for transport fuels http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/JEC_Biofuels_2013_report_FINAL.PDF

support market introduction of CP- and FP-biofuel. With regard to the 15.7 million tonnes fuel consumption in the study area an amount of 330,000 t fuel with a GHG-avoidance of about 80% would fill the gap. The optimisation model calculates the fuel production costs of the CP-value chain to about 1.25 EUR/L gasoline and 1.4 EUR/l diesel according to the production slate of the refinery and about 1.8 EUR/L gasoline from the FP-value chain.

The following wholesale prices and legal conditions were observed in March 2016 in Germany, which has implemented a GHG-emission reduction target of 3.5%:

- A price of 0.26 EUR/L fossil fuel at a rate of 1.12 USD/EUR
- 465 EUR/m³ for RED Ethanol T2 fob Rotterdam
- 665 EUR/m³ for FAME biodiesel free German producer[9]
- An energy tax of 450.3 EUR/m³ diesel and 655 EUR/m³ gasoline
- VAT of 19%
- A penalty of 470 EUR for every tonne CO_2-emission, which exceeds the GHG-reduction target
- Adjustment for energy content (e.g. E10 only 96% compared to pure fossil)
- Exclusion of costs for logistic to filling station, marketing and profit (about 0.1 to 0.15 EUR/l)

Using these conditions but a GHG-emission reduction target of 6%, CP-diesel would cost 0.95 EUR/l which is somewhat above the costs of 0.91 EUR/L for B7-diesel. For comparison a purely fossil diesel would cost 1.18 EUR/l due to a CO_2-penalty of 44.8 EUR/m³. The gasoline prices would be 1.16 EUR/L for E10-gasoline, which is slightly below the 1.17 for CP-gasoline and the 1.22 for FP-gasoline. The CO_2-penalty for purely fossil gasoline would be 76.8 EUR/m³ leading to a retail price of 1.18 EUR/l. Altogether, the first generation biofuels compensate the somewhat lower GHG-avoidance by lower purchase costs but the CP-fuel is more economic than paying the CO_2-penalty. FP-gasoline is at the currently low price for the fossil base fuel not competitive. The break even is calculated to be at about 0.75 EUR/L gasoline or 110 USD per barrel Brent crude, a price exceeded sometimes in the past. To be competitive to the CO_2-penalty it would have to cost 1.31 EUR per litre.

Two issues which influence the production costs were remarked in the preparation of this study:

1. The operation costs of the decentral and central plants have no scaling exponent. It was estimated that such an exponent would reduce the production costs by about one quarter.
2. Both pathways are net-producers of renewable electricity. The EC-Renewable Energy Directive foresees to take this side product into account but the calculation carried out in the BioBoost project (Del 6.4) has 100% of the GHG-

[9] http://www.cmegroup.com/trading/energy/, http://www.ufop.de/biodiesel-und-co/biodiesel-preis/

emissions on the biofuel production. If 5.71 g CO_2-equivalents are credited per MJ of net excess power (RED default value for a straw fired power plant) the GHG-intensity of e.g. the FP-pathway drops by 0.76 g/MJ or 5%.

Although the biofuel production costs are high, it has to be remarked that a high share is paid in the study area as loan to workers and as income to farmers and forest owners for the biomass. Another high share (FP-35%; CP-30%) is depreciation for the equipment supposedly sourced from countries of the European Community. Disregarding the construction costs 55% of the added value of the FP-pathway occurs at the rural areas supplying the straw, 21% in regions with FP-plants and 24% in regions with the central fuel production plants. For the CP-pathway, 50% of the added value goes to rural areas supplying forest residues, and each 25% to regions hosting the CP-plants and the refineries. In contrast, the product price of the fossil fuel (before consumer taxes) is composed to about 75% of fees and royalties to the crude oil supplying countries.

However, the pathways described in this case study are not yet commercially available. The FP-value chain is demonstrated at the Karlsruhe Institute of Technology on a level of 2 to 5 MW (TRL 7), the CP-value chain is at small pilot scale (TRL4-5) at CERTH (Centre for Research and Technology Hellas), Royal DSM (The Netherlands) and Neste (Finland). Further efforts for development and precommercial demonstration have to be spent in order to bring these technologies to the market.

7. The case study conclusions

1. In the study area the available and sustainable exploitable potential of straw and forest residues amounts to 300 PJ or 7.1 million tonnes oil equivalent per year.

2. Fully implemented the CP- and FP-biofuel value chains converts about 50% of the available straw and forest residue biomass to 1.5 million tonnes of transport fuel.

3. The synthetic gasoline of the FP-value chain and the CP-biofuel are drop-in fuels and can be blended in high shares with fossil fuel without impacting engine performance or consumption.

4. The CP- and FP-biofuel potential covers about 10% of the annual transport fuel demand in the study area.

5. At a GHG-avoidance of about 80% and assuming local consumption of the CP- and FP-biofuels the CO_2-emissions of the transport sector would be reduced by 7.7 %. This is 25% more than required by the present regulations.

6. At today's price levels, blends in line with the GHG-reduction target for 2020 would costs 0.01 to 0.06 EUR/L more that respective RME- or ethanol-blends. Today such a B10 (RME) or E11(Ethanol 1. Gen.) fuel is not in line with the fuel specifications.

7. The total turnover amounts to 3.500 million EUR per year. About 1/3 is depreciation for the decentral and central plants, 1/3 is for operation of the conversion plants and 1/3 goes to the rural areas supplying the straw and forest residue feedstock.

8. The investment required for full implementation of the CP- and FP-value chains in the study area amounts to about 23 billion EUR. Specific measures to support and back these investments would be needed.

9. The conversion technology of both, the CP- and FP-value chain is currently not commercial available. Further efforts for development and demonstration of these technologies are needed prior to commercialisation.

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