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Techno-economic assessment of fast pyrolysis for the valorisation of short rotation coppice cultivated for phytoextraction

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Tom Kuppens

Promotor: prof. dr. Theo Thewys

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KNOWLEDGE IN ACTION

Dankwoord

"Reach out and lend a hand
Let's change the world somehow
Children across the land
Let's build a better future now!
Hello, brand new day!
Let's change the world and how!
We're gonna find a way
And build a better future now!"

(Het Meneer Konijn Lied, 2012)

Wie een doctoraat schrijft, doet dit om velerlei redenen: het behalen van een diploma als start voor een academische carrière, het behalen van het hoogst mogelijke diploma aan een universiteit als ultieme zelfontplooiing, ... Mijn motivatie (en die van vele anderen) was misschien wat naïef, idealistisch, een tikkeltje utopisch, maar alleszins positief: ik wou mijn steentje (hoe klein of groot ook) bijdragen aan een betere wereld door een onderwerp te kiezen dat aansluit bij duurzame ontwikkeling en de verbetering van ons leefmilieu. Deze bijdrage zou onmogelijk geweest zijn zonder de hulp van velen, die ik hier graag even wil bedanken.

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"You raise me up, so I can stand on mountains
You raise me up, to walk on stormy seas
I am strong, when I am on your shoulders
You raise me up: to more than I can be!"

(Secret Garden, 2003; covered by Westlife and Celtic Woman)

Tom Kuppens
December 2012

Samenvatting

Op het einde van de 19de eeuw en tijdens een groot deel van de 20ste eeuw, werd de Belgische Kempen matig vervuild met zware metalen uitgestoten door de zinkindustrie. Vooral voor cadmium worden de bodemsaneringsnormen in deze regio overschreden. De aanwezigheid van cadmium heeft gevolgen voor de menselijke gezondheid en brengt risico's met zich mee voor de landbouwers in de Kempen. Door de lage pH-graad van de zandgronden, nemen planten immers gemakkelijk zware metalen op. Bijgevolg wil de groentensector niet langer contracten afsluiten met landbouwers die het risico lopen om veiligheidsnormen voor voedsel te overschrijden. De gevolgen voor landbouwers die hoofdzakelijk voedergewassen telen zijn kleiner, maar desalniettemin storend. Daarom dringt een goed beheer van de bodems zich op, indien mogelijk via sanering.

Door de uitgestrektheid van het gebied zijn conventionele physicochemische bodemsaneringstechnieken niet geschikt. Fytoremediatie (of bodemsanering met planten) wordt voorgesteld als een kosteneffectiever en duurzamer alternatief om de metalen te verwijderen of te stabiliseren. Energiemaïs blijkt uiterst geschikt voor fytoattenuatie (waarbij de verwijdering van metalen eerder secundair is), terwijl wilg eerder voorgesteld wordt om de metalen effectief op te ruimen. De lange duurtijd is echter de grootste hinderpaal voor de commerciële ontwikkeling van fytoremediatie, wat gecompenseerd kan worden door combinatie met winstgevende activiteiten zoals energieproductie. Daarom is het van belang om een geschikte conversietechniek te vinden voor de fytoremediërende gewassen, die tegelijkertijd winstgevend is en een oplossing biedt voor het afvalprobleem van de zware metalen. Snelle pyrolyse lijkt veelbelovend dankzij de lage procestemperatuur, waardoor de zware metalen niet vervluchtigen en achterblijven in de koolrest. Daarom is een techno-economische evaluatie van snelle pyrolyse voor de valorisatie van korteomloophout afkomstig uit fytoremediatie het onderwerp van deze thesis.

Hoewel het een vaak gebruikt concept is, bestaan er tot vandaag nog geen goede richtlijnen voor het uitvoeren van een techno-economische evaluatie. Daarom begint hoofdstuk 2 van deze dissertatie met een bijdrage aan de ontwikkeling van een geschikt methodologisch kader. Een techno-economische evaluatie kan gedefinieerd worden als de beoordeling van de technische prestatie of potentieel en de economische haalbaarheid van een nieuwe technologie voor de verbetering van de sociale of milieugerelateerde impact van een bestaande technologie. Dergelijke beoordeling helpt beslissingnemers bij het richting geven aan onderzoek en ontwikkeling en bij het kiezen van investeringen. Een techno-economische evaluatie beantwoordt idealiter drie belangrijke vragen: "Hoe werkt de technologie?", "Is de technologie winstgevend?", "Is de technologie wenselijk?". Het beantwoorden van deze vragen vergt per definitie een multidisciplinaire aanpak. De focus in deze thesis ligt op de rendabiliteit van snelle pyrolyse vanuit het standpunt van een investeerder, inclusief een diepgaande analyse van het economisch risico van de investering door middel van Monte Carlo simulaties en een techniek uit het domein van experimenteel ontwerp.

Vooraleer men de economische haalbaarheid kan inschatten, is er eerst kennis vereist over de technische prestaties van een technologie. Hoofdstuk 3 vat daarom de werkingsprincipes van de beschouwde technologieën samen, en vormt de basis voor de veronderstellingen in het kasstroommodel van hoofdstuk 4. Nog in hoofdstuk 3 wordt uitgelegd waarom pyrolyse een interessante optie is voor de verwerking van vervuilde biomassa: de lagere procestemperatuur in vergelijking met verbranding en vergassing verhindert de vervluchtiging van de zware metalen naar de (rook)gassen. Verbranding en vergassing daarentegen moeten mogelijk aangevuld worden met dure rookgasreiniging om emissie van de zware metalen naar de atmosfeer te vermijden. Aan de andere kant blijkt vergassing meer energetisch efficiënt dan pyrolyse en verbranding.

Vervolgens werden de technische veronderstellingen van hoofdstuk 3 vertaald naar de economische haalbaarheid door middel van een kasstroommodel in hoofdstuk 4. Dit hoofdstuk begint met een meta-analyse van de kapitaalkost van pyrolyseplant, gegeven de grote onzekerheid die daarover bestaat. Eerst wordt de netto contante waarde (NCW) van de kasstromen gegenereerd door een investering in snelle pyrolyse voor de productie van warmtekrachtkoppeling bepaald. Omdat het niet zeker is dat alle warmte afgezet kan worden, wordt ook de NCW berekend voor de productie van elektriciteit alleen en vervolgens vergeleken met die van verbranding en vergassing. Hoewel vergassing tot betere technische resultaten leidt, heeft snelle pyrolyse betere vooruitzichten op economisch vlak dankzij de lagere kosten. Omdat een investeerder niet gemakkelijk bereid zal zijn om vervuilde wilg tegen dezelfde prijs aan te kopen als zuiver hout als biomassabron voor zijn installatie, wordt er een subsidie berekend die gelijk is aan de extra kosten (i.e 30 EUR t_{dm}^{-1}) die vervuild hout met zich meebrengt. Daarnaast werd aangekondigd dat het huidige systeem van groenestroomcertificaten zal veranderen. Mogelijk heeft dit een belangrijke weerslag op de rendabiliteit van de investering, omdat de opbrengsten uit de verkoop van groenestroomcertificaten het grootste deel van de operationele opbrengsten uitmaken. De exacte impact kan nog niet worden berekend, want het observatorium dat instaat voor de berekening van de onrendabele toppen en bandingfactoren, meldde dat de resultaten pas in april 2013 worden gepubliceerd. Bovendien is het niet duidelijk onder welke “representatieve” categorie snelle pyrolyse zal vallen. Daarom wordt op basis van onze veronderstellingen voor zuiver hout, een berekening gemaakt van de onrendabele top (en bijhorende bandingfactoren) voor de huidige gevalstudie.

Omdat een groot deel van de aannames gemaakt in hoofdstukken 3 en 4 onzeker zijn, gaat hoofdstuk 5 in op het economisch risico van snelle pyrolyse. In het eerste deel van het hoofdstuk wordt rekening gehouden met dit risico bij de verkenning van een mogelijke prijsvork voor wilg geteeld in de Belgische Kempen met het oog op fyto-extractie. In het volgende deel wordt het economisch risico van snelle pyrolyse voor warmtekrachtkoppeling bepaald door middel van Monte Carlo simulaties. Het voordeel van deze simulaties is dat men rekening kan houden met de kansverdeling voor de waarden van de verschillende onzekere variabelen. De simulaties (waarbij de waarden van de variabelen gelijktijdig veranderen) worden vervolgens gebruikt om de kans te bepalen dat de netto contante waarde van de investering positief is, om de belangrijkste factoren te identificeren die een invloed hebben op de variabiliteit van deze netto contante waarde en om een vereenvoudigd metamodel te ontwikkelen van de economische modellen uit hoofdstuk 4. Het nadeel is echter dat er geen data beschikbaar zijn voor de werkelijke kansverdelingen van de verschillende variabelen, maar dat deze gebaseerd zijn op het oordeel van de expert. De Monte Carlo simulaties werden daarom aangevuld met Plackett-Burman scenario's (een methode uit het domein van experimenteel ontwerp die geen kennis vereist m.b.t. de kansverdeling van de waarden van de variabelen). De Plackett-Burman designs blijken een interessante aanvulling, maar de informatiewaarde bleek beperkt tot het in kaart brengen van de grootst mogelijke verliezen voor een investeerder.

Uit de analyses in hoofdstuk 5 blijkt dat de netto contante waarde erg afhangt van de schaalgrootte, de waarde van de groenestroomcertificaten en de olie-opbrengst. Daarom worden in hoofdstuk 6 en 7 enkele strategieën uitgewerkt om de afhankelijkheid van deze onzekerheden te verkleinen. Zo kan de schaalgrootte bijvoorbeeld toenemen door (afval)stromen te zoeken die samen met de wilg kunnen worden gepyrolyseerd (zie hoofdstuk 6). Biopolymeren zijn een mogelijke afvalstroom die enerzijds de inkomsten kunnen doen stijgen door middel van een "gate fee", en anderzijds enkele synergetische effecten heeft op het pyrolyseproces. Er werd aangetoond dat deze synergetische effecten de economische haalbaarheid verbeteren, zeker in het geval dat er naast olie ook chemicaliën (crotonzuur) worden geproduceerd.

Terwijl hoofdstuk 6 ingaat op de reductie van het risico door wijziging van de inputs van het pyrolyseproces, gaat hoofdstuk 7 in op mogelijke strategieën aan de outputzijde. Immers, indien men in staat is om de koolrest te valoriseren, kan de rendabiliteit van de fabriek toenemen door een economische trade-off die dan ontstaat tussen de productie van olie en kool. Er werd berekend dat de activatie van de koolrest winstgevender is dan het storten van de koolrest (ondanks de hogere activatiekosten in vergelijking met de stortkosten). De trade-off werd vervolgens berekend met behulp van de netto-opbrengstenmethode, waardoor het mogelijk wordt om een trade-off te berekenen voor producten waarvoor nog geen markt bestaat.

De thesis besluit door te stellen dat snelle pyrolyse mogelijk een winstgevende technologie is voor de valorisatie van wilg afkomstig uit fytoextractie. Toch is deze conversietechniek onderhevig aan grote economische en technologische onzekerheden, die kunnen worden beperkt door een verandering van de inputs of outputs van het pyrolyseproces. Vooral wanneer pyrolyse leidt tot de productie van hoogwaardige materialen of chemicaliën neemt het economisch potentieel van deze technologie aanzienlijk toe.

Summary

During the last quarter of the nineteenth century and the beginning of the twentieth century, the northern part of the Campine region has moderately been polluted with heavy metals emitted by the zinc industry. Land remediation standards have been exceeded especially for cadmium (Cd). The presence of cadmium in soils poses a risk for human health. Besides, most of the metal enriched soils in the Belgian Campine are in agricultural usage. Moreover, the Campine’s sandy soils have a relatively low pH value, which causes high mobility of cadmium and which results in a more easy uptake of the metals in crops. As a consequence, the vegetable sector is no longer willing to conclude contracts with farmers who face the risk of surpassing legal threshold values of food. The impact for farmers growing fodder crops is smaller, but nevertheless disturbing. Therefore, the soils need proper management, if possible through remediation.

Because of the vastness of the contaminated area, conventional physicochemical remediation techniques are not appropriate in order to remove the metals. Phytoremediation has been proposed as a cost-effective and sustainable alternative. Because heavy metals are elements that cannot be degraded by living organisms, decontamination of the soils requires the removal or stabilisation of the toxic metals. Energy maize is suggested as a suitable crop for phytoattenuation, whereas willow is suggested for phytoextraction, i.e. real take up of the metals from the soils. The main barrier in the development of commercially viable phytoextraction is the long time period for effective soil remediation, which can be countered by using the biomass from phytoextraction for profit making. A conversion technology should therefore both be profitable and provide a solution to the disposal problem of the biomass/metals. Fast pyrolysis seems promising because of the lower process temperature which prevents heavy metal volatilisation. This dissertation therefore contains a techno-economic assessment of fast pyrolysis for the valorisation of short rotation willow cultivated for phytoextraction.

Although it is a widely used concept, to date no guidelines exist on how to perform a techno-economic assessment. Therefore, in chapter 2, this dissertation starts with and contributes to the development of a proper framework for techno-economic assessments, which can be defined as the evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision makers in directing research and development or investments. A techno-economic assessment ideally answers three important questions: "How does the technology work?", "Is the technology profitable?" and "Is the technology desirable?". Answering these questions requires by definition a multidisciplinary approach. In this dissertation the focus is on the economic profitability of fast pyrolysis from the viewpoint of an investor, including an in depth analysis of economic risk by means of Monte Carlo simulations and a technique from the field of experimental design.

Before the economic feasibility and risk can be assessed, knowledge is required about the technologic performance. Chapter 3 therefore briefly describes the considered technologies, and its assumptions serve as an input to the discounted cash flow model of chapter 4. In chapter 3 it has been explained that fast pyrolysis is especially interesting because of its lower process temperature compared to combustion and gasification, whereas the latter might require costly gas treatment. On the other hand it has been illustrated that gasification for power production probably performs better energetically compared to pyrolysis and combustion.

The technological assumptions of chapter 3 have been translated into economics in the discounted cash flow model of chapter 4. The chapter starts with a meta-analysis of the total plant cost of a fast pyrolysis plant, due to the large uncertainty with regard to it. First, the net present value of fast pyrolysis for combined heat and power production has been calculated. Because it is not sure whether heat can be sold, the NPV of fast pyrolysis for electricity production only has been calculated and compared to combustion and gasification. Although gasification performs better from an energetic point of view, fast pyrolysis has better economic prospects for the expected scale of operation thanks to lower expected costs. None of the three conversion technologies shows a positive NPV for electricity production only. Only fast pyrolysis for combined heat and power production appears profitable. Besides it is expected that an investor will not be very eager to use contaminated willow, due to the incurred extra costs of metal disposal. Therefore a government incentive of 30 EUR t_{dm}^{-1} has been proposed in order to encourage the use of contaminated willow in a fast pyrolysis plant. Moreover it has been illustrated that the revenues from the sales of green power certificates constitute the most important share of total revenues. As the certificate system is currently changing and the impact cannot be calculated yet (due to expected date of publication of April 2013 announced by the Flemish Energy Agency), the unprofitable top and banding factors required for fast pyrolysis (under the assumption of clean willow) have been calculated.

Because a number of values that have been assumed in chapters 3 and 4 are uncertain, chapter 5 deals with economic risk of fast pyrolysis. In the first part of chapter 5, this economic risk has been taken into account when exploring a possible price range for willow cultivated for phytoextraction. In the next section the economic risk of fast pyrolysis followed by combined heat and power production has been assessed by means of Monte Carlo simulations, which has the advantage that the value of several variables can be simulated simultaneously taking into account the probability of occurence. This information has then been used to determine the chance of a positive NPV, the main factors contributing to the variability of the NPV and the development of a meta-regression model. Monte Carlo simulations however suffer from the drawback that the probabilities have been assigned based on expert judgment (i.e. best guess) due to a lack of real data with regard to these probabilities. Therefore they have been complemented with Plackett-Burman designs (i.e. a method from experimental design which does not require knowledge about the probability distributions of the variable’s values), though it has been concluded that their information value is rather limited to the calculation of maximum possible losses.

After the analyses in chapter 5, it has been concluded that the NPV is highly dependent on the scale of operation, the value of the green power certificates and the oil yield amongst others. In chapter 6 and chapter 7 therefore some strategies have been proposed and evaluated for reducing the operational risk. For instance, the scale of operation can be increased by searching other feedstocks or waste streams that can complement the stream of willow that might be available from the Belgian Campine (chapter 6). Biopolymer waste streams have the potential advantage of increasing revenues by means of a gate fee on the one hand, and they synergistically improve the fast pyrolysis process. It has been illustrated that these synergistic effects beneficially contribute to the fast pyrolysis plant's profitability. One of the suggested biopolymers even results in the production of a high value chemical.

In chapter 7 the focus has been shifted from risk reduction by a change in inputs towards a change in outputs. It has been illustrated that the char byproduct of fast pyrolysis can be valorised by subsequent processing to activated carbon (AC). Although higher costs are incurred during activation compared to disposal of the char, the revenues generated by sales of the active coal outweigh these extra costs. As a consequence an economic trade-off exists between the production of pyrolysis oil and char. The trade-off has been calculated by means of the net revenues generated by subsequent processing steps which result in marketable products: AC production from char and CHP from oil. It can be concluded that AC production (and a shift to char production) is profitable as long as the AC price is at least 2 kEUR t_{dm}^{-1}, whereas the combined production of heat and power from pyrolysis oil is more profitable when AC prices fall beneath 1,4 kEUR t_{dm}^{-1}.

Concluding, fast pyrolysis is a potential profitable technology for the conversion of willow cultivated for phytoextraction when the pyrolysis oil is used to produce combined heat and power. This application however suffers from high economic risks, which can be reduced by a change in inputs and outputs, and results in higher economic profits when materials and/or chemicals are produced.

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List of abbreviations

AC	active coal or activated carbon
BTG	Biomass Technology Group
$c_{landfill}$	unit cost of landfilling one tonne of waste (e.g. char, in EUR t^{-1})
c_{water}	cost price of water (EUR m^{-3})
c_{willow}	unit cost of cultivating willow (EUR t^{-1})
C_{biom}	annual cost of biomass supply (pretreatment, purchase and transport, expressed in EUR yr^{-1})
C_{by-pr}	annual cost of by-product disposal (EUR yr^{-1})
C_{lab}	annual labour cost (EUR yr^{-1})
C_{phyto}	cost of phytoextraction (EUR ha^{-1} yr^{-1})
C_{util}	annual cost of the use of utilities (e.g. water, expressed in EUR yr^{-1})
Cd	cadmium
CEPCI	Chemical Engineering Plant Cost Index
CFB	circulating fluidised bed
CF_n	the cash flow after tax in year n
CHP	combined heat and power
d	day
D	depreciation
DOE	design of experiments
DPC	direct plant cost
E_e	electricity production (MWh_e)
E_n	the total expenditure in year n

E_{th}	heat (thermal energy) production (MWh_{th})
EUR	euro (€)
FCI	fixed capital investment
FC_n	fixed cost in year n
GBP	Pound Sterling (£)
GPC	green power certificates
GHG	greenhouse gas
GIS	geographic information system
h	hour
HHV	higher heating value
HPC	combined heat and power certificates
i	the discount rate
I_0	initial investment expenditure in year zero
I_{CHP}	initial investment expenditure for combined heat and power production
I_{eng}	initial investment expenditure of an internal combustion engine
I_{py}	intial investment expenditure of a fast pyrolysis plant
IPC	indirect plant cost
k	investment allowance percentage (percentage of the total plant cost that can be deduced from an enterprise's profits to lower tax payments)
L_{eng}	number of operators per shift for an internal combustion engine for power
LHV	lower heating value
m%	percentage of the original mass (mass percentage)

M & S	Marshall & Swift equipment cost index
MW_{th}	thermal megawatt
N	annual amount of labourers required
NLG	Dutch guilder
NPV	net present value
nr_{char}	net revenue of the char
nr_{oil}	net revenue of pyrolysis oil
OH_{CHP}	number of operation hours per year of a CHP engine (h yr^{-1})
OH_{py}	number of operation hours per year of a fast pyrolysis plant (h yr^{-1})
OVAM	Openbare Vlaamse Afvalstoffenmaatschappij (Public Waste Agency of Flanders)
p_{AC}	sales price of activated carbon
p_{ch}	sales price of chemicals (e.g. crotonic acid)
p_{CHP}	specific investment cost of combined heat and power production (EUR MW^{-1})
p_e	sales price of electricity
p_{th}	sales price of heat
p_{GPC}	market price of one green power certificate
p_{HPC}	market price of one combined heat and power certificate ($\neq p_{CHP}$)
p_{willow}	unit willow price (EUR t^{-1})
P_e	electrical capacity (MW_e)
$P_{e(int)}$	internal requirement of electricity for plant operation
P_{gt}	net electric power generated by a gas turbine
P_{in}	energy available in the prepared feedstock (MW_{th})

P_{ge} gross electric energy power output of a combustion plant (MW_e)

P_{ne} net electric energy power output of a combustion/gasification plant (MW_e)

P_{oil} thermal production capacity of pyrolysis oil (MW_{th})

P_{st} net electric power generated by the combined steam cycle (MW_e)

P_{th} thermal capacity (MW_{th})

$P_{th(int)}$ internal requirement of heat energy for plant operation (MW_{th})

PB Plackett-Burman designs

PES (absolute) primary energy saving

PTC product transformation curve

q_{AC} sold quantity of the activated carbon

q_{by-pr} quantity of by-products (e.g. char) produced and to be landfilled

q_{ch} sold quantity of chemicals (e.g. crotonic acid)

q_{char} sold quantity of the char

q_{oil} sold quantity of the oil

q_{water} quantity of water required for plant operation

q_{willow} yearly amount of willow sold ($t\ ha^{-1}\ yr^{-1}$)

r discount rate

R_n the total revenues in year n

RPES relative primary energy savings

S_{AC} revenues from the sales of activated carbon

S_{ch} revenues from the sales of chemicals

S_e revenues from the sales (or savings) from electricity

S_n total sales revenues received in year n

S_{th}	revenues from the sales (or savings) of heat
SRC	short rotation coppice
SRF	short rotation forestry
t_{dm}	ton dry matter
T	the life span of the investment
TCI	total capital investment (EUR)
TEA	techno-economic assessment
TPC	total plant cost (EUR)
U_n	total subsidies received in year n
U_{exp}	exploitation subsidies received in year n
U_{inv}	investment subsidies received in year n
U_{GPC}	revenues from the sales of green power certificates
U_{HPC}	revenues from the sales of combined heat and power certificates
USD	United States dollar ($)
VC_n	variable cost in year n
w	annual wage or salary of one labourer/employee
X	monthly fraction of the primary energy savings for which a heat and power certificate is awarded
yr	year
Y_{dairy}	income of dairy cattle rearing (EUR ha^{-1} yr^{-1})
Y_{phyto}	income during phytoextraction (EUR ha^{-1} yr^{-1})
α_{th}	reference efficiency of separate heat production;
α_e	reference efficiency of separate electricity production
η^{CHP}_{th}	thermal efficiency of the combined heat and power engine

η^{CHP}_{e} electric efficiency of the combined heat and power engine

η^{py}_{char} pyrolysis char yield as a weight percentage of biomass

η^{py}_{oil} pyrolysis oil yield as a weight percentage of biomass

τ tax rate

φ percentage of fixed costs (percentage applied to TPC)

Φ^{d}_{co} daily processed feedstock in a combustion plant (t_{dm} d^{-1})

Φ^{d}_{ga} daily processed feedstock in a gasification plant (t_{dm} d^{-1})

Φ^{yr}_{py} yearly processed feedstock in a fast pyrolysis plant (t_{dm} yr^{-1})

Φ^{d}_{py} daily processed feedstock in a fast pyrolysis plant (t_{dm} d^{-1})

Φ^{h}_{ga} hourly processed feedstock in a gasification plant (kg h^{-1})

Φ^{h}_{hrsg} steam flow rate produced by the heat-recovery steam generator

Φ^{h}_{py} hourly processed feedstock in a fast pyrolysis plant (t_{dm} h^{-1})

Φ^{s}_{py} processed feedstock in a fast pyrolysis plant per second (kg_{dm} s^{-1})

1 Introduction

1.1 Heavy metal pollution in the Campine

1.1.1 Historical background

During the last quarter of the nineteenth century and the beginning of the twentieth century, the northern part of the Campine region (‘*Kempen*’) became the centre of the Belgian non-ferrous industry. At that time this region was sparsely populated and therefore it was an interesting location for a space requiring industry that brought about severe environmental pollution and health risks. Besides, the savage moorlands were cheap and the wages were very low while trade unions were still absent in the Campine. Another opportunity to the development of the non-ferrous industry was the presence of artery such as the Meuse-Schelde canal, the canal of Beverlo and the railroad between Antwerp and Mönchengladbach (better known as the “Iron Rhine”) that aided the transport of raw materials (e.g. zinc ore) and manufactured products. In 1888 the zinc and lead factory called “Société et Commandité Simple W. Schulte en Co” was built in the municipality of Overpelt. One year later, in 1889, the “S.A. des Mines et Fonderies de Zinc de la Vieille Montagne” built an establishment in Balen where zinc ore was roasted and purified, i.e. the most unhealthy step in the production process of zinc. The municipality of Lommel remained largely agrarian until 1904 because the town council then predominantly consisted of farmers who feared loss of heathland and labourers in favour of the non-ferrous industry, environmental pollution and mental and physical illness of the citizens of Lommel. After the elections of 1899 the changed constitution of the council altered the attitude of the municipality towards industrialisation, probably because of the worsening municipal finances. Five years later, in 1904, the German family Schulte started building the zinc and sulphuric acid factory “N.V. Société Métallurgique de Lommel” which employed 740 labourers in 1910. Contemporaneous development of the non-ferrous industry took place in the municipalities of Reppel, Rotem, Beerse, Olen, Hoboken and Budel (across the border with the Netherlands). (Vanduffel 1983; Leysen 2001)

Zinc was produced from zinc ore which contains besides zinc (Zn), cadmium (Cd), lead (Pb), copper (Cu) and arsenic (As). At first (until 1963 in Lommel and until 1974 in Overpelt) zinc was mined by means of pyrometallurgical production processes, i.e. thermal refinement whereby zinc ore was heated to 1 300 °C to form metal vapours. In a next step, these vapours were condensed and moulded. Part of the metals could not be retained during the condensation step, but instead were bound to dust particles which were emitted through the fume stack. The boiling point of cadmium however lies about 780 °C, so that cadmium was easily volatilised as a by-product of zinc mining. The pyrometallurgical production of zinc and cadmium thus caused emission of large quantities of heavy metals in the air due to high process temperatures. As a consequence of atmospheric deposition the soils in the vast surroundings of the zinc factories have been diffusely polluted with heavy metals. The zinc manufacturers also discharged polluted industrial wastewater in the brooks that flew alongside the factories. A third source of heavy metal pollution stemmed from the usage of waste zinc ashes as a material for pavements. Fortunately pollution largely stopped in the 1970s thanks to the demolition of the zinc factory in Lommel in 1974, the switch from pyrometallurgical to the more environmentally friendly electrolytic refinement procedure in Overpelt in 1974 and the stop of cadmium production in Overpelt and Balen in 1992 and 2002 respectively. (Staessen, Roels et al. 1995; Vangronsveld 2002; Verlaek and Wynants 2006; Hogervorst, Plusquin et al. 2007)

As a consequence the historical metal enrichment of the soils covers a surface of more than 700 km² in the trans-border region of the Dutch and Belgian Campine, of which 280 km² in the Belgian municipalities of Balen, Mol, Hamont-Achel, Lommel, Neerpelt, Overpelt and Hechtel-Eksel. In the Dutch part of the Campine, especially the municipalities of Bergeijk, Valkenswaard, Cranendonk, Weert and Nederweert have been polluted with metals as a consequence of the emissions by the zinc factory of Budel-Dorplein and the factories in Belgium (Oomen, Janssen et al. 2007). For instance, the cadmium concentration of the sandy soils in this region is often larger than 1 mg kg^{-1} which is high compared to the natural prevalence of cadmium in the soils at concentrations between 0,1 and 0,8 mg kg^{-1}.

In the Belgian part of the Campine two highly contaminated subareas can be discerned close to the zinc factories of Balen, Lommel and Overpelt with a cadmium concentration in the soil of even more than 3 mg kg^{-1} (Staessen, Roels et al. 1995). The latest estimate of cadmium pollution in the municipalities of Balen, Mol, Lommel, Overpelt, Neerpelt, Hamont-Achel and Hechtel-Eksel has been predicted by Schreurs, Voets et al. (2011) and Van Dael, Witters et al. (2012) in figure 1, based on data about Cd concentrations in soil samples taken in the studied area.

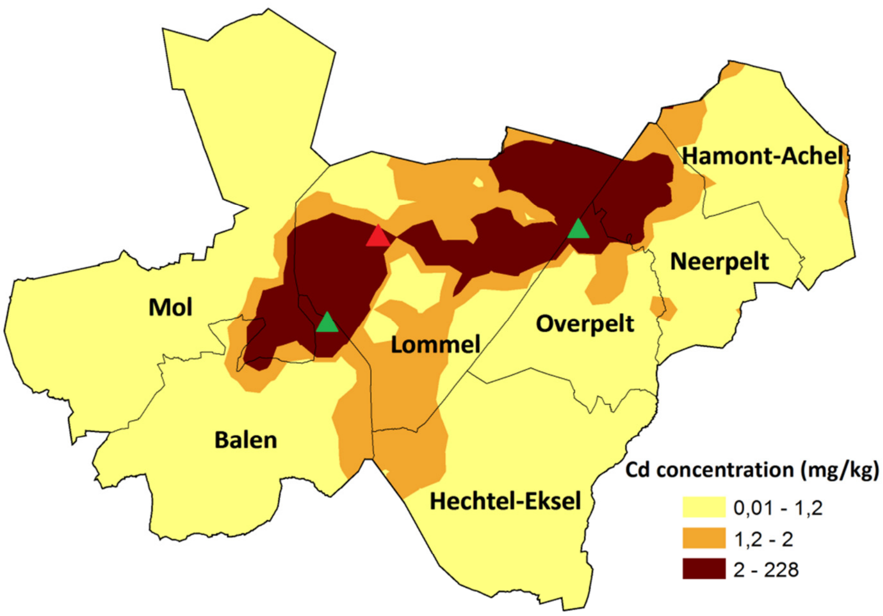

figure 1: Prediction of the Cd concentration in the Belgian Campine (Schreurs, Voets et al. 2011; Voets 2011a; Van Dael, Witters et al. 2012)

The dark brown area corresponds to cadmium (Cd) concentrations higher than the relevant land remediation standard (see also paragraph 1.2), which signifies that the concentration of cadmium in the soil is greater than 2 mg Cd per kg of dry soil and is considered to pose a risk of harmful effects on human beings and the environment.

The location of the zinc smelters has been indicated by the colored triangles in figure 1. The red triangle is the location of the zinc smelter in Lommel that has been closed down in 1974, and the green triangles represent the two still existing locations of zinc smelters in Balen and Overpelt respectively. There is a clear indication of atmospheric deposition in the north-east direction due to the air currents predominantly coming from the south-west in Belgium. It is remarkable that the former site of Lommel-Fabriek is rather free of metals, but this is due to the point in time at which the site's soil samples have been taken, i.e. after soil reclamation by Sibelco, which now exploits the former site of Lommel-Fabriek for extraction of sand. Because the researchers did not dispose of samples or data before soil reclamation at the site, they were unable to predict atmospheric deposition stemming from the pollution at Lommel-Fabriek and hence metal pollution to the north of it is probably strongly underestimated.

1.1.2 Risks associated with metal pollution

Following the Soil Decree issued by the Flemish Parliament, the soil contamination in the Belgian Campine is classified as an "historical soil contamination" because the soil has been polluted before 29th October 1995 (see the definition of historical soil contamination according to article 2 of the Soil Decree). Remediation of historic soil contamination is directed towards the avoidance of risks of harmful influence of soil quality on man or environment (Soil Decree, art. 21) (Vanheusden 2007). For new contamination, soil remediation is obliged when a descriptive examination of the soil indicates that land remediation standards are exceeded (Soil Decree, art. 9 § 3). These land remediation standards are defined as the levels of contamination that contain considerable risks of negative effects for man or the environment (Soil Decree, art. 9 § 1). For historic contamination, there are no land remediation standards, although they are one of the criteria for detecting serious threats in case of historical soil contamination (Witters 2011). The land remediation standards for heavy metals can be found in annex IV of the Flemish regulation concerning the remediation and the conservation of soils (VLAREBO). They differ according to the destination and use of the soil and can be found in table 1.

	Destination type of the soil				
	I	**II**	**III**	**IV**	**V**
As	58	***58***	103	267	267
Cd	2	***2***	6	9,5	30
Cu	120	***120***	197	500	500
Pb	200	***200***	560	735	1 250
Zn	333	***333***	333	1 000	1 250

table 1: Land remediation standards for heavy metals in the soil expressed in mg/kg dry matter (VLAREBO, annex IV)

The land remediation standards for farmland are the ones mentioned under destination type II. Summarized, the land remediation standards mentioned for type I are valid for soils destined for nature, type III refers to residential areas, type IV to recreational areas and type V corresponds to industrial areas. Actually these land remediation standards should be adjusted for the characteristics of the soil, such as the content of clay and organic material and the acidity of the soil (the results can be found in (Witters 2011)), but according to Ruttens, Vangronsveld et al. (2008) standards are only exceeded for Cd, and not for Pb and Zn on the experimental phytoremediation site in Lommel.

The presence of cadmium in soils poses a risk for mankind because it can enter the human body either by consumption of contaminated food or water or by inhalation of tobacco smoke or polluted air. Unless cadmium is removed from the Campine soils, it poses a risk on both ways of cadmium uptake by humans. Cadmium is accumulated in kidneys and leaves the human body only very slowly, given a half-life of cadmium of 10 to 30 years (Staessen, Roels et al. 1995). The loading rates of cadmium and lead are significantly higher in house dust in the contaminated region which was associated with higher blood cadmium and urinary cadmium (Hogervorst, Plusquin et al. 2007). Consequences for health are multiple: e.g. risk of renal dysfunction and higher loss of calcium through urine potentially leading to higher incidence of osteoporosis. Besides, Nawrot, Plusquin et al. (2006) have shown a significant association between the risk of lung cancer and environmental exposure to cadmium in the north-east of Belgium. If no action is undertaken, these metals will reside in the soils for thousands of years, so they pose a permanent risk for human health (Vassilev, Schwitzguébel et al. 2004).

Besides, most of the metal enriched soils in the Belgian Campine are in agricultural usage (Van Slycken, Meers et al. 2008). Moreover, the Campine's sandy soils have a relatively low pH value, which causes high mobility of cadmium (Cd) and results in a more easy uptake of the metals in crops and leaching in groundwater, so that food and fodder crops often exceed prevailing threshold values according to European product safety standards (Meers, Van Slycken et al. 2010; Ruttens, Boulet et al. 2011). Especially leaf and root crops such as lettuce, spinach, carrots, etc. are very sensitive for high levels of Cd in soils. In 2005, the Federal Agency for Food Safety (FAVV) observed Cd concentrations exceeding legal limits in carrots and scorzonera, with a resulting confiscation of the harvests (BeNeKempen 2006). As a consequence, the vegetable sector is no longer willing to conclude contracts with farmers who face the risk of surpassing legal threshold values of food (Witters 2011). Examples of vegetables that should not be cultivated on soils exceeding the stated cadmium concentrations are represented in table 2.

3 mg Cd kg^{-1}	6 mg Cd kg^{-1}	12 mg Cd kg^{-1}
endive	potatoes	beans
chervil	strawberries	peas
parsley	cauliflower	tomatoes
lettuce	leek	paprika
spinach	radish	
cress	carrots	
rhubarb	onion	
celery	chicory	
	eschalot	

table 2: Vegetables that should not be cultivated on soils exceeding stated cadmium concentrations (Staessen, Roels et al. 1995)

The impact for farmers growing fodder crops is smaller, but nevertheless disturbing (Witters 2011). By eating contaminated grass, maize or beets, animals can take up an excess of heavy metals which accumulate in kidneys and liver, although no elevated levels of heavy metals were found in milk and meat of the cows (ABdK 2008). These effects limit the marketing of agricultural products and reduce the profitability of the agricultural industry (McGrath, Zhao et al. 2001).

The potential health effects and threats for the income of farmers in the north-east of Belgium are the indirect consequence of air pollution by the zinc smelters. Air is an example of a rivalrous, non-excludable good (Lipsey and Chrystal 2011) as no two persons can breathe the same unit of air (rivalrous) and people cannot be prevented from using air (non-excludable). As such, air is an example of common property because it can be used by everyone but does belong to no one. This is one example of the failure of markets in achieving efficient resource allocation. Besides, the potential health effects and income threats are examples of externalities, i.e. they are an unintended effect of one agent on some other agent (Common and Stagl 2007; Perman, Ma et al. 2011). Tietenberg (2006) states that "an externality exists whenever the welfare of some agent, either a firm or household, depends not only on his or her activities, but also on activities under the control of some other agent". The welfare of the citizens and farmers in the northern Campine is influenced by historical activities that were beyond their own control. Their welfare has been impacted by activities of the former pyrometallurgical zinc smelters. More specifically, the externalities are examples of external diseconomies or negative external effects because the affected party is damaged by the external effects. Stated otherwise "an externality exists when a person does not bear all the costs or receive all the benefits of his or her action" and "when the market price or cost of production excludes its social impact, cost, or benefit" (Hanley, Shogren et al. 2001). It is clear that the zinc smelters are not the agents that pay for the potential treatment costs in case of disease or for the risk of income loss borne by the farmers. Hence the latter can be considered as external effects of the pyrometallurgical zinc refinement in the past. For all these risks, the Public Flemish Waste Agency (OVAM) decided that the soils need proper management, if possible through remediation.

1.2 Phytoextraction with willow for metal uptake

Because of the vastness of the contaminated area, conventional physicochemical remediation techniques (e.g. excavation and land filling, biological treatment, soil washing or thermal desorption) are not appropriate in order to remove the metals, because these techniques are too expensive and tend to destroy every biological activity in the soil (McGrath, Zhao et al. 2001; Pulford and Watson 2003). Phytoremediation - i.e. the use of living plants to remove, degrade or stabilise pollution (e.g. heavy metals, pesticides, solvents, explosives, crude oil, polyaromatic hydrocarbons, radio nuclides, landfill leachates) in soils, groundwater, sludge or sediment (US Environmental Protection Agency 1998; Mirck, Isebrands et al. 2005) - is proposed as a *cost-effective* alternative for excavation and disposal of hazardous soil: e.g. the estimated costs for phytoremediation of a site contaminated with lead are 20 to 80 USD per tonne soil compared to 150 to 350 USD per tonne soil for conventional remediation (Ensley 2000). The cost of purifying arable land of cadmium by means of excavation and landfilling or ex situ cleaning of the soil is estimated to be between 280 and 680 kEUR ha^{-1} (Lewandowski, Schmidt et al. 2006). Vangronsveld, Herzig et al. (2009) compared the cost of phytoremediation with soil washing and excavation and concluded that phytoremediation is at least 50 % less expensive. The major costs of phytoremediation are the tilling and preparation of the soil, planting the seeds, weed and pest control, and harvesting and disposal of the biomass (Glass 2000). Above this, phytoremediation is also suggested as a *sustainable* alternative for conventional remediation technologies for functional repair or management of agricultural soils contaminated with heavy metals when phytoremediation crops are used for renewable energy production and hence CO_2 abatement (Witters, Mendelsohn et al. 2012b). Phytoremediation thus is being mainly developed by the drive to search for a cheaper way of soil remediation and the desire to apply a "green", sustainable process (Pulford and Watson 2003). In the case of the Campine the purpose of phytoremediation is also directed towards durable land management where phytoremediation gradually improves soil quality so that eventually crops with higher market value again can be cultivated (Vangronsveld, Herzig et al. 2009).

The main barrier in the development of commercially viable phytoremediation is the long time period for effective soil remediation. This can be countered by using the biomass from phytoremediation for profit making (Robinson, Fernández et al. 2003). To make phytoremediation of low to moderate polluted soils economically viable for farmers, additional benefits should be provided (Schmidt 2003). There are many tangible and intangible economic opportunities for biomass production from pollutant removal systems based on phytoremediation: for instance, the biomass can be used for bioenergy production (tangible), while abating carbon emissions (intangible) (Licht and Isebrands 2005). The need for additional benefits to phytoremediation by obtaining products with economic value from plants used in the clean-up of soils has also been stressed by Bañuelos (2006). This way phytoremediating crops have a double advantage: they both take up pollution from the soil and are a potential source of renewable energy (Bardos, Andersson-Sköld et al. 2009). Sometimes a third advantage is mentioned: when hyperaccumulators (i.e. plants who tolerate very high concentrations of metals in their aerial parts) are used, one could consider *phytomining*, i.e. the generation of economic gain by extracting saleable heavy metals from soils rich in metal content (Koppolu and Clements 2003; Robinson, Fernández et al. 2003). However, this is expected to be irrelevant for cadmium, because its price is relatively low compared to other metal prices. Besides, for biomass production, crops that combine significant heavy metal accumulation with high biomass yields are more suitable than hyperaccumulators (Lewandowski, Schmidt et al. 2006) as the latter have lower biomass yields. Pulford and Watson (2003) confirm that the ideal plant species to phytoremediate a heavy-metal contaminated soil would be a high biomass producing crop that can accumulate the contaminants of interest, which is not possible with hyperaccumulators because of the trade-off between hyperaccumulation and biomass production.

Because heavy metals are elements that cannot be degraded by living organisms (Vangronsveld, Herzig et al. 2009), decontamination of soils requires the removal or stabilisation of the toxic metals (Lasat 2000; Mirck, Isebrands et al. 2005). Phytoextraction or phytostabilisation are thus the most appropriate forms of phytoremediation in the Campine. Phytoextraction is the use of plants for metal accumulation (the metals present in the soil are taken up by the roots of the plant and are then translocated to the above-ground shoots of the plant) and subsequent removal of the contaminated biomass from the site (Schmidt 2003). The metal-rich plant material can be collected and removed from the soil via using conventional agricultural practices, without the loss of topsoil associated with traditional remediation practices (Blaylock and Huang 2000). Another option is phytostabilization aimed to decrease soil metal bioavailability using a combination of plants and soil amendments, so that the plants immobilise the contaminants in the soil (Mirck, Isebrands et al. 2005). *"Phytoattenuation"* is also possible. It differs from traditional phytoextraction in the sense that the safe use of the soil and the conservation of the farmer's labour income are of paramount importance to the application of energy crops that has the additional advantage of a gradual decrease of the soil contamination in the very long run. Sustainable risk-based land management generating an alternative income for agriculture then is a primary objective, whereas the remediation aspect is only of secondary importance, analogous to "natural attenuation" of organic pollutants in soils (Meers, Van Slycken et al. 2010). Energy maize is suggested as a suitable crop for phytoattenuation: its metal extraction potential is rather low compared to other crops, but its high biomass yield has the potential to generate a positive extra income compared to fodder maize (Witters 2011).

1.2.1 Crop choice: short rotation willow

In order to really remove the metals from the soils, in other words for *phytoextraction*, poplars (Populus spp.) and willow (Salix spp.) are the most common tree species used because they grow rapidly, have many and deep roots, and take up large quantities of water (Pulford and Watson 2003; Licht and Isebrands 2005). Abhilash and Yunus (2011) confirm that willow is "a model plant for biomass production and in situ remediation of heavy metal contaminated soils" because of its rapid growth, extensive and deep root system, high biomass production, ability to grow on diverse soil conditions and pollutant accumulation potential. Short rotation coppice of willow has been indicated by the Institute for Nature and Forest as having the right characteristics to serve as a remediating crop (Meiresonne 2006). Willow has a high remediation capacity for Cd contaminated soils: field trials with different potential biomass crops (e.g. sunflowers, corn, ryegrass, willow and miscanthus) have shown that willow is most effective in taking up high amounts of heavy metals (Schmidt 2003). Dickinson and Pulford (2005) confirm that willow is suited for clean-up of soils moderately polluted with cadmium with high cadmium uptake rates compared to other species. For instance, willow has higher uptake and translocation rates of metals compared to rapeseed (Máthé-Gáspár and Anton 2005) and no yield reduction is expected when grown on lightly to moderately polluted land (Vermeulen, Harmsen et al. 1998). The drawback of phytoextraction using trees with a cropping rotation of greater than 1 year, is that during autumn the leaves are being recycled back onto the ground. This can lead to even more metals in the upper part of the soil, though this might be readily removed by "Surface Scraping" (Robinson, Fernández et al. 2003).

The production of heavy metal accumulating willow is proposed as an alternative crop for farmers in a cadmium contaminated case study area in the Rhine valley (Germany) who, otherwise, either have to set their land aside or switch from high value vegetable production to the production of cereals that generate a lower gross margin (Lewandowski, Schmidt et al. 2006). Experiments with cadmium clean-up have also been performed in North-West England where phytoextraction with willow could reduce contamination of Cd within a 25 to 30 year life cycle of the short rotation crop (French, Dickinson et al. 2006). Also in Sweden, where high concentrations of Cd are found in soils (due to natural high backgrounds or agricultural practices), short rotation willow is being developed more and more for environmental applications combined with biomass production, e.g. in the village of Enköping where 1 200 ha is available for the cultivation of short rotation coppice (Mirck, Isebrands et al. 2005). The same is true in the United States, where research on the development of short rotation willow for the combined goal of bioenergy production and phytoremediation is ongoing (Volk, Abrahamson et al. 2006).

Vermeulen, Harmsen et al. (1998) expect that growing energy crops on polluted land has the potential to cut cultivation costs thanks to lower land costs when compared to clean multifunctional arable land. More importantly, the growth of energy crops on marginal land can be motivated in order to avoid conflicts with food production. McKendry (2002) suggests the use of marginal and fallow lands for energy farming if biomass is expected to contribute to a larger extent to the world's energy supply. Mitchell, Stevens et al. (1999) state that short rotation forestry is seen in Europe as a means to produce a non-food crop on agricultural land that has to be taken out of food production, as a means to provide an alternative livelihood for farmers. Besides, according to Vande Walle, Van Camp et al. (2007) farmers in Flanders will certainly not use their best agricultural soils for growing short rotation forestry, but instead will put forward marginal land for the growth of energy crops.

1.2.2 Case study: the Belgian Campine

Vangronsveld, Herzig et al. (2009) summarized the phytoextraction potential of different species on a field experiment in Lommel. Their summary has been adopted in table 3. It can be seen from this table that willow is able to phytoremediate a polluted soil relatively sooner compared to the other crops, except for tobacco, even when only the stems are harvested. Willow generally performs better than poplar, which confirms the findings of Robinson, Mills et al. (2000) who state that willow clones accumulate significantly more Cd than poplar clones. According to Ruttens (2008) a minimal annual biomass production of 4,7 ton dry matter (t_{dm}) per hectare was achievable on an experimental plantation in the municipality of Lommel with a willow trees of the type "Belgisch Rood". The most probable annual biomass production of willow however is 8 ton dry matter per hectare per year according to Vangronsveld, Herzig et al. (2009), although even annual yields of 15,6 ton dry matter have been obtained for some willow clones. The figures mentioned above are related to the harvest of the first rotation.

Volk, Abrahamson et al. (2006), who measured average yields of willow of 7,5 t_{dm} ha^{-1} yr^{-1} in North America, state that the yield of the second rotation of the best clones increased by 18 to 62 % compared to the first rotation. From a precautionary point of view this increase has not been taken into account in the remainder of the text, because other authors (Mitchell, Stevens et al. 1999) mention that the increased productivity assumption from the first to subsequent rotations has not borne out in practice.

Crop	Biomass (t_{dm} ha^{-1} yr^{-1})	Cleanup time (years)
Maize	20	188
Rapeseed	8	234
Sunflower	10	117
Tobacco	8	58
Poplar stems	8	255
Poplar leaves	2,4	
Poplar stems + leaves		144
Willow stems	8	117
Willow leaves	2,4	
Willow stems + leaves		67

table 3: Phytoextraction potential of different species on a field experiment in Lommel (Vangronsveld, Herzig et al. 2009)

Voets (2011a) calculated that more or less 1 300 ha of farmland in the Belgian part of the Campine (i.e. in the municipalities of Lommel, Balen, Mol, Overpelt, Neerpelt, Hamont-Achel and Hechtel-Eksel) possess a cadmium concentration above the land remediation standard of 2 mg Cd per kg soil. For new contamination this would involve an obligation to remediate the soil until the guide value of 1,2 mg Cd per kg soil has been reached. At least 650 ha of this farmland can be remediated by means of willow within a time span of 42 years, which is true for all farmland with a cadmium concentration between 2,0 and 2,88 mg Cd per kg soil. It is expected that these 650 ha is the absolute minimum amount of farmland that has to be phytoremediated. However if government would decide to phytoremediate all farmland that exceeds the guide value of 1,2 mg Cd per kg soil, then a total of 2 400 ha of farmland can be remediated with willow within 42 years. When no limit is put on the time frame for phytoextraction, then a maximum area of 3 000 ha of agricultural land can be dedicated to energy crops in the Belgian Campine. The corresponding surfaces of farmland that are disposable for phytoextraction in the Dutch part of the Campine region (i.e. in the municipalities of Bergeijk, Valkenswaard, Heeze-Leende, Cranendonck, Someren, Nederweert and Weert) according to Voets (2012) can be found in table 4, next to the relevant surfaces for the Belgian Campine.

Area available for phytoextraction	Belgian Campine	Dutch Campine	Total Campine
Minimal	650 ha	510 ha	1160 ha
Probable	2400 ha	4020 ha	6420 ha
Maximal	3000 ha	4350 ha	7350 ha

table 4: Expected minimal, probable and maximal area available for phytoextraction in the Belgian and the Dutch part of the Campine region (Voets 2011a; Voets 2012)

In the region of the Belgian Campine (municipalities of Balen, Lommel, Neerpelt and Overpelt), dairy cattle farming is the most important activity with 61 % of the farmland dedicated to fodder crops and temporary grassland (Witters 2011). Voets (2011b) was able to analyse the contaminated area in terms of crops. The contaminated farmland can be described by the currently grown crops presented in table 5. As can be seen from this table, 43,32 % of the contaminated area consists of pasture (grassland for cows) and 39,36 % is dedicated to the growth of maize (which can be used as a fodder crop for cows).

Crop	Surface (ha)	Share (% of total)
Potatoes (consumption)	40,78	1,76
Other bedding	0,14	0,01
Vegetables	52,48	2,25
Pasture (grassland)	1005,42	43,32
Oat	4,38	0,19
Italian rye-grass	1,31	0,06
Maize	913,31	39,36
Perennial clover	35,83	1,54
Non-seeded cropland	3,16	0,14
Unspecified crop (small farm)	100,67	4,34
Spelled	0,45	0,02
Spontaneous cover	46,24	1,99
Sugar beet	27,59	1,19
Triticale	40,14	1,73
Fodder beet	4,25	0,18
Meadow with trees	2,00	0,09
Barley	14,68	0,63
Winter rye	8,73	0,38
Wheat	19,23	0,83
TOTAL	2 320,76	100

table 5: Inventory agricultural land use contaminated area

1.3 Fast pyrolysis of the biomass

It is expected that farmers would experience a serious decline in their income when they would shift to phytoextracting crops, which might explain why they hesitate to make an appeal to this technique. If phytoextraction is accompanied by activities that (partially or totally) prevent income to decline during the remediation period, the social acceptability of starting such projects would certainly be enhanced. Such activities (e.g. renewable energy production) aim at valorising the harvested biomass of the accumulating crop. One possibility is to use this biomass as the feedstock for renewable energy production. The revenue that the farmer receives by selling the willow to an energy producer compensates for the lesser income during the reclamation period. Vassilev, Schwitzguébel et al. (2004) confirm that phytoextraction will be more economically feasible if, in addition to metal removal, plants produce biomass with an added economic value, especially because phytoextraction suffers from the drawback that it often takes a long time to reach a clean status of the soil. The disposal of the contaminated crop material is one of the other remaining hurdles for the commercial application of phytoextraction (Sas-Nowosielska, Kucharski et al. 2004). They state that pyrolysis can significantly reduce the volume and mass of the contaminated plant biomass while obtaining useful products. Because an economically viable secondary use of the phytoremediating biomass is desirable, it is investigated to which extent fast pyrolysis can contribute to this purpose while offering a solution to the disposal problem associated with the Cd concentration in the plant tissue of willow. The focus in this dissertation is on the economic viability of the conversion technology, which is a prerequisite if one wants to provide farmers with a sufficiently high income.

Surely the cadmium in the harvested Salix (willow) stems needs to be collected and deposited in a safe manner (Berndes, Fredrikson et al. 2004). A biomass conversion technology is considered to be successful when the metals taken up by the plant are not re-released in the environment.

Because heavy metals are not degradable and will always occur in the products of a conversion process, it is advised that heavy metals are entrained in only one of the process' outputs, preferably one with a compact size (Stals 2011). This might be a motivation to choose for fast pyrolysis of the biomass, i.e. rapid heating of the biomass to moderate temperatures (350 – 650 °C) in the absence of oxygen directed towards the production of oil, gas and char. The heavy metals are then controlled and reside mainly in the char that remains as a by-product after pyrolysis. Fast pyrolysis has an advantage over combustion and gasification, because combustion and gasification typically happen at higher temperatures (850 – 1 000 °C) than pyrolysis and metals appear to volatilise more easily at higher temperatures (especially Cd, which is the most problematic in the area studied). The gases resulting from combustion and gasification will contain more heavy metals than those resulting from pyrolysis. Without appropriate fume gas treatment, metal containing combustion gases might be emitted through the chimney back in the atmosphere because of the high temperatures that cause volatilisation of the heavy metals. In the case of gasification, part of these gases will be converted into energy (electricity and/or heat) by using them as a fuel in for instance gas engines. The metals present in these gases (mainly as fly ashes, see chapter 3) are noxious for the engine's components. Since pyrolysis typically happens at lower temperatures, its product gases will contain almost no metals.

Experiments in the laboratory of Applied and Analytical Chemistry of Hasselt University, performed by Stals, Thijssen et al. (2009), showed that most of the metals indeed remain in the pyrolysis char, as long as the process temperature is below 450 °C. At an elevated temperature of 550 °C it was shown that the greatest part of the cadmium volatilises to the other pyrolysis products. It is therefore recommended to control the process temperature to a maximum of 450 °C. At this temperature only a small quantity of heavy metals ends up in the pyrolysis oil, which is considered as an "acceptable level, taking into account the guidelines of Belgian environmental law constraints" (Stals, Thijssen et al. 2009).

Other research performed by Koppolu, Agblevor et al. (2003); Koppolu and Clements (2003); Koppolu, Prasas et al. (2004) confirms the fact that metals remain in the char during pyrolysis. The authors pyrolysed hyperaccumulators, which have a higher metal tolerance and concentration than the polluted willow under investigation in the Campine region. Experiments have been performed at laboratory scale in a fluid bed reactor at a temperature of 600 °C (873 K) and a pressure of 1 atm with a residence time of pyrolysis gases of 0,6 seconds. More than 98,5 % of the metals in the product stream (120 g of feedstock) was concentrated in the pyrolysis char. The experiments were repeated in a pilot-scale reactor that processed samples between 445 g to 761 g of hyperaccumulators and which was based on the same process principles as the pyrolysis reactor of the laboratory experiments. Almost 99 % of the metals was concentrated in the pyrolysis char during the pilot-scale experiments.

Conclusively the accumulation of the metals in the plants can be viewed as a first concentration step in the soil remediation process, and pyrolysis can be considered as a second step leading to further concentration into an even smaller volume assuming that the metals reside in the pyrolysis char at process temperatures between 450 and 550 °C. This smaller volume though should be treated as hazardous waste and disposed at a hazardous waste dumping site (Sas-Nowosielska, Kucharski et al. 2004). For this reason fast pyrolysis is also preferred to slow pyrolysis as the longer residence time of slow pyrolysis favours char formation, whereas fast pyrolysis mainly yields liquid products and hence results in a more compact volume of contaminated solids with a higher concentration of metals.

1.4 Techno-economic assessment

Techno-economic assessment (TEA), techno-economic analysis, techno-economic evaluation or techno-economic feasibility are widely used concepts, mostly set up for investigating the technical feasibility of and exploring the economic potential of newly found or adjusted existing technologies. Techno-economic assessments have been performed on a multiplicity of subjects, but especially for evaluating new technologies that are designed for environmental purposes. For instance, they have been performed for biomass conversion (Mitchell, Bridgwater et al. 1995; Rodrigues, Faaij et al. 2003). Techno-economic assessments that specifically pay attention to general or specific process designs for fast pyrolysis have already been performed by Westerhout, Van Koningsbruggen et al. (1998), Bridgwater, Toft et al. (2002), Solantausta (s.d.), Mullaney (2002) Peacocke, Bridgwater et al. (2006), Uslu, Faaij et al. (2008), Magalhães, Petrovic et al. (2009), Trippe, Fröhling et al. (2010), Wright, Daugaard et al. (2010)

Unfortunately there are no "rules" on the way how to perform a techno-economic evaluation, like there are for life cycle analysis. There are also no textbooks on techno-economic assessment, unlike for cost-benefit analysis. Besides, the performers of these assessments are usually the developers of the technology, e.g. process engineers, or members of the research staff of universities' departments of engineering, technology or science who often carry out the techno-economic assessment without the help of economists. Boldly speaking (without judging the references above), this might raise questions about the objectivity that has been manifested during the execution of some techno-economic assessments: sometimes the discussions on the economics of a new technology appear superficial and quite optimistic, which might give the impression that the economics are reported merely for promoting new or adjusted technologies as an underlying agenda. However, a large part of the techno-economic assessments do contain an elaborate economic analysis, though without an in-depth study of economic risk. Often uncertainty is treated only by means of one-factor-at-a-time sensitivity analysis of the key economic indicator. Finally, an in-depth study of ecological and environmental aspects is often lacking.

Therefore this dissertation also aims to contribute to the quality of techno-economic assessments by proposing a first general methodological framework for techno-economic assessments with a focus on the economic aspects (which can be refined in subsequent research). Although the starting point was the search for viable phytoremediation strategies for farmers, the focus in this dissertation is on the economic viability of the conversion technology itself, thus from the point of view of an investing company. Economic profitability of biomass conversion is a prerequisite if one wants to provide farmers with a sufficiently high income. A sufficiently high price for the biomass can only be guaranteed if the most profitable conversion technology is selected. Therefore, the profitability of fast pyrolysis is compared to other thermochemical conversion technologies, followed by a thorough investigation of economic risk from the investor's point of view.

1.5 Research questions

The main research question to be answered at the end of this dissertation is:

What is the techno-economic potential of fast pyrolysis for the economic valorisation of short rotation willow cultivated for phytoextraction?

In order to make this research question operational, it has been subdivided into subquestions. Each subquestion is motivated and it is indicated in which chapter its answer can be found. A summary of the answers to the subquestions is provided in paragraph 8.2 of chapter 8, after a brief recapitulation of the problem statement in paragraph 8.1. The dissertation then concludes with a discussion of unsolved problems and recommendations for further research in paragraph 8.3.

Subquestion 1:
What is an appropriate methodological framework for techno-economic assessments?

Before one can assess a new technology, one should first clearly define the purpose of the assessment. After defining the goals, an appropriate methodological framework should be selected and developed, including the indication of the reference comparison base, and the boundaries of the investigation should be clearly stated. Paragraph 2.1 of chapter 2 introduces the selected methods by clarifying the main problems that are associated with the way in which techno-economic assessments are often performed. Next, in paragraph 2.2, the possible goals that a techno-economic assessment can or should have are identified. The case study under investigation then creates the setting for the focus of this dissertation, i.e. to deepen our understanding of the economic profitability and economic risk of an investment in fast pyrolysis. This dissertation thus is limited by an investigation of the techno-economic performance from the point of view of a private investor. This means that we first need to know how the technology works (see also chapter 3). Then a discounted cash flow analysis (or *private* cost benefit analysis) should be executed and complemented with a thorough assessment of economic risk.

The structure of the discounted cash flow model is explained in paragraph 2.3. Besides, the possible link with phytoremediation research is briefly explained, by clarifying how the information generated in this dissertation can be used in a more general cost benefit analysis of soil remediation by means of plants. In paragraph 2.4 the methods applied to deal with uncertainties are explained. In fact, the economic risk of fast pyrolysis of willow has been explored by applying Monte Carlo simulations and a method from experimental design (Plackett-Burman designs). The outline and the (dis)advantages of those methods have been clarified. Finally, some general risk reduction strategies have been formulated in paragraph 2.4.4. By changing the inputs (feedstock) or outputs (pyrolysis products) of the fast pyrolysis plant, the economic performance might be enhanced so that the dependence on highly insecure variables (cf. green power certificates) might be lowered. Chapter 2 ends by explaining how the economic trade-off between the fast pyrolysis products has been calculated.

Subquestion 2:
What are the technological advantages of fast pyrolysis for valorising short rotation coppice compared to other thermochemical conversion technologies?

In chapter 2 it has been concluded that it is important to know how a technology works, before one can study its economic profitability. The discounted cash flow model surely stands or falls with the technical assumptions that have been made. Therefore, some basic understanding of the technologies under investigation is required. It is not our purpose though to explain the detailed chemistry and physics behind every technology. The focus of this dissertation is on investigating the economic profitability and economic risk. Hence, the basics of each technology are covered in chapter 3 and each technology will be briefly described based on an extensive literature survey.

The introduction in paragraph 3.1 of chapter 3 starts with explaining that the lignocellulosic chemical composition of short rotation willow, i.e. the lignin fraction, motivates the choice for studying thermochemical technologies (combustion, gasification and pyrolysis) for converting willow into energy. After explaining the main differences between combustion, gasification and pyrolysis, in paragraph 3.2, paragraph 3.3 describes the essential features, advantages and applications of fast pyrolysis by means of a simplified process design, mass and energy balance. Paragraph 3.4 does the same for combustion and paragraph 3.5 for gasification. Chapter 3 thus elucidates the technical assumptions that form the base for the discounted cash flow model of chapter 4.

Subquestion 3:

What is the economic potential of fast pyrolysis for valorising short rotation coppice compared to other thermochemical conversion technologies?

In chapter 2 it has been stated that the techno-economic potential of fast pyrolysis will be studied from an investor's point of view. Therefore, a discounted cash flow model has been developed for the three thermochemical conversion technologies considered. A discounted cash flow model requires estimation of the initial investment expenditure at the start of the project, and identification and estimation of the relevant revenues and expenditure items throughout the expected operational lifetime of the investment. After studying the relevant literature, it became clear that the investment cost of a fast pyrolysis plant is highly uncertain. A meta-analysis of the capital cost for an investment in fast pyrolysis was appropriate. The results of this meta-analysis are reported in paragraph 4.2.

Following the analysis and estimation of the capital cost, one should translate the technical data of chapter 3 into their economic consequences. This means that inputs and outputs should be priced. The assumptions with regard to the required amount of inputs and produced amount of outputs have been reported together with their corresponding prices and sources. Finally, incentives issued by the government for producing renewable energy and combined heat and power are relevant from an investor’s point of view. The result of the discounted cash flow model for fast pyrolysis of willow followed by a CHP plant for the production has been presented at the end of paragraph 4.3.

Combined heat and power production however is only relevant when there is sufficient demand for heat. Ideally this heat demand is mapped during a micro-screening of the region, which might include an extensive investigation of the required heat by industry, residential housing, healthcare, swimming pools and agriculture, amongst others, by means of geographic information systems (GIS). The latter however is beyond the scope of this dissertation and as a consequence the heat demand cannot yet be assured. Therefore, in paragraph 4.4, a discounted cash flow model has also been built for fast pyrolysis of willow for electricity production only. Although fast pyrolysis might be a promising option for the conversion of contaminated willow from the viewpoint of metal control, its economics should be compared to the profitability of combustion and gasification, because finding a conversion technology that yields a higher sales price for the biomass is in the interest of farmers growing short rotation coppice. Therefore, paragraphs 4.5 and 4.6 reflect the net present value of an investment in respectively combustion and gasification for electricity production. Chapter 4 concludes with a comparison of fast pyrolysis, combustion and gasification in paragraph 4.7 and discusses the cost difference with converting clean biomass.

Subquestion 4:

What is a possible price range for willow cultivated in the Belgian Campine as an energy crop?

This subquestion implies an *exploration* of the possible price for willow cultivated in the Belgian Campine (e.g. during phytoextraction). This exploration starts with estimating the cost of growing and harvesting the willow year after year. A discounted cash flow model has been built, based on information received from project partners during research projects on phytoremediation in the Belgian Campine. The information in the discounted cash flow model then has been used in order to calculate the production cost of willow by means of the levelised cost method.

The cost of growing and harvesting willow (which can be considered as the minimal sales price that a farmer wants to receive for growing willow) can then be compared to the price that an investor might be willing to pay for using willow as a feedstock in a thermochemical conversion technology. This price can be considered as the maximum achievable sales price for willow cultivated on contaminated farmland in the Belgian Campine. The maximum willow price has been defined as the highest price that an investor can pay for purchasing willow assuming that an investor wants a 95 % chance of a positive net present value. This is when uncertainties come into play for the first time in this dissertation. Unfortunately we did not dispose of sufficient information from the viewpoint of a farmer to extend this reasoning to the minimum price that a farmer wants to receive, as this minimum price depends on more than the cost of growing and cultivating willow alone (e.g. the share that short rotation coppice has in the farmer’s activities/rotation scheme, the opportunity cost of growing other crops on the same farmland, amongst others). Therefore the lower limit of the price range corresponds to the production cost of willow. The maximum willow sales prices as defined above can then be considered as the upper limit of the price range.

Because the maximum willow price is a function of the uncertainties to which an investor is confronted, we first identify the uncertain variables in paragraph 5.2. Next, we quantify the uncertainties by defining a range of values and a corresponding probability distribution for each uncertain variable. Finally Monte Carlo simulations have been used to determine the probability distribution and the chance of a positive net present value of the discounted cash flows, so that the expected maximum willow price can be calculated. Because none of the thermochemical conversion technologies for electricity production anticipates to a satisfactory willow price, the maximum prices have also been calculated for fast pyrolysis for combined heat and power production.

Subquestion 5:

What is the economic risk of fast pyrolysis?

With the economic risk of fast pyrolysis, we intend to study the uncertainties that might have an important impact on the net present value. This impact can be determined by means of the Monte Carlo simulations that have been performed for determining the possible willow sales price. The information generated for answering subquestion 4 can be used to study the sensitivity of the net present value for the uncertainties identified in paragraph 5.2.

Because fast pyrolysis for combined heat and power production was the only scenario that yielded a positive net present value, we concentrated on analyzing the economic risk of fast pyrolysis for combined heat and power production in paragraph 5.3. The data that result from Monte Carlo simulations have been used to determine a meta-regression model which explicitly displays the amount of the net present value of the cash flows in function of the identified uncertain variables. The resulting equation can be used by investors to have a quick glance at the expected net present value when there is more certainty about the value of the uncertain variables.

Because Monte Carlo simulations are often criticised for the subjectivity in assigning probability distributions, we also applied a method that does not require definition of probability distributions. This method (Plackett-Burman designs) has been borrowed from the discipline of experimental design and will also be used to determine a meta-regression model for the net present value in paragraph 5.3.3.

Chapter 5 then concludes by comparing the findings of the Monte Carlo simulations with the Plackett-Burman designs and discusses some potential scenarios for risk reduction strategies. As the largest risk is posed by factors that lie outside the decision power of the investor (e.g. the value of the green power certificates, or the available farmland for growing willow), we identify some strategies that are in control of the investor of the fast pyrolysis plant. These strategies can be applied in order to enlarge the economic profitability of the pyrolysis plant, so that the chance of a positive net present value is higher and the dependency on the value of the green current certificates, amongst others, diminishes. For instance, risk can be reduced by changing the inputs or feedstock of the fast pyrolysis plant or by changing the proportion of the fast pyrolysis products. These potential risk strategies are the subject of chapters 6 and 7.

Subquestion 6:

How can the economic risk of fast pyrolysis be reduced by changing the inputs (i.e. feedstock) of the pyrolysis plant?

One of the main problems with pyrolysis oil is originated by its water content. The latter determines the viscosity, the combustibility (ignition) and the lower heating value of the pyrolysis oil. It has been presumed that pyrolysis of willow together with plastics might result in esterification reactions that lower the water content of the pyrolysis oil. Therefore, the research group of analytical and applied chemistry performed several experiments on fast co-pyrolysis of willow with biopolymers. The choice for biopolymers has been motivated by avoiding the greenhouse gas emissions that are accompanied with pyrolysis of regular plastics. Besides, biopolymers are a growing waste stream that currently is disposed of at composting installations at a cost of 80 EUR t_{dm}^{-1}. Because of technical insecurities caused by possible impurities in the waste stream, composters themselves ask for an alternative waste treatment which is an additional incentive for investigating the economic potential of fast co-pyrolysis of willow with biopolymers.

The influence of the biopolymers appeared to be somehow complex. One of the goals of the experiments was to rank several biopolymers with regard to their potential in increasing pyrolysis oil quality. The ranking has been executed by the researchers of chemistry by means of multi criteria decision analysis, but they asked to validate the ranking by translating the chemical experiments into economic results. We first reported the results of the chemical experiments in paragraph 6.2. As a next step, we developed discounted cash flow models for each of the experiments in order to check the impact of fast co-pyrolysis of willow with the respective polymers on its economic profitability in paragraph 6.3. Subsequently risk analysis has been performed in order to evaluate the uncertainties accompanied with fast co-pyrolysis. The generated information during the Monte Carlo simulations can thereafter be used to determine the gate fee that an investor in fast co-pyrolysis wants to receive for processing the biopolymer waste stream. When the gate fee is lower than the disposal cost of 80 EUR t_{dm}^{-1}, a potential alternative for composting has been found. Finally, chapter 6 ends with a scenario analysis in order to determine the impact of several possible scenarios on the height of the gate fee.

Subquestion 7:

How can the economic risk of fast pyrolysis be reduced by changing the outputs (i.e. the proportion of the pyrolysis products) of the pyrolysis plant?

Until chapter 6 it has been assumed that the char should be disposed of at a landfill site, that the gas is needed for fulfilling internal energy requirements and that the oil is converted in an internal combustion engine to produce combined heat and power. Other applications of the pyrolysis products might once again increase the profitability of the fast pyrolysis plant. As an example, chapter 7 starts with the identification of two alternative applications of the pyrolysis char. Indeed, the latter is often referred to as a resource for the production of soil amendments or activated carbons. As paragraph 7.2 concludes that the metal content of the char is too high for application as a soil amendment, the remainder of the chapter focusses on the valorisation potential of char activation by, once again, building a discounted cash flow model for steam activation of the pyrolysis char.

Besides, the product yields of the fast pyrolysis process differ according to the process parameters, such as temperature. When the pyrolysis products have different economic values, the choice of the process temperature might influence the overall profitability of a fast pyrolysis plant. The impact of temperature has been investigated by plotting the economic trade-off between char production and oil production. Next, this information is used for calculating the optimal process temperature under different scenarios in paragraph 7.4.

2 Techno-economic assessments

2.1 Introduction

Techno-economic assessment, techno-economic analysis, techno-economic evaluation, techno-economic feasibility or techno-economic viability are widely used concepts. Techno-economic assessments have been performed on a multiplicity of subjects, such as innovations in communication networks (Jerman-Blazic 2007; Staessens, Angelou et al. 2011) and logistics (Lannoo, Naudts et al. 2012) and on solutions for problems in the electricity grid (Didden 2003), but especially for evaluating new technologies that are designed for environmental purposes. Some illustrative topics with an environmental goal that have been the subject of techno-economic assessments are recycling practices (Athanassiou and Zabaniotou 2008), applications of CO_2 capture (Myles, Herron et al. 2012), the application of smart meters (Tahon, Van Ooteghem et al. 2012), wind and solar energy (Bakos and Soursos 2002; Chong, Naghavi et al. 2011; Hernández and Tübke 2011), hydrogen production (Mueller-Langer, Tzimas et al. 2007), biomass conversion (Mitchell, Bridgwater et al. 1995; Rodrigues, Faaij et al. 2003; Jones and Zhu 2009), biofuel production (Enguídanos, Soria et al. 2002; Klein-Marcuschamer, Oleskowicz-Popiel et al. 2010), algae (Ma 2011). Techno-economic assessments that specifically pay attention to general or specific process designs for fast pyrolysis have already been performed by Westerhout, Van Koningsbruggen et al. (1998), Bridgwater, Toft et al. (2002), Solantausta (s.d.), Mullaney (2002) Peacocke, Bridgwater et al. (2006), Uslu, Faaij et al. (2008), Magalhães, Petrovic et al. (2009), Trippe, Fröhling et al. (2010), Wright, Daugaard et al. (2010).

Unfortunately no standards have been found on the way how to perform a techno-economic evaluation, like there are for life cycle analysis. There are even no textbooks on techno-economic assessment, unlike cost-benefit analysis. Besides, the performers of these assessments are usually the developers of the technology, who carry out the techno-economic assessment without the help of economists. Only rarely one of the authors can be explicitly identified as a fellow worker of an economic department of a university, a research institution or a government agency. Sometimes the discussion on the economics of a new technology is quite superficial, and an in-depth analysis of economic risk is lacking. Therefore this dissertation aims to contribute to the quality of techno-economic assessments by proposing for the first time a general methodological framework for techno-economic assessments with a focus on the economic aspects, based on a qualitative assessment or desk research of the existing techno-economic assessments.

2.2 Defining techno-economic assessments

To date no definition exists for techno-economic assessments. They often start with a specific technological problem statement in the introduction of an article or a research report. The problem statement is framed within the state-of-the-art of a certain technology (by means of a comprehensive literature review) and is often inspired by finding the right solutions to social or environmental challenges. Next potential solutions to the problem are proposed and evaluated by developing models that are based on experiments and/or literature, so that one can conclude which emerging technology has the highest potential for (commercial) application. The importance of improving the technical potential has for instance been stressed by Swanson, Satrio et al. (2010) who write: "The purpose of this techno-economic analysis is to compare ... technologies selected for their promise and near-term technical viability." Finally, the economic feasibility is explored, which assists the author in finding arguments for directing research towards the commercialisation of the proposed solutions. Hence a techno-economic analysis can provide information for decision making (Ma 2011). The National Advance Biofuels Consortium of the United States for instance describes the goal of techno-economic analysis (TEA): "TEA combines process modeling and engineering design with economic evaluation to qualitatively understand the impact that technology and research breakthroughs have on the financial viability of a conversion strategy" (NABC 2011). An interesting view on the role of technology assessments has been formulated by Smits, Leyten et al. (1995): they start from the observation that technologic potential is underutilised in social and economic terms and conclude that technological assessments "can play an important role in increasing the social and economic returns on investments in the development of new technology". In other words, technological assessments should aid technology policy to shift attention from the supply side to the demand side or more precisely stated in their own words: "technology policy should no longer concentrate primarily on the generation of new technologies, but on the question how options can be translated into successful products, services and solutions to social problems." In general a techno-economic assessment can thus be described as *the evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision makers in directing research and development or investments.*

In other words, it can be stated that a techno-economic assessment ideally answers three important questions. These questions are depicted in the red boxes in figure 2. The green boxes are examples of methods and concepts that can assist in answering each question. In the next pages, the relevance of each question is explained and possible methods for answering each question are briefly elucidated. The case study under investigation then creates the setting for the focus of this dissertation, i.e. to deepen our understanding of the economic profitability and economic risk of an investment in fast pyrolysis. This dissertation thus is limited by an investigation of the techno-economic performance from the point of view of a private investor. Therefore, after introducing all questions, the remainder of this chapter deals with the methods suited for answering the second question.

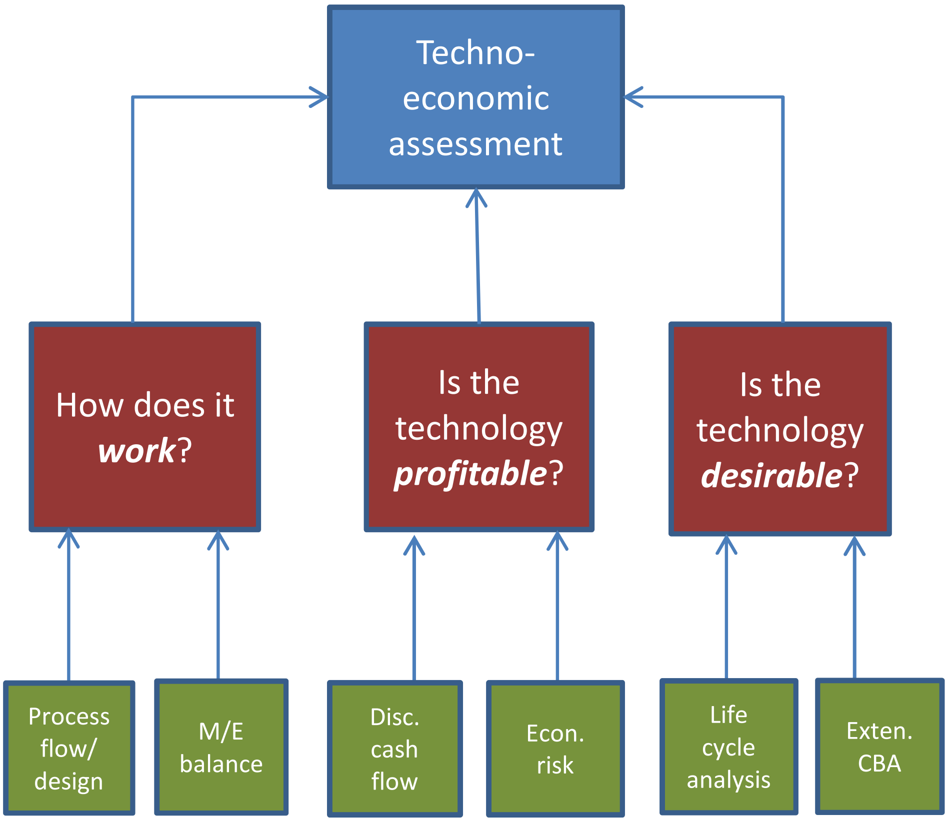

figure 2: Methodological framework for techno-economic assessments

1. <u>How does the technology work?</u>

Before one can answer the other questions, one should first have a thorough understanding of the technology under investigation. Therefore, the new technology should first be thoroughly described. This step comprises a comprehensive description of the state-of-the-art of a technology, indicating its advantages and limitations in comparison to other or older technologies. For biomass conversion technologies specifically, mass and energy balances are required, based on a schematic process design. Here the description of fast pyrolysis has been treated in chapter 3 by means of a literature review.

2. Is the technology profitable?

The answer to this question should depict the economic feasibility of the technology under investigation. It should give a clear picture of the capital and operational costs of the technology, and at best also contains calculations of the benefits. Sometimes, when the goal of the technology is limited to improving cost-effectiveness (e.g. Hernández and Tübke (2011)) or the reduction of capital expenditure (sometimes labelled as "capex") and operational expenditure (sometimes labelled as "opex"), studying the costs suffices to answer the second question. A full economic picture however also estimates the economic benefits of a new technology in a discounted cash flow analysis, which finally yields the net present value (NPV) of cash flows as an indicator of the technology's profitability (see also paragraph 2.3). Other popular measures for evaluating whether an investment is financially worthwile are the payback time and the internal rate of return (IRR). The payback time is defined as the point in time when the initial investment is paid back by the net incoming cash flows, but it has the disadvantage of not taking into account the time value of money. The IRR is the discount rate at which the NPV is zero. Because the IRR is a percentage, it can only be used as a decision rule for selecting projects when there is only one alternative to a status quo and should certainly not be used to select one project from a group of mutually exclusive projects that differ in size (Boardman, Greenberg et al. 2006). Therefore, it is preferred to evaluate conversion technologies only by means of the NPV of the cash flows generated by the initial investment expenditure.

Determining cash flows requires to "predict the future", so that one is often confronted with uncertainties with respect to technological and economical variables. It is important to take into account these uncertainties so that one gets a better understanding of the economic aspects of the technology. One option is to characterise the future in terms of a number of distinct contingencies (or scenarios), i.e. possible events or states of the world.

When one is able to assign probabilities of occurence to each of these states, one can calculate the *expected value* of the project's net benefits, though it is often difficult to assign accurate probabilities. As a consequence the probabilities attached to the events are often subjective assessments that cannot be made with great confidence (Boardman, Greenberg et al. 2006). Another problem with expected value analysis is that risk sometimes can only be pooled across few individuals or policies, so that the actually realised values of costs and benefits are very far from its expected value (cf. the incidence of an asteroid collision is so low, that the expected value of the damage is far below real costs of the occurence of such a collision).

Another option, which is often applied in techno-economic assessments, is the investigation to which extent the key technologic or economic indicators change when a single assumption has been changed. This is called one-factor-at-a-time or *partial sensitivity analysis* which implies varying the value of one variable and checking the impact on the economic indicator under investigation (often the net present value of the cash flows) without taking into account whether the change in the value of the variable is realistic, sometimes resulting in many useless calculations because of a lack of practical relevance. Some authors though take into account real possible outcomes by determining several scenarios for the uncertain variables during *scenario analysis*, though these scenarios are often only limited to a pessimistic, an optimistic and a most expected scenario. The latter can provide very useful information. The worst case scenario provides information on the maximal economic loss. When the worst case yields a positive NPV, an investment is worthwile taking the risk, whereas in the other case, i.e. when the best case yields a negative net present value it is wise to conclude that an investment should not be carried out. However, values near the base case assumptions are often more likely to occur than values near the extremes, so that worst and best cases are actually not very likely to occur because they require the joint occurence of low probability events. The analysis of economic risk can therefore be enhanced by taking into account realistic ranges and probability distributions for the values of uncertain variables, while jointly changing them (because in practice variables often jointly change) by means of *Monte Carlo simulations*. Paragraph 2.4 illustrates how economic risk has been investigated by means of these Monte Carlo simulations. Sometimes it can be useful to delay a decision, especially with regard to irreversible investments for which relevant information can become available in the future. The expected value of the information gained is called a *quasi-option value* (Arrow and Fisher 1974). Here, the quasi-option value has not been adopted, but given the uncertainty with respect to the capital cost of fast pyrolysis (see chapter 4) it might be interesting to incorporate it in future research.

3. <u>Is the technology desirable?</u>

The final question that a techno-economic assessment should address is whether the technology indeed solves the social or environmental issues it has been designed for. Because this dissertation focuses on the economic feasibility of willow conversion from the point of view of a private investor, the answer to this question is beyond the scope of this dissertation, though it would certainly provide useful information in future research (e.g. when the results of the current dissertation are coupled to previous and contemporaneous research on the phytoextraction case). Therefore, the methods that are useful in providing an answer to this part of a techno-economic assessment are briefly mentioned in the next paragraphs.

Life cycle analysis (LCA) is one of the most quoted methods for assessing the environmental impact of a product, service or technology, from raw materials to waste removal. It is an environmental assessment methodology which analyses all resource requirements (e.g. water and energy) and material flows (inputs and outputs, emissions, etc.) of a product system (Jungk, Patyck et al. 2000). LCA methodology has been standardized in ISO standards (ISO-14040 to ISO -14043). Key components of such an LCA are goal and scope definition, inventory analysis, impact analysis and interpretation (Klöpffer 1997; Jungk, Patyck et al. 2000). During inventory analysis all inputs and outputs are first quantified and then expressed in terms of the functional unit defined during goal and scope definition. In a second step all resources and emissions linked to the material flows are quantified. During impact assessment, the inventoried quantities are aggregated into several impact categories that correspond to an environmental problem (Jungk, Patyck et al. 2000). Life cycle analysis can be complemented by (environmental) life cycle costing (LCC). Environmental life cycle costing envisages to calculate all costs associated with the life cycle of a product, regardless of the agent who bears the costs (Ciroth, Hunkeler et al. 2008). Together with a social LCA (or SLCA), LCA and LCC can be integrated in what is called a life cycle sustainability assessment or LCSA (Swarr, Hunkeler et al. 2011). Such an LCSA analyses a product, service or technology for each of the three pillars of sustainability, i.e. environment (LCA), economy (LCC) and social equity (SLCA).

Especially when technologies are developed for environmental purposes, a traditional cost-benefit analysis will provide incomplete information for the evaluation of a new technology. When environmental externalities are present, it is advised to also valuate these externalities and extend the traditional cost-benefit analysis in what is called an "extended cost-benefit analysis" or "environmental cost-benefit analysis".

After answering these three questions the assessor can have a thorough understanding of the techno-economic potential of the technology. A comprehensive techno-economic assessment thus requires knowledge from several disciplines (chemistry, process engineering, economics, risk analysis, ecology, and so on), an thus requires a multidisciplinary approach. Therefore the techno-economic assessment in this dissertation has been performed in close cooperation with chemists, using their experimental data with remaining assumptions based on technical information available in scientific journals. Hence the amount of references from betasciences (e.g. chemistry, engineering, biology) compared to social sciences (economics) is substantial.

One of the remaining disadvantages of techno-economic assessments is that they are often quite “static”, whereas research is actually often continuous evolving. TEAs are based on experimental data or assumptions from literature and although changes in the values of input variables might have been taken into account during risk analysis, the performers of a techno-economic assessment can only study a limited set of scenarios and it is impossible for them to address all possible process designs or value choices that are of interest to the multiple actors involved (see also the discussion on experimental design), especially in the biofuels community (Klein-Marcuschamer, Oleskowicz-Popiel et al. 2010).

2.3 Cost-benefit analysis and discounted cash flows

2.3.1 Link with previous phytoremediation research

In this case study, which is very comparable to the case of Lewandowski, Schmidt et al. (2006), a large share of the contaminated land is in agricultural use. Farmers in the Belgian Campine risk confiscation of their crops by the Federal Agency for the Safety of the Food Chain (Belgium) because the cadmium content in the food and fodder crops often exceeds legal threshold values (Witters, Van Slycken et al. 2009). Farmers who do not remove the heavy metals from their farmland, cannot use it for the production of high value crops like vegetables. This threat on agriculture encourages proper soil management. The status quo thus implies a potential loss of income because the farmers currently have to grow crops that take up less heavy metals than vegetables, e.g. fodder maize, which might provide less income per hectare to the farmer. One of the economic benefits of phytoremediation results from the fact that the farmer can take the land into vegetable production again after the cleaning period (Lewandowski, Schmidt et al. 2006; Witters 2011). One way to increase agricultural income and to improve soil quality is to grow nonfood agricultural crops that remediate the soil (Witters, Van Slycken et al. 2009).

The investigation of the economic impact of phytoextraction on agricultural income is beyond the scope of this dissertation, but there is an important link between the valorisation of phytoextracting biomass and the potential income of the farmer. This possible impact of phytoextraction on the farmer's income has been described by Vassilev, Schwitzguébel et al. (2004) who proposed a cost-benefit approach to investigate the economic attractiveness of phytoremediation compared to traditional soil reclamation techniques. Phytoremediation is often proposed as a low cost remediation technology with the longer time frame required for reclamation (compared to traditional excavation) as its main advantage. They state that traditional remediation techniques have the advantage that higher revenues (from cultivation of high value crops such as some vegetables) can be gained at an earlier moment in time compared to phytoremediation. The adoption of phytoremediation thus depends, among other things, on the repercussions on the income of farmers. If phytoextraction could be combined with a revenue earning operation, the time constraint may become less important. The cost-benefit analysis proposed by Vassilev, Schwitzguébel et al. (2004) is based on the "income per hectare per year" as a measurement concept. They distinguish the following (private) costs and benefits (see figure 3) to be taken into account for determining the income per hectare per year:

- the costs involved with cultivating phytoextracting crops (capital costs such as land preparation, plant material, and operational costs such as labour costs, harvesting equipment, …);
- the opportunity cost of switching from current activities to phytoextraction, i.e. the income lost by not growing current crops, e.g. fodder maize for dairy cattle;
- the income from biomass valorisation, which can be considered as a way of "recovering" the costs of phytoextraction;
- the potential higher income for farmers who can grow crops for human consumption after phytoextraction.

A simplified presentation of the evolution of farmer's income can be found in figure 3 where reference is made to the above mentioned costs and benefits.

The figure has been split in two time periods: A and B. The left part of figure 3, part A, represents the time period during which phytoextraction takes place. The right part of figure 3, part B, represents the time period after phytoextraction, or in other words, the period in which the soil is clean. During phytoextraction (in part A) a farmer receives a certain income (measured on a per hectare per year basis) from growing phytoextracting crops of which the produced biomass subsequently is sold to a conversion plant. This income thus depends on the amount of phytoextracting biomass produced, the sales price of the biomass and the cost of growing and harvesting it. It is expected that the income during phytoextraction is much lower than the income that could have been earned by the current activities (mainly from dairy cattle rearing) of the farmers in the Campine. A farmer who switches from current activities to growing phytoextracting crops, thus loses a certain amount of income. This "lost income" during the remediation period is to be considered as the difference between the abandoned revenue from current activities on the polluted soil and the possible "income during phytoextraction" from the cultivation and sales of the metal accumulating biomass. This lost income can be seen as the private cost of phytoremediation (Vassilev, Schwitzguébel et al. 2004). The height of the cost depends both on the height of the income during soil reclamation (the vertical question mark in figure 3) and the time required for soil sanitation (the horizontal question mark in figure 3). From the point of view of the user of the soil, this is the opportunity cost of phytoextraction.

After phytoextraction (time frame B), the cleaned up soil can be used for other purposes such as the cultivation of high value vegetables (Vassilev, Schwitzguébel et al. 2004; Lewandowski, Schmidt et al. 2006). It is expected that these vegetables grown on clean soils generate an income that is higher than the income from current activities on polluted soils (e.g. dairy cattle rearing). This "regained income in new cleaned up situation" can be considered as the benefit of phytoextraction. By discounting the costs and benefits over the total time period, one arrives at the net present value (NPV) of phytoextraction.

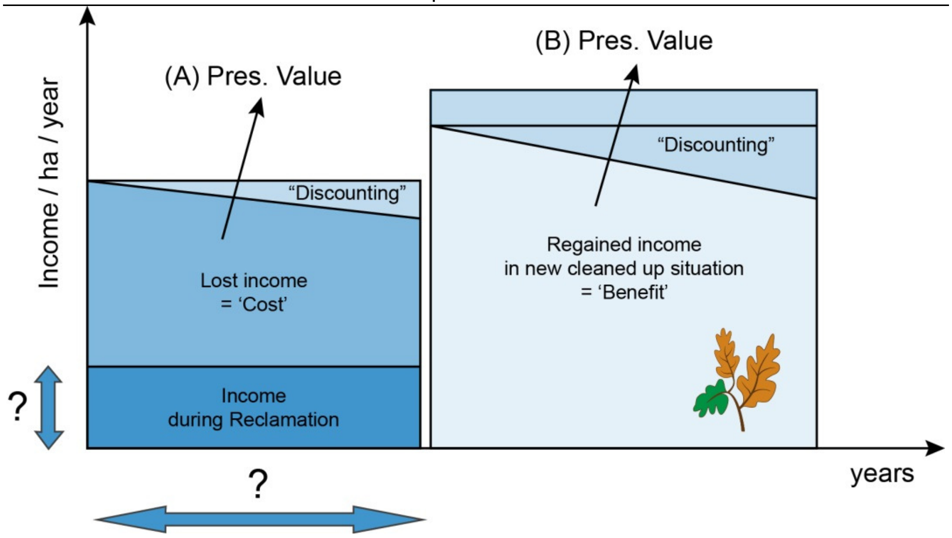

figure 3: The framework of cost-benefit analysis of phytoremediation (Vassilev, Schwitzguébel et al. 2004)

Witters, Van Slycken et al. (2009) were the first to refine and concretise the aforementioned cost-benefit model. They calculated the net present value of the agricultural gross income per hectare per year for willow, maize and rapeseed, which they defined as "total revenues, including grants, diminished with variable costs and costs for contractors", then summed and discounted the yearly gross income over 21 years (the largest of the life cycle, i.e. for willow) at a discount rate of 5 %. The adapted gross income is a method of measurement specifically constructed for the purpose of investigating the income effect of phytoextracting crops (Witters 2011). It is based on the gross balance (i.e. the difference between total revenues minus related variable costs), thus excluding fixed costs and wages, though it has been adjusted by incorporating equipment costs, third party labour costs and fuel costs as these are important costs to willow and rapeseed (for a detailed discussion on different income measurements we refer to the doctoral dissertation of Witters (2011)). Some of these costs (especially in the case of willow, e.g. planting costs in the first year and harvest costs every three years) are not recurring each year, so that figure 3 will show a more irregular and less smooth course over the years. Subsequently, Witters, Van

Slycken et al. (2009) use this income calculation in a multicriteria decision analysis for assessing crop choice for contaminated land remediation. However they assumed that willow would be cocombusted in a coal plant and did not take into account the potential of other conversion technologies such as gasification and fast pyrolysis. In more recent research (Witters, Mendelsohn et al. 2012a; Witters, Mendelsohn et al. 2012b) they added the abatement of CO_2 for each phytoremediating crop to the private economic analysis, in order to value the advantage of phytoremediation compared to conventional remediation.

This dissertation focuses on the economic potential of the valorisation of the biomass from phytoextracting willow by means of other conversion technologies. By assessing the techno-economic potential of fast pyrolysis, it is our purpose to (indirectly) contribute to determining the potential height of the farmer's income during phytoextraction with willow. The higher this income, the lower the difference with the currently earned income of dairy cattle rearing and thus the lower the lost income for the farmer, possibly convincing a larger amount of farmers willing to switch from fodder maize to phytoextracting crops (in this case: willow). This information can then be used in the larger cost-benefit framework and combined with information on the phytoextraction duration, so that the cost of phytoextraction can be determined.

Concluding, in line with figure 3 and with Robinson, Fernández et al. (2003) the *private* cost of phytoextraction (C_{phyto}) with willow can be approached by deducting the farmer's income during phytoextraction (Y_{phyto}) from the currently earned income for rearing dairy cattle (Y_{dairy}) (see equation 2.1, illustrated by the left part of figure 3). Robinson, Fernández et al. (2003) determined the cost of phytoextraction as the difference between the cost of planting and production of the biomass minus the sales revenues from the saleable biomass.

$$C_{phyto} = Y_{dairy} - Y_{phyto} \tag{2.1}$$

with: C_{phyto} = private cost of phytoextraction (EUR ha^{-1} yr^{-1});
Y_{dairy} = income of dairy cattle rearing (EUR ha^{-1} yr^{-1});
Y_{phyto} = income during phytoextraction (EUR ha^{-1} yr^{-1}).

The farmer's income during phytoextraction (Y_{phyto}) is the difference between the turnover of the sold willow and the costs of cultivating the phytoextracting willow. In other words the farmer's income during phytoextraction (Y_{phyto}) equals the amount of willow sold (q_{willow}) multiplied by the profit margin per unit of sold willow (see equation 2.2).

$$Y_{phyto} = q_{willow} \times (p_{willow} - c_{willow}) \qquad (2.2)$$

with: Y_{phyto} = income during phytoextraction (EUR ha^{-1} yr^{-1});
q_{willow} = yearly amount of willow sold (t ha^{-1} yr^{-1});
p_{willow} = unit willow price (EUR t^{-1});
c_{willow} = unit cost of cultivating willow (EUR t^{-1})

The unit cost of cultivating willow in the Belgian Campine case has been calculated in paragraph 5.2.1, whereas the unit willow price is the subject of paragraph 5.2.2, so that the information in both paragraphs can be used to approach potential income per hectare per year for short rotation willow.

2.3.2 Net present value and the production model

The unit willow price (p_{willow}) in equation 2.2 is the sales price of the willow, i.e. the price that a farmer receives for selling one tonne of willow to an investor in renewable energy. The latter invests in a conversion technology for the production of energy and/or materials and pays for obtaining the willow feedstock. The price that an investor is willing to pay for obtaining one tonne of willow depends on the profitability of the investment. In economics the concept of "net present value" (NPV) is used to evaluate the profitability of an investment decision (Laveren, Engelen et al. 2002; Mercken 2004). In paragraph 2.4.1 it is explained how the NPV is used in calculating this unit willow price that an investor is willing to pay. The NPV of an investment is today's value of current and future cash flows, which are the result of an investment using a predetermined discount rate. The NPV formula is:

$$NPV = \sum_{n=1}^{T} \frac{CF_n}{(1+r)^n} - I_0 \qquad (2.3)$$

with: T = the life span of the investment; every year is indexed by the symbol "n";

CF_n = the cash flow, i.e. the difference between revenues and expenditure after tax in year n;

I_0 = the expenditure in year 0 connected with the initial net investment;

r = the discount rate.

The initial net investment in year zero is the difference between the total plant cost of a conversion technology which transforms biomass into valuable products (TPC, see paragraph 4.2.1 for a definition of the total plant cost) and the investment subsidy (U_{inv}):

$$I_0 = TPC - U_{inv} \qquad (2.4)$$

The investment subsidy takes the form of an investment allowance, i.e. a percentage k of the total plant cost can be deduced from the company's profit, so that payable taxes can be lowered:

$$U_{inv} = \tau \times k \times TPC \qquad (2.5)$$

To determine the NPV, we will only work with "cash flows" (CF). As companies must pay taxes on profits, cash flows are distinguished as "before tax" and "after tax". Depreciation (D_n), however, lowers tax payments as it diminishes profit. The CF formula thus takes into account the depreciation in year n (D_n), not as a yearly expenditure, but because it lowers tax expenditures. Linear depreciation over the operational life of the plant is assumed. For instance, when the operational life is assumed to be 20 years, yearly depreciation equals one twentieth part of the total plant cost. CF_n is calculated according to equation 2.6 with R_n, E_n, and τ representing the total revenues in year n, the total expenditure in year n, and the tax rate, respectively:

$$CF_n = (1-\tau) \times (R_n - E_n) + \tau \times D_n \tag{2.6}$$

Equations 2.3 and 2.6 can be combined into:

$$NPV = \sum_{n=1}^{T} \left[\frac{(1-\tau) \times (R_n - E_n) + \tau \times D_n}{(1+r)^n} \right] - I_0 \tag{2.7}$$

By discounting the cash flows, i.e. by dividing them by $(1+ r)^n$ in equation 2.3 and 2.7, the "time preference" of money has been taken into account. The discount rate is set higher for risky investments. As a minimal condition, an investment should only be carried out if the NPV is at least 0.

The total revenues in year n consist of total subsidies in year n (U_n) and total sales revenues in year n (S_n):

$$R_n = U_n + S_n \tag{2.8}$$

The total subsidies consist of investment subsidies (U_{inv}) on the one hand and exploitation subsidies (U_{exp}) on the other hand. Investment subsidies however are only received in the year of investment, which is mostly the year of the initial investment or year zero (see equation 2.4). Unless there are reinvestments for plant components with a shorter life span, the investment subsidies will be zero in the remainder of the life span of the investment. As an example, an internal combustion engine (which is required for the conversion of pyrolysis oil into energy) has a life span of only 10 years, which is shorter than the 20 year life span of a fast pyrolysis plant. As a consequence a reinvestment in an internal combustion engine with an accompanying investment allowance will be assumed in year ten, so that the pyrolysis oils produced during the twenty year life span of the pyrolysis reactor can be combusted without interruptions. The exploitation subsidies on the other hand will be received every year and consist of the revenues from the sales of green power certificates (U_{GPC}). When an investment in combined heat and power is considered revenues are also generated from the sales of combined heat and power certificates (U_{HPC}), so that:

$$U_{exp} = U_{GCC} + U_{HPC} \tag{2.9}$$

The system of green power certificates and of the combined heat and power certificates is subject to major changes which will be explained in more detail in chapter 4, but currently it still boils down to one green power certificate awarded per MWh of green electricity and one combined heat and power certificate awarded per MWh of primary energy savings (100 % in the first four years and from then on one combined heat and power certificate is awarded for a fraction X of the total primary energy savings), which subsequently can be sold at their respective market prices (p_{GPC} and p_{HPC}):

$$U_{GCC} = p_{GCC} \times P_e \times OH \tag{2.10}$$

$$U_{HPC} = p_{HPC} \times X \times PES \tag{2.11}$$

The calculation of the primary energy savings (PES) is explained in paragraph 4.3.3. It will be explained that the primary energy savings are already expressed in MWh, whereas for the green power certificates the electric capacity (P_e) is expressed in MW and should be multiplied with the number of operating hours in order to get the number of MWh of green electricity that are expected to be produced.

Sales revenues either stem from the sales (or savings) of electricity (S_e), sales (or savings) of heat (S_{th}), and potentially the sales of chemicals (S_{ch}, e.g. crotonic acid) or other products (S_{AC}, e.g. activated carbon).

$$S_n = S_e + S_{th} + S_{ch} + S_{AC} \tag{2.12}$$

Sales revenues in general are the product of price and quantity (e.g. the quantity of activated carbon produced). The revenues from heat and electricity sales or saving equals the product of the sales price and the quantity of electricity and heat that can be sold (i.e. after deduction of internal energy requirements). As will be illustrated in table 8 heat will partly be provided from the combustion of the pyrolysis gases, and extra heat is required from the combined heat and power engine (although here, for generic purposes we pretend as if all internal heat is provided by the CHP):

$$S_e = p_e \times (P_e - P_{e_{int}}) \times OH \tag{2.13}$$

$$S_{th} = p_{th} \times (P_{th} - P_{th_{int}}) \times OH \tag{2.14}$$

$$S_{ch} = p_{ch} \times q_{ch} \tag{2.15}$$

$$S_{AC} = p_{AC} \times q_{AC} \tag{2.16}$$

With respect to the total expenditure in year 1 until 20, they consist of fixed costs (FC, such as overheads) on the one hand, and variable costs (VC, which vary along with production:

$$E_n = FC_n + VC_n \tag{2.17}$$

Fixed costs are often expressed as a percentage of the total plant cost:

$$FC_n = \varphi \times TPC \tag{2.18}$$

The variable costs are the sum of purchase, transport and pre-treatment costs of the biomass (C_{biom}), labour costs (C_{lab}), costs of utilities (C_{util}, e.g. water) and energy (although in this dissertation energy requirements are subtracted from the production of energy) and costs for by-product disposal ($C_{by\text{-}pr}$) .

$$VC_n = C_{biom} + C_{lab} + C_{util} + C_{by-pr} \tag{2.19}$$

The total costs of biomass supply depend on the annual amount of biomass to be processed (or the product of the hourly feedstock flow and the number of operational hours) and the unit cost for pre-treatment (c_{pretr}), purchase of the biomass (c_{purch}) and transporting the biomass from the field to the plant (c_{trans}), the three of which are all expressed in EUR t_{dm}^{-1}.

$$C_{biom} = \Phi^h \times OH \times (c_{pretr} + c_{purch} + c_{trans}) \tag{2.20}$$

The labour cost is the product of the annual wage (w) with the number of labourers required (N):

$$C_{lab} = w \times N \tag{2.21}$$

The utility cost, i.e. the cost of water is the price of water multiplied with the required water quantity (which is a fixed quantity per tonne of biomass):

$$C_{util} = c_{water} \times q_{water} \tag{2.22}$$

The cost of the by-products disposal is the product of the quantity of by-product multiplied with the landfill cost:

$$C_{by-pr} = c_{landfill} \times q_{by-pr} \tag{2.23}$$

2.4 Risk analysis

An economic discounted cash flow model has been built for private cost-benefit analysis: the outgoing and incoming cash flows from an investment in fast pyrolysis, combustion or gasification have been predicted. During private cost-benefit analysis it became clear that the estimation of expenditure and revenue items is highly uncertain. The prediction of revenues and expenditure in each year is based on literature and checked with expert opinion where possible. Most of the times a range of values has been found for the revenue and expenditure items which causes economic risk. For each item, base case values have been determined as the average of the most prevalent values (excluding outliers) or as the most current figure available. These base case values, however, are quantities that will take some value in the future, but that are unknown at the moment of decision making because of a lack of knowledge: i.e. the uncertainty is expert based or epistemic (Aven 2003).

Therefore Monte Carlo simulations have been performed in order to check the sensitivity of the NPV for changes in the input factors of the economic model and to predict the probability of a positive NPV. Uncertainties have been taken into account when exploring a possible price range for willow.

2.4.1 Exploration of a possible price range for willow

The *exploration* of the possible price for willow cultivated in the Belgian Campine (e.g. during phytoextraction) implies calculating the cultivation costs of willow on the one hand (i.e. the costs born by a farmer for growing willow) and approximating an investor's willingness to pay for using willow as a feedstock for a conversion plant. The exploration starts with estimating the cost of growing and harvesting the willow year after year. A discounted cash flow model has been built, based on information received from project partners during research projects on phytoremediation in the Belgian Campine. The information in the discounted cash flow model then has been used in order to calculate the production cost of willow by means of the levelised cost (LC) method, a concept which is often used in energy calculations (El Kasmioui and Ceulemans 2012). It is defined as:

$$LC = \frac{\sum_{t=0}^{21}(1+r)^{-t}.C_t}{\sum_{t=0}^{21}(1+r)^{-t}.q_{willow}} \quad (2.24)$$

It can be interpreted as the price at which willow cultivated in short rotation must be sold in order to break even. The cost of growing and harvesting willow (which can be considered as the minimal sales price that a farmer wants to receive for growing willow) can then be compared to the price that an investor might be willing to pay for using willow as a feedstock in a thermochemical conversion technology. This price can be considered as the maximum achievable sales price for willow cultivated on contaminated farmland in the Belgian Campine.

The net present value of cash flows calculated by the economic model is subject to uncertainties. These uncertainties need to be taken into account when one wants to estimate the maximum price for willow. An entrepreneur will only invest in thermochemical conversion if he is *sure* that it will lead to profits. The willow price corresponding to a zero NPV thus is an insufficient condition for setting the maximum unit willow price. Therefore, uncertain variables are identified in order to perform Monte Carlo sensitivity analysis, so that the maximum unit willow price can be calculated corresponding to a 95 % chance of a positive NPV.

The maximum unit willow price thus is defined as the price guaranteeing a 95 % chance of a positive net present value of cash flows generated by an investment in fast pyrolysis, gasification or combustion of willow for electricity production. In other words, it is the maximum price an investor can pay for using metal containing willow as a profitable resource for energy or high value chemicals. A higher price will lower chances of a positive net present value of cash flows for the investor below 95 %.

As stated at the end of paragraph 1.3, fast pyrolysis is preferred to gasification and combustion for the thermal conversion of short rotation willow from the viewpoint of phytoextraction. From an economic point of view however, the preferred conversion technique is the one leading to the highest possible maximum unit willow price, thus being the one leading to the highest income for the farmer during phytoextraction.

The maximum price an investor can pay has been calculated by applying (private) cost-benefit analysis (or investment calculation), followed by Monte Carlo analysis in order to take into account uncertainties. The cost-benefit model first calculates the net present value (NPV) of the cash flows generated by an investment in combustion, gasification or fast pyrolysis of short rotation energy willow for power production.

Monte Carlo simulations are used for the calculation of the maximum unit willow price, which represents possible values of the biomass purchase price. By means of the functionality *OptQuest,* maximum unit willow prices are calculated with the objective of a 95 % certainty that the NPV of the cash flows will fall between zero and infinity. The OptQuest approach is actually a meta-heuristic that is able to find (near) optimal solutions within a few minutes whereas an exhaustive examination of relevant alternatives requires days or months by combining scatter search (i.e. the generation of reference points that constitute good solutions obtained from previous solutions efforts) and tabu search (i.e. the use of adaptive memory for avoiding the reinvestigation of solutions that have already been evaluated) (Glover, Kelly et al. 2000). Monte Carlo software sets a random value for the willow purchase price and calculates the corresponding probability of a NPV between zero and infinity after ten thousand draws for the other variables. If the chance on a positive NPV does not correspond to 95 %, Monte Carlo software chooses another value for the willow purchase price and the ten thousands draws for the other variables are rehearsed. After more or less hundred rehearsals, a robust willow price is found, i.e. the willow price corresponding to a 95 % chance of a positive NPV is found.

2.4.2 Monte Carlo analysis

The investment in a pyrolysis plant for the economic valorisation of biomass by conversion into pyrolysis oil, gas and char is considered as a new stand-alone project in an innovative technology. It is impossible to use a risk-adjusted discount rate applying capital asset pricing models (CAPM), because there are no historical data for calculating the covariance of the value of the project and the variance in the market (Aven 2003). It is also not possible to compare with the industry sector to which the project belongs as there is no such thing as a clearly defined industry for pyrolysis of phytoextracting crops. Therefore, a risk-free discount rate of 9 % has been chosen and uncertainty is expressed for the yearly cash flows.

Decision makers facing uncertainties in key assumptions of these yearly cash flows need more information than just the expected value. An assessment of the uncertainty is required which can be measured by probabilities (Hertz 1979; Aven 2003). Besides, information about the impact of a change in the assumptions on the predicted NPV is required. Often this is dealt with by means of partial sensitivity analysis or by developing best and worst case scenarios. However, if base-case assumptions are more likely to occur than the extremes of the ranges found in literature, then best and worst case scenarios contain little information value because they require the joint occurrence of independent low-probability events. Monte Carlo analysis overcomes this problem by taking into account probability distributions for important uncertain quantitative assumptions (Vose 2000; Boardman, Greenberg et al. 2006).

Monte Carlo analysis has been integrated in the unifying approach for expressing economic risk proposed by Aven, Nilsen and Nilsen (Aven 2003; Aven, Nilsen et al. 2004):

1. The overall system performance measure (i.e. observable quantity on a high level) has been identified as the NPV of the investment in a fast pyrolysis plant;
2. A deterministic model of the system linking the system performance measure (NPV) and observable quantities on a more detailed level (low-level) has been determined by means of the economic cost-benefit model;
3. Collect information about low-level observable quantities by means of literature review and expert opinions. Use probabilities to express uncertain observable quantities;
4. Calculate the probability distribution of the NPV given the assumed probability distributions of the determining variables and predict the net benefits taking into account these distributions, which has been executed by means of Monte Carlo simulations.

Step 3 has been elaborated as the identification step of uncertain variables according to the following principles:

1. some variables are uncertain by definition, e.g. prices can fluctuate when markets exist due to exogenous forces;

2. the value of other variables might have a very large impact on the NPV of cash flows, and should be incorporated in any risk analysis even if they are only slightly uncertain;

3. after selecting the variables following principles (a) and (b), their impact on the variability of the NPV is investigated. E.g. if the value of the variables are allowed to fall within a realistic range, Monte Carlo analysis results in a distribution of NPVs. Then it can be calculated to which degree the variability of one variable contributes to the variability of the NPV. The variables which explain the largest part of the variability of the NPV then also need to be taken into account as a slight change in the value of the variable can have a large impact on the variance of the NPV and the variables which explain the largest part of the variability of the NPV are withheld for performing Monte Carlo analysis.

The probabilities that are used to express uncertainty are assumed to have triangular distributions. The normal distribution $N(\mu,\sigma^2)$ cannot be used because the standard deviation (σ) of the distribution is often unknown. When only literature data or expert judgments and no large datasets or historical data are available, only the lowest value, the highest value and the most likely value of the input variables can be assessed. The triangular distribution is an adequate solution when literature is insufficient for deriving probabilities (Haimes 2004). It is also the most commonly used distribution for modeling expert opinion (Vose 2000). All possible correlations between input variables have been built in the cost-benefit model, so that the remaining uncertain variables can be considered as independent and the construction of correlated variables in the Monte Carlo simulations is not appropriate. E.g. it is reasonable to expect some negative covariance between unit costs and produced quantity due to economies of scale. When probability distributions are defined for these two variables it would be interesting to restrict the random generation of values for the two variables, so that unrealistic scenarios (e.g. when both unit costs and produced quantity are high) are avoided (Savvides 1994). As an example, economies of scale are assumed in the total plant cost of an investment: the total plant cost increases at a decreasing rate with increasing quantity, i.e. the specific (unit) investment cost per unit produced decreases with increasing production capacity. This correlation between investment cost and quantity produced has been built in the economic cost-benefit model by the structure defined for investment equations (see equation 4.3: $C = aQ^d$) developed during the meta-analysis of the investment costs in paragraph 4.2. By this structure there is already a correlation present in the model between the produced quantity Q and the investment cost C which reflects the assumption of economies of scale. The only uncertainty remaining is about the exact height of the constant a and exponent d in this equation, which is independent of the produced quantity Q but rather is technology dependent. Therefore it is not appropriate to construct an extra correlation between a and Q or d and Q, because then we would be double counting economies of scale. In step 4 Oracle's Crystal Ball software has been used to perform 10 000 Monte Carlo simulation runs, which results in a distribution of the NPV.

Monte Carlo software now draws for each variable a random value within the min-max range and calculates the corresponding NPV. This process is rehearsed ten thousand times, taking into account the triangular distribution when drawing random values. Monte Carlo analysis finally can be used to analyze the distribution (including histogram, median and variance) of NPVs.

The underlying data can be used for constructing a regression meta-model, whereby the NPV is modeled in terms of a linear combination of the input variables representing the main effects. The meta-model thus is a simplified approximation of the discounted cash flow model. The resulting equation can be used to have a quick glance at the most important variables and to help decision makers. Decision makers can use this equation in order to get a first estimate of the economic feasibility. The model can also be applied if more information about the true value of some variables is available and can be used to plan risk reduction policies.

2.4.3 Plackett-Burman designs

Monte Carlo simulations require knowledge about the distribution function (probability distribution) of the values of the relevant variables in the economic model. Information with respect to these probabilities is often absent, and the best way one can do is to assign probabilities on the basis of their own opinion based on experience. Because the probabilities used in the Monte Carlo simulations are estimated on a subjective basis expressing our degrees of belief, Van Groenendaal and Kleijnen doubt the usefulness of Monte Carlo simulations (Van Groenendaal and Kleijnen 1997). They propose methods from *design of experiments* (DOE), which is often used in industrial research, as an alternative for Monte Carlo simulations to provide information on which factors can make a project or investment "go wrong", without requiring the knowledge of probability distributions. Because Van Groenendaal (1998) expects that decision makers are mainly interested in information in what can go wrong, he suggests to analyse changes in variable values that have a negative impact on the NPV. To determine these negative effects the first step is to apply a one-factor-at-a-time sensitivity analysis. It is assumed that every factor or variable takes on either one of two values: -1 if the factor is "off" and +1 if the factor is "on". In other words, +1 corresponds to the base case value of the corresponding variable, whereas -1 stands for the value that has a negative influence on the base case result. In DOE the effect of changes in the value of the uncertain variables on the NPV is thus obtained by simulating the extreme points of the value ranges, and estimating a linear regression meta-model to detect which variables are important (Van Groenendaal and Kleijnen 2002).

The most prevalent experimental designs are *one-factor-at-a-time*, *full factorial designs,* and *fractional designs*. Changing one factor at a time ignores combined effects. Full factorial designs allow estimating all main effects, and possibly some interaction effects. Full factorial designs however have the disadvantage that it requires substantial computer time which is not feasible in commercial settings. For instance, given k uncertain variables and with every variable at two levels only, it requires 2^k simulation runs for estimating k + 1 effects (i.e. k main effects plus the overall mean), thus ten variables require 2^{10} = 1 024 simulations. It has been proved that with less observations (i.e. fractional designs with less simulation runs) the same information can be obtained as in one-factor-at-a-time and full factorial designs: in principle k + 1 observations suffice to estimate k + 1 effects (Kleijnen and Van Groenendaal 1988). In other words, it suffices to simulate only a fraction 2^{k-p} of the 2^k possible observations so that $2^{k-p} \geq k + 1$. Therefore these designs are also called 2^{k-p} designs. They have a number of simulation runs equal to a power of two. So when the number of uncertain variables or factors becomes large, the number of simulation runs is still large (Van Groenendaal 1998). A class of designs that allows a more gradual increase in the number of simulatons runs is the *Plackett-Burman design* type (Plackett and Burman 1946), which require a number of runs equal to a multiple of four. Thus for ten uncertain variables, a Plackett-Burman design with twelve runs can be used (instead of sixteen runs when 2^{k-p} designs are applied, because when k = 10, p must equal 4 for 2^{10-p} to be at least equal to 10 + 1). The Plackett-Burman design has been applied following the approach of Van Groenendaal and Kleijnen for constructing a meta-model for the NPV and compared to the results from Monte Carlo simulations. In order to compare both models, the same "uncertain variables" have been identified, i.e. if Monte Carlo simulations are performed for 10 uncertain variables, the same 10 variables are considered in the Plackett-Burman designs. In table 6 one can find the construction of the 12 runs for 10 uncertain variables following Plackett and Burman (1946). Each column represents one simulation run with a plus sign (+) reflecting the base case value of the variable and the minus sign (-) reflecting the worst case value negatively impacting the NPV. Each column can be interpreted as a scenario, some of which may make economic sense, others being less likely (Van Groenendaal 1998).

Var.	*PB1*	*PB2*	*PB3*	*PB4*	*PB5*	*PB6*	*PB7*	*PB8*	*PB9*	*PB10*	*PB11*	*PB12*
1	+	+	-	+	+	+	-	-	-	+	-	-
2	-	+	+	-	+	+	+	-	-	-	+	-
3	+	-	+	+	-	+	+	+	-	-	-	-
4	-	+	-	+	+	-	+	+	+	-	-	-
5	-	-	+	-	+	+	-	+	+	+	-	-
6	-	-	-	+	-	+	+	-	+	+	+	-
7	+	-	-	-	+	-	+	+	-	+	+	-
8	+	+	-	-	-	+	-	+	+	-	+	-
9	+	+	+	-	-	-	+	-	+	+	-	-
10	-	+	+	+	-	-	-	+	-	+	+	-

table 6: Plackett-Burman design for ten variables

The tables of design are constructed in such a way that each variable is replicated at its base case value the same number of times that it is replicated at its worst case value. Any combination of values of two variables also appears the same number of times. In the final run all the variables take on their worst case value (Plackett and Burman 1946). Identifying the base case with only plus signs, means that all other runs focus on conditions that jeopardize the investment project.

The disadvantage of the NPV's meta-model based on Plackett-Burman (PB) designs is that it can lead to erroneous conclusions in the presence of interaction effects. Meta-modelling the Plackett-Burman designs will only result in an approximation of the simulation model (i.e. the discounted cash flow model), when there are no interactions between variables. However, if the "no interactions" assumption is not valid, then the parameter estimates in the meta-model are biased. A suggested solution for avoiding biased estimates, is to augment the Plackett-Burman design with the Box-Wilson foldover theorem resulting in the enlargement of the original design matrix. This means that the 12 runs of the Plackett-Burman design are complemented with their opposite Box-Wilson foldover. In other words, another 12 runs are designed but the variables that take on their base case value in the Plackett-Burman design will now take their worst case value, and the variables that are at their worst case value in the Plackett-Burman design will take their base case value in the runs of the Box-Wilson foldover. In total, the main effects of the 10 uncertain factors are estimated by means of 24 simulation runs. Finally the results of these 24 simulation runs served as an input for the regression meta-model that has been developed by means of ordinary least squares regression.

2.4.4 Risk reduction strategies

Next, risk strategies are devised in order to reduce risks. Companies can reduce risk in three fundamental ways (Meulbroek 2005): by modifying the firm’s operations, by changing its capital structure, or by employing targeted financial instruments (such as insurance). Because this dissertation aims to evaluate the economic potential of new technologies, the focus is on the management of operational risk. The operational risk of a fast pyrolysis plant can be reduced through combining inputs for increasing the scale of operation so that one can benefit economies of scale, or just because other inputs are less costly (or even result in revenues by receiving a gate fee) or are available on a more continuous basis, or because the combination of inputs results in products with deviant beneficial characteristics. Operational risk can also be reduced by output optimisation: i.e. by subsequent processing of your outputs so that its economic value increases or by changing process temperature so that more of the most valuable products can be produced. By changing the conditions of operation, it is hoped to increase the probability of a positive net present value so that it becomes less dependent on the main factors identified during risk analysis.

At the input side, experimental data on fast co-pyrolysis of willow and biopolymer waste have been translated in economic figures by private cost-benefit analysis. Co-pyrolysis of willow and biopolymer waste has several advantages:

- it is expected to decrease the water content of the pyrolysis oil;
- it can have other synergistic effects (e.g. higher calorific value, higher pyrolysis oil yield, etc.);
- the economic scale of operation is increased so that the pyrolysis plant can enjoy economies of scale;
- a willow/biopolymer mix might result in the production of pyrolysis oil containing special high-value chemical products;
- waste can be processed at a gate fee, so that the investor does not have to pay for the biopolymer waste feedstock but instead is getting paid to process the waste.

Maximum prices for biopolymer waste have been calculated taking into account uncertainties in the same way as this has been done for willow, i.e. what is the price that an investor of a pyrolysis plant is maximally willing to pay for obtaining the biopolymer waste (assuming that the probability of a positive NPV should be at least 95 %)? If this maximum price is negative, this should be interpreted as a gate fee, i.e. that the investor is only willing to process the biopolymer when he is paid to do so. If the gate fee is lower than the disposal cost of biopolymer waste, i.e. the price that an owner of biopolymer waste has to pay for composting, a good alternative has been found both for the owner of biopolymer waste and for the investor of a fast pyrolysis plant.

Another option is to optimise fast pyrolysis output aimed at lower economic risks. Fast pyrolysis typically results in three valuable products: pyrolysis oil, gas and char. The gas is needed for internal energy requirements, so the only products left for economic valorisation are the pyrolysis oil and char. The economic trade-off between oil and char production has been mapped and a production strategy is presented dependent on the price ratio of the potential revenues generated by oil and char, as is explained in the next section.

2.5 Economic trade-off of two outputs

Fast pyrolysis of biomass results in three end products: pyrolysis oil, gas and char, each of which has different economic value. The pyrolysis gases are used as a provider of internal energy requirements for a pyrolysis plant and hence are not considered as a source of revenue. As a result, economic trade-offs exist in the joint production of pyrolysis oil and char. For instance, the pyrolysis process can be operated at different process temperatures and heating rates. These process parameters influence the quantity and quality of the pyrolysis products and hence affect the potential revenues from their production and sale. For instance, depending on the heating rate, pyrolysis technologies can be classified into slow versus fast pyrolysis. Low heating rates and low pyrolysis temperatures result in higher yields of char, whereas intermediate pyrolysis temperatures and high heating rates maximise pyrolysis oil yields (approximately 450 to 500 °C). At very high temperatures the production of non-condensable pyrolysis gases is favoured, which means that oil yields increase up to a point beyond which it declines again (Bridgwater, Meier et al. 1999; Cornelissen 2009; Stals, Thijssen et al. 2009; Yoder, Galinato et al. 2011).

Yoder, Galinato et al. (2009) estimated quadratic production functions for biochar and bio-oil, i.e. the production relationships between temperature and both pyrolysis oil and char, by estimating how much char and oil is produced at given temperatures based on published studies in conjunction with primary data that are in line with the findings at Hasselt University. These estimates can then be used to estimate a product transformation curve for fast pyrolysis which expresses the quantity trade-off between pyrolysis oil and char as a consequence of a change in temperature. In a next step, it can be used to calculate the optimal process temperature for the fast pyrolysis plant for a given ratio of pyrolysis oil and char prices. A high pyrolysis oil to pyrolysis char price ratio will call for more oil production at the expense of char production, whereas more revenue can be made by producing more char when the pyrolysis oil to char price ratio is low.

A conceptual model for maximising the revenue with two products has been developed by Yoder, Galinato et al. (2009) aimed at creating a decision rule on the optimal fast pyrolysis temperature for a given set of pyrolysis oil and char market prices and applications. They assume that both the pyrolysis char and oil will be used as an energy source, and relate the price to the energy content of the product. There are two problems with this approach. First of all, one can hardly say that fast pyrolysis technology is commercially available, let alone that there is a real market for pyrolysis oils and chars yet. When needed markets do not exist, markets fail to allocate resources, which is known as missing markets. Besides one might think of pyrolysis char and oil markets to develop in the future, but there is no way that the future prices can be equated by economic transactions made today (Lipsey and Chrystal 2011). Basing the price on its energy content results in erroneous price estimates and hence wrong conclusions because there are many other factors (such as production costs, government policy, different elasticities of demand for biofuels compared to fossil fuels, ...) that influence the possible pyrolysis oil price. Therefore the model of Yoder, Galinato et al. (2009) has been adapted by incorporating subsequent processing of the pyrolysis products for which markets do exist: here it is assumed that pyrolysis char can be converted into activated carbon (AC), and the oil will be converted into electricity and heat. As a consequence our model uses *net revenues* instead of *prices* for oil and char, which take into account both the sales price of AC and oil and the relevant processing costs.

The core of the methodological framework however, i.e. the economic model of revenue maximisation however is basically the same as proposed by Yoder et al. (2009). Their two product objective is to maximise the net value of production of the two outputs (oil and char) or profit (π) per unit of feedstock processed, i.e. the sum of the revenues from the oil and the char minus the input costs, by choosing temperature. In other words, the optimal temperature maximises the pyrolysis plant's profits π, i.e. the difference between total revenues (TR) and total cost (TC):

$$\max_{T} \pi = TR - TC \tag{2.25}$$

The total cost (TC) represents the total costs of a fast pyrolysis plant that converts willow from phytoextraction into pyrolysis oil and char. TC is assumed to be constant for a given amount of willow (Yoder, Galinato et al. 2011). The costs of char activation and energy production by combusting the pyrolysis oil is not comprised in TC. The latter costs have been taken into account in the net revenue of the char output and oil output respectively. The total revenues (TR) consist of the turnover generated by the conversion of pyrolysis char into active coal and the turnover from converting pyrolysis oil into heat and power. The generated turnover for one output is the product of the sold quantity of that output and its net revenue. So, total revenues equal:

$$TR = nr_{char} \cdot q_{char} + nr_{oil} \cdot q_{oil} \tag{2.26}$$

With: nr_{char} = the net average revenue of the char (EUR t^{-1})
q_{char} = the sold quantity of the char (t)
nr_{oil} = the net average revenue of pyrolysis oil (EUR t^{-1})
q_{oil} = the sold quantity of the oil (t)

Because TC is assumed to be constant, the plant's management only needs to decide on the output it wants to produce in order to maximise profits: how much of the original biomass do we want to convert into pyrolysis oil, respectively into biochar? Therefore the relationship between product yields in function of temperature has been quantified by Yoder (Yoder, Galinato et al. 2011). The quantities of char and oil produced in function of temperature (T) can be described by equations 2.27 and 2.28:

$$q_{char}(T) = \alpha_0 + \alpha_1 T + \alpha_2 T^2 \quad (2.27)$$

$$q_{oil}(T) = \beta_0 + \beta_1 T + \beta_2 T^2 \quad (2.28)$$

The net average revenue for each output is defined as the difference between the sales price of the end product (e.g. active coal or energy) expressed in terms of the intermediate output (i.e. char or oil respectively) minus the cost of processing the intermediate output into the end product. The net revenue of the char thus equals the difference between the sales price of active coal (expressed in terms of the char feedstock, i.e. in EUR kg^{-1} char) and the unit processing cost of thermal activation of the char into active coal (again expressed in terms of the char feedstock, in EUR kg^{-1} char). The net average revenue of the pyrolysis oil equals the difference in revenues stemming from the sales and/or savings of electricity and/or heat, green power certificates and combined heat and power certificates (each expressed per kilogram of oil) minus the unit processing cost of combusting the oil in an internal combustion engine.

As the produced quantities of oil and char depend on temperature, also the net revenue generated by activation of the char and energy production from the oil are expected to be function of the process temperature. Indeed, if temperature augments, the produced quantity of oil also increases up to temperatures of more or less 500 °C. Hence more oil can be combusted in an internal combustion engine for the production of heat and/or electricity. It has been illustrated that converting more and more pyrolysis oil into energy exhibit economies of scale (see chapter 4). Therefore, net average revenue (nr) can also be expressed in terms of temperature (T):

$$nr_{char}(T) = \delta_0 + \delta_1 T + \delta_2 T^2 \quad (2.29)$$

$$nr_{oil}(T) = \gamma_0 + \gamma_1 T + \gamma_2 T^2 \quad (2.30)$$

Equation 2.25 can now be rewritten as:

$$\max_T \pi = nr_{char}(T).\, q_{char}(T) + nr_{oil}(T).\, q_{oil}(T) - TC \qquad (2.31)$$

Because temperature increases pyrolysis oil yields, it also increases revenues from pyrolysis oil at the expense of revenues as a consequence of biochar production. Maximal revenues are attained at the temperature at which the increase in revenue from pyrolysis oil no longer outweighs the revenue losses from char production with an increase in temperature, i.e. the optimal temperature is the one at which the marginal revenue gains from pyrolysis oil production equal the marginal revenue losses from biochar. For a function f (here π) that is continuous over a closed bounded interval (in this case the temperature interval), the optimum (maximum or minimum) must occur either at an interior point of the interval or at one of the end points. If it occurs at an interior point and f is differentiable, then the first derivative f’ is zero at that point, but the first derivative alone does not provide enough information to determine whether it is a maximum or a minimum. If f is twice differentiable in the temperature interval, the sign of the second order derivative determines whether the optimum is a maximum or a minimum. The optimum is a local maximum if the second order derivative is negative (and it is a local minimum otherwise) (Sydsaeter and Hammond 2006).

In order to find the optimal profit π we thus must calculate the first and second order derivatives with respect to temperature of equation 2.31. Assuming that TC is constant for a given amount of biomass, the first derivative must satisfy the following condition:

$$\frac{d\, nr_{char}}{dT}.\, q_{char}(T) + nr_{char}(T).\frac{dq_{char}}{dT} + \frac{d\, nr_{oil}}{dT}.\, q_{oil}(T) + nr_{oil}(T).\frac{dq_{oil}}{dT} = 0 \qquad (2.32)$$

In other words:

$$\frac{d\,nr_{char}}{dT}.\,q_{char}(T) + nr_{char}(T).\frac{dq_{char}}{dT} = -\left(\frac{d\,nr_{oil}}{dT}.\,q_{oil}(T) + nr_{oil}(T).\frac{dq_{oil}}{dT}\right) \tag{2.33}$$

With:

$$\frac{d\,nr_{char}}{dT} = \delta_1 + 2\delta_2 T \tag{2.34}$$

$$\frac{d\,nr_{oil}}{dT} = \gamma_1 + 2\gamma_2 T \tag{2.35}$$

$$\frac{dq_{char}}{dT} = \alpha_1 + 2\alpha_2 T \tag{2.36}$$

$$\frac{dq_{oil}}{dT} = \beta_1 + 2\beta_2 T \tag{2.37}$$

Substituting equations 2.27 to 2.30 and 2.34 until 2.37 in equation 2.32 yields:

$$\begin{aligned}&(\delta_1 + 2\delta_2 T).\,(\alpha_0 + \alpha_1 T + \alpha_2 T^2)\\&+ (\delta_0 + \delta_1 T + \delta_2 T^2).\,(\alpha_1 + 2\alpha_2 T)\\&+ (\gamma_1 + 2\gamma_2 T).\,(\beta_0 + \beta_1 T + \beta_2 T^2)\\&+ (\gamma_0 + \gamma_1 T + \gamma_2 T^2).\,(\beta_1 + 2\beta_2 T) = 0\end{aligned} \tag{2.38}$$

Applying distributivity yields:

$$\begin{aligned}&\alpha_0\delta_1 + \alpha_1\delta_1 T + \alpha_2\delta_1 T^2 + 2\alpha_0\delta_2 T + 2\alpha_1\delta_2 T^2 + 2\alpha_2\delta_2 T^3\\&+\alpha_1\delta_0 + \alpha_1\delta_1 T + \alpha_1\delta_2 T^2 + 2\alpha_2\delta_0 T + 2\alpha_2\delta_1 T^2 + 2\alpha_2\delta_2 T^3\\&+ \beta_0\gamma_1 + \beta_1\gamma_1 T + \beta_2\gamma_1 T^2 + 2\beta_0\gamma_2 T + 2\beta_1\gamma_2 T^2 + 2\beta_2\gamma_2 T^3\\&+\beta_1\gamma_0 + \beta_1\gamma_1 T + \beta_1\gamma_2 T^2 + 2\beta_2\gamma_0 T + 2\beta_2\gamma_1 T^2 + 2\beta_2\gamma_2 T^3 = 0\end{aligned} \tag{2.39}$$

Equation 2.39 can be rearranged in the form $AT^3 + BT^2 + CT + D = 0$ with:

$$A = 4(\alpha_2\delta_2 + \beta_2\gamma_2) \tag{2.40}$$

$$B = 3(\alpha_1\delta_2 + \alpha_2\delta_1 + \beta_1\gamma_2 + \beta_2\gamma_1) \tag{2.41}$$

$$C = 2(\alpha_0\delta_2 + \alpha_1\delta_1 + \alpha_2\delta_0 + \beta_0\gamma_2 + \beta_1\gamma_1 + \beta_2\gamma_0) \tag{2.42}$$

$$D = \alpha_0\delta_1 + \alpha_1\delta_0 + \beta_0\gamma_1 + \beta_1\gamma_0 \tag{2.43}$$

The second order derivative now can be calculated: $3AT^2 + 2BT + C$. By calculating the first and second order derivative of the original profit function, one can localise optima and the gradient of the profit function in the relevant temperature interval.

This optimal temperature corresponds to the optimal combination of oil and char yield on the so-called *product transformation curve (PTC)*. The product transformation curve is an implication of equations 2.27 (char yield in function of temperature) and 2.28 (oil yield in function of temperature) and represents the combinations of char and oil yields that correspond to a given temperature for a given feedstock. The PTC which expresses the char yield in function of oil yield can be derived by first solving for the inverse of equation 2.28, i.e. temperature in function of oil yield: $T = f(q_{oil})$

$$T(q_{oil}) = \frac{-\beta_1 + \sqrt{\beta_1^2 - 4\beta_2(\beta_0 - q_{oil})}}{2\beta_2} \tag{2.44}$$

Equation 2.44 can now be substituted in equation 2.27, so that the char yield can be expressed in function of the oil yield. An increase in temperature now will lead to a movement along the product transformation curve down and to the right, i.e. towards more oil and less char.

This optimality condition has been graphically represented in figure 4 by Yoder, Galinato et al. (2011). On the horizontal axis the quantity of pyrolysis oil is represented (L which is the same as q_{oil}), whereas the vertical axis represents the quantity of produced char (C or q_{char}). The curved line is the *product transformation curve* which indicates the output of pyrolysis oil and char that will be produced for a given feedstock quantity and type. A movement along the product transformation curve up and to the left corresponds to a decrease in temperature which yields more char and less oil. The full straight line represents an *isorevenue line* or the set of combinations of oil and char which yields a given total revenue for a given pair of char and oil given their prices.

The isorevenue line or total revenue TR can be represented by equation 2.45 which is a simplified version of equation 2.26 but with the assumption that char and oil can be sold at constant prices independent of temperature (in equation 2.26 these prices have been replaced by net revenues in function of temperature):

$$TR = P_C C + P_L L \tag{2.45}$$

which can be rearranged into:

$$C = \frac{R - P_L L}{P_C} = \frac{R}{P_C} - \frac{P_L}{P_C} L \tag{2.46}$$

The price ratio P_L/P_C thus corresponds to the slope of the isorevenue line. The optimality condition displayed in equation 2.33 is actually a more complex formulation of the optimality condition derived by Yoder et al. (2009). Assuming that the char quantity and oil quantity are a function of temperature, that the oil and char price are initially held constant and that TC is a fixed cost, the first order derivative of equation 2.25 with respect to temperature can also be written as:

$$P_C C'(T) + P_L L'(T) = 0 \tag{2.47}$$

where C'(T) and L'(T) should be interpreted as the *marginal productivity* of char and oil in function of temperature, respectively. Equation 2.47 is actually the analogous and simplified version of equation 2.32. Equation 2.47 can be rearranged into a simplified version of equation 2.33:

$$P_C C'(T) = -P_L L'(T) \qquad (2.48)$$

or into the following optimality condition:

$$\frac{P_L}{P_C} = -\frac{C'(T)}{L'(T)} \qquad (2.49)$$

Equation 2.49 thus implies that the optimal combination of pyrolysis product yields corresponds to the point on the product transformation curve (PTC) where its slope dC/dL (or C'(T)/L'(T)) equals the slope of the isorevenue line, or in other words where the isorevenue line is tangent to the production transformation curve.

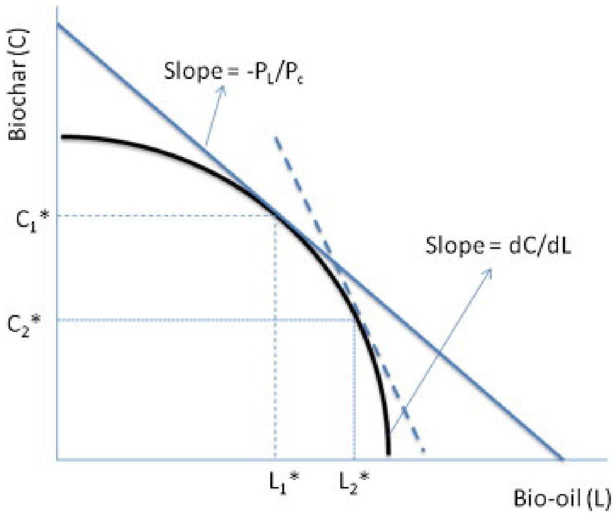

figure 4: Optimal combination of pyrolysis char and oil yield for prices P_L and P_C (Yoder, Galinato et al. 2011)

The optimal level of oil and char production is represented by the combination (L_1^*, $C1^*$) in figure 4. The dotted isorevenue line represents a situation where either the oil price has increased or the char price has decreased, so that the oil/char price ratio increases and the slope of the isorevenue is steeper compared to the full isorevenue line, favouring the production of pyrolysis oil so that the optimal combination of oil yield and char yield equals the point (L_2^*, C_2^*) on the product transformation curve.

2.6 Conclusion

In chapter 2 a methodological framework has been presented for a techno-economic assessment of fast pyrolysis as a conversion technology for phytoextracting willow from the viewpoint of an investor in such a conversion plant. In general a techno-economic assessment can be described as the evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision makers in directing research and development or investments. In other words, it can be stated that a techno-economic assessment ideally answers three important questions:

1. How does the technology work?
2. Is the technology profitable?
3. Is the technology desirable?

A full techno-economic assessment thus requires a multidisciplinary approach. Given the viewpoint of the investor, the main focus in the remainder of chapter 2 was on methods for answering question 2. The starting point of this research was to find the most profitable conversion route for phytoexctracting willow cultivated by the farmers in the Belgian Campine. The exploration of the possible price for willow cultivated in the Belgian Campine (e.g. during phytoextraction) implies calculating the cultivation costs of willow on the one hand (i.e. the costs born by a farmer for growing willow) and approximating an investor’s willingness to pay for using willow as a feedstock for a conversion plant. In other words, it is investigated which conversion technology corresponds to the highest possible price that an investor is willing to pay a farmer for using phytoextracting willow as a feedstock. This price depends on the profitability of the conversion technology, which is best measured by means of the net present value of the investment's cash flows, calculated in a discounted cash flow model.

The estimation of expenditure and revenue items however is highly uncertain. The maximum unit willow price that an investor is willing to pay is therefore defined as the price guaranteeing a 95 % chance of a positive net present value of cash flows generated by an investment in fast pyrolysis, gasification or combustion of willow. An assessment of the uncertainty is required which can be measured by probabilities. Monte Carlo analysis overcomes this problem by taking into account probability distributions for important uncertain quantitative assumptions. Information with respect to these probabilities however is often absent, and the best way one can do is to assign probabilities on the basis of their own opinion based on experience. Because the probabilities used in the Monte Carlo simulations are estimated on a subjective basis expressing our degrees of belief, methods from *design of experiments* (DOE) are proposed as an alternative for Monte Carlo simulations to provide information on which factors can make a project or investment "go wrong", without requiring the knowledge of probability distributions. The underlying data from the Monte Carlo simulations and the experimental designs can be used for constructing a regression meta-model, whereby the NPV is modeled in terms of a linear combination of the input variables representing the main effects. A class of designs that allows a gradual increase in the number of simulatons runs is the *Plackett-Burman design* type, which are complemented with their Box-Wilson foldover in order to estimate unbiased main effects. The meta-model thus is a simplified approximation of the discounted cash flow model. The resulting equation can be used to have a quick glance at the most important variables and to help decision makers. Decision makers can use this equation in order to get a first estimate of the economic feasibility.

The meta-model can be used to plan risk reduction policies. Companies can reduce risk in three fundamental ways: by modifying the firm's operations, by changing its capital structure, or by employing targeted financial instruments (such as insurance). Because this dissertation aims to evaluate the economic potential of new technologies, the focus is on the management of operational risk. By changing the conditions of operation, it is hoped to increase the probability of a positive net present value so that it becomes less dependent on the main factors identified during risk analysis. The operational risk of a fast pyrolysis plant can be reduced by combining inputs for increasing the scale of operation so that one can benefit economies of scale, or just because other inputs are less costly (or even result in revenues by receiving a gate fee) or are available on a more continuous basis, or because the combination of inputs results in products with beneficial characteristics. Operational risk can also be reduced by output optimisation: i.e. by subsequent processing of your outputs so that its economic value increases or by changing process temperature so that more of the most valuable products can be produced. Besides, economic trade-offs exist in the joint production of pyrolysis outputs. This economic trade-off can be calculated by first estmating a product transformation curve for fast pyrolysis which expresses the quantity trade-off between pyrolysis oil and char as a consequence of a change in temperature. Next, it can be used to calculate the optimal process temperature for the fast pyrolysis plant for a given ratio of pyrolysis oil and char prices. A high pyrolysis oil to pyrolysis char price ratio will call for more oil production at the expense of char production, whereas more revenue can be made by producing more char when the pyrolysis oil to char price ratio is low. Because a real market for pyrolysis oils and chars does not exist, the economic trade-off model of Yoder, Galinato et al. (2009) has been adapted by incorporating subsequent processing of the pyrolysis products for which markets do exist: it is assumed that pyrolysis char can be converted into activated carbon (AC), and the oil will be converted into electricity and heat. As a consequence our model uses *net revenues* instead of *prices* for oil and char, which take into both the sales price of AC and oil and processing costs.

3 Thermochemical conversion of willow

3.1 Introduction

In chapter 2 it has been concluded that it is important to know how a technology works, before one can study its economic profitability. The discounted cash flow model surely stands or falls with the technical assumptions that have been made. Therefore, some basic understanding of the technologies under investigation is required. It is not our purpose though to explain the detailed chemistry and physics behind every technology. The focus of this dissertation is on investigating the economic profitability and economic risk. Hence, this chapter covers the basics of each technology by means a simplified process flow, mass balance and energy balance based on an extensive literature survey.

The lignocellulosic chemical composition of short rotation willow, i.e. the lignin fraction, motivates the choice for studying thermochemical technologies (combustion, gasification and pyrolysis) for converting willow into energy. After explaining the main differences between combustion, gasification and pyrolysis in paragraph 3.2, paragraph 3.3 describes the essential features, advantages and applications of fast pyrolysis by means of a simplified process design, mass and energy balance. Paragraph 3.4 does the same for combustion and paragraph 3.5 for gasification. This chapter thus elucidates the technical assumptions that form the base for the discounted cash flow model of chapter 4.

3.2 Thermochemical conversion

As willow mainly consists of lignin, cellulosis, and hemi-cellulosis, it cannot be converted by digestion or fermentation because the microorganisms responsible for the conversion in these processes are not capable of decomposing lignin (Hackett, Durbin et al. 2004; Yaman 2004; ODE-

Vlaanderen 2006) . Therefore, willow needs to be transformed into energy by thermal conversion. Three thermal conversion techniques can be distinguished depending on the available amount of oxygen (O_2): combustion, gasification, and pyrolysis. The three result in a gas (fumes or product gas) and a residual. Their composition depends on the conversion technique applied. The distinction between combustion, gasification, and pyrolysis is based upon the *air ratio* or *lambda* (see figure 5). Lambda (λ) is defined as "the ratio between the amount of oxygen added to the process and the amount that is required for complete transformation of the feed into the combustion products carbon dioxide (CO_2) and water (H_2O)" (ECN 2001). Combustion happens in excess of O_2 ($\lambda \geq 1$), gasification occurs in an atmosphere short of O_2 ($\lambda < 1$), and pyrolysis takes place in the absence of O_2 ($\lambda = 0$).

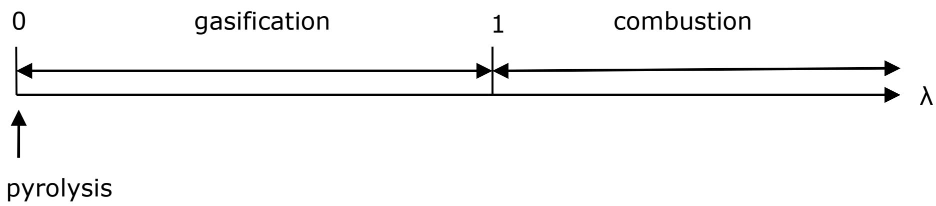

figure 5: Distinction between combustion, gasification, and pyrolysis based on the air ratio

For the conversion of phytoextracting willow, pyrolysis might be the preferred conversion technology because of its moderate process temperature compared to combustion and gasification. Both combustion and gasification typically happen at higher temperatures than pyrolysis. Metals (especially Cd, which is the most problematic in the area studied) appear to volatilise more easily at higher temperatures. This means that the gases resulting from combustion and gasification will contain more heavy metals than those resulting from pyrolysis. In the case of combustion, these gases would be emitted through the chimney back in the atmosphere without appropriate fume gas treatment. In the case of gasification, part of these gases will be converted into energy (electricity and/or heat) by using them as a fuel for gas engines. The metals present in these gases are noxious for the engine’s components. Therefore, the product gases from gasification require cleaning from fly ashes that contain the heavy metals. Since pyrolysis typically happens at lower temperatures, its product gases will contain almost no metals. Research shows that the metals remain in the residual char that results from the pyrolysis process (Koppolu, Agblevor et al. 2003; Koppolu and Clements 2003; Koppolu, Prasas et al. 2004; Cornelissen 2005; Stals, Carleer et al. 2010). Besides, pyrolysis and gasification are considered as alternative technologies that can increase the conversion efficiency compared to combustion (Volk, Abrahamson et al. 2006). In the next paragraph the state of the art of fast pyrolysis will be described based on an extensive literature review. In order to be able to compare its economic performance in chapter 4 with combustion and gasification, the latter conversion technologies will also briefly described in the subsequent paragraphs.

3.3 Fast pyrolysis

During pyrolysis, biomass is heated in the absence of oxygen. This means that not real combustion, but only a thermal cracking of the willow molecules takes place. A distinction can be made between slow and fast pyrolysis. The latter is sometimes called “flash pyrolysis”. The difference lies in the time used to heat the biomass and the residence time of the resulting gases in the pyrolysis reactor. Slow pyrolysis obviously takes more time than fast or fast pyrolysis. Slow pyrolysis typically lasts for half an hour or even several hours, whereas biomass and gases reside only a few seconds in the reactor during fast pyrolysis. Fast pyrolysis means that the biomass is rapidly heated at moderate temperatures (400 until 500 °C) with a *vapour residence time* of only a few seconds, very often a maximum of 3 seconds. The hot gases then need to be quenched rapidly. Part of the gases are then condensed into a dark brown fluid, which "is referred to by many names including pyrolysis oil, bio-oil, …, wood liquids, wood oil, liquid smoke, …, pyroligneous tar, …" (Bridgwater, Czernik et al. 2002). In the course of this text "pyrolysis oil" will be used. The pyrolysis process ultimately results in three products: char (the residue that remains during the heating which contains the ashes and the metals), gas and pyrolysis oil.

Liquefaction converts biomass into liquefied products through physical and chemical reactions: macromolecular substances are decomposed into smaller molecules by heating and in the presence of catalysts. Although they are both thermo-chemical conversion technologies, pyrolysis and liquefaction differ in operating conditions (Xu, Hu et al. 2011). When high pressures and medium temperatures are applied, one speaks of (hydrothermal) liquefaction, whereas low pressures and medium temperatures are associated with fast pyrolysis (Siemons 2002).

Slow heating rates and long residence times (i.e. slow pyrolysis) result in a higher yield of char. A short residence time (i.e. flash or fast pyrolysis) results in a higher yield of pyrolysis oil (Bridgwater, Meier et al. 1999; Cornelissen 2005). Long residence times cause secondary cracking (Bridgwater, Meier et al. 1999). Fast pyrolysis seems preferable to slow pyrolysis because oil holds more perspectives for biomass valorization because almost all metals originally present in the biomass remain in the char (Koppolu, Agblevor et al. 2003; Koppolu and Clements 2003; Koppolu, Prasas et al. 2004; Cornelissen, Jans et al. 2009; Lievens, Carleer et al. 2009; Stals, Thijssen et al. 2009; Shackley and Sohi 2010).

3.3.1 Reactor types

Fast pyrolysis reactors have been reviewed and described by Bridgwater, Meier et al. (1999), Meier and Faix (1999), Mohan, Pittman et al. (2006) and more recently by Bridgwater (2010) and Venderbosch and Prins (2011). Currently, six reactor types are discerned: bubbling fluid beds, circulating fluidised beds and transported beds, ablative pyrolysis, entrained flow, rotating cone and vacuum pyrolysis. These reactor types are briefly summarised in the next section. For detailed information on the reactor configurations, we refer to the authors mentioned before.

Bubbling fluidised beds

The bubbling fluidised bed (or adiabatic fluidised bed) is a well-understood and the most common reactor type used for fast pyrolysis. It is usually referred to simply as fluidised bed and is among the most successful methods for rapid heating of biomass particles. It uses an inert solid, usually sand, as the heat transfer medium for the biomass particles. A fluidised bed provides efficient heat transfer to biomass particles because of the high solids density in the bed. The sand rises by blowing gas through the nozzles at the bottom of the reactor. The gas thus is injected vertically upward through this bed of granular material (sand) at sufficient velocity to cause a violent mixing of gas and solid into an emulsion that resembles a fluid. The heat transfer limitation is within the biomass particle, requiring very small particles of not more than 3 mm to obtain good liquid yields. These conditions are very favourable for fast pyrolysis as the biomass is rapidly heated and the vapours released are rapidly transported from the reactor. Char does not accumulate in the fluidised bed, but is rapidly eluted, though the residence time for char is higher than for vapours. The sand bed is heated by externally combusting the produced pyrolysis gases and/or chars. Bubbling fluidised beds give high liquid yields of typically 70 to 75 m% from wood on a dry-feed basis. The Canadian company Dynamotive Corporation commercialised the fluidised-bed technology of the University of Waterloo in two commercial plants at West Lorne and Guelph, but operational performances for both plants are not available in the open literature.

Circulating fluidised beds/transported beds

Circulating fluid beds (CFBs) and transported bed reactors have many of the features of bubbling beds, but differ in the amount of gas used to fluidise the bed and the residence time of the char which is almost the same as for vapours and gas. In CFBs this gas flow is intentionally set high enough to transport particles out of the bed, which are recovered by gas cyclones and returned to the fluidised bed. Both char and sand are entrained in the gas flow (which can lead to higher char contents in the condensed pyrolysis oil without extensive char removal), with heat transfer and pyrolysis occurring in the rising gas flow. The particulate matter (char and sand) enters a close coupled combustion chamber where the char is burnt in air, heating the sand bed media, which is recirculated to the bottom of the riser. The system is more complicated to design and operate than a bubbling fluidised bed, but has the advantage that it is potentially suitable for larger throughput as this technology is widely used at very high throughputs in the petroleum and petrochemical industry. The Canadian company Ensyn has developed industrial applications for their rapid thermal processing (RTP) technology which is a patented form of CFB. Just like bubbling fluidised beds, CFB technology is relatively well developed. A more innovative reactor design under development by Clean Fuels in the Netherlands is IFB, i.e. intermittent fluid bed pyrolysis which uses the heat buffering capacity of a fluidised sand bed (Siemons and Baaijens 2010). During IFB, pyrolysis takes place in two phases: a productive phase during which stored heat is released to the reactants and bed temperature decreases, and a heating phase during which the bed temperature is restored and energy is accumulated. Its advantages are reduced investment costs, and the potential to use the pyrolysis char as a fuel by combustion at very low temperatures, amongst others.

Ablative pyrolysis

The mode of reaction in ablative pyrolysis is substantially different from other methods of fast pyrolysis. Biomass is pressed onto a rotating hot surface, which is heated by hot flue gas of combusting pyrolysis gases and/or pyrolysis char. It is like pressing butter down and moving over a heated pan surface. By pressing it against the heated surface, the wood melts and leaves an oil film behind which evaporates. The process uses larger particles of wood and leads to compact and intensive reactors. Some pioneering work on a special form of ablative pyrolysis was carried out by the National Renewable Energy Laboratory (NREL) in the USA in their "vortex reactor" in which the biomass particles are accelerated to supersonic velocities. Also Aston University in Birmingham (UK) built and tested a prototype rotating blade reactor for ablative pyrolysis on a small scale of 3 kg h^{-1}. There are plans for demonstration of ablative pyrolysis in Germany, at the PyTec company, where the liquid product is used in an engine for power generation.

Entrained flow

In an entrained flow reactor, biomass particles are fed into a stream of hot, inert gas. Unlike many other fast pyrolysis reactors, no extra hot solid material is used to transport and heat the biomass particles. Heat transfer thus only takes place from a gaseous heat carrier to solid biomass. Liquid yields of up to 50 and 60 m% on dry feed have been reported, which is lower than the usual yields of bubbling and circulating fluid-bed systems. Besides, most developments have not been as successful as had been hoped. An early process developed by the Georgia Institute of Technology (USA) was built for scale-up in Egemin in Belgium, but the plant was dismantled in 1993 because the feedstock was incompletely pyrolysed.

Rotating cone

The rotating cone technology has been invented by researchers at the University of Twente (the Netherlands). The technology aims at achieving intense mixing and heat transfer between biomass and heat carrier (as compared to a fluidised bed) without the large amounts of fluidising gas. A rotating cone thus mechanically mixes biomass and hot sand without the aid of an inert gas. The system is in a way similar to CFB because sand and char are separated from the pyrolysis vapours and transported to a fluidised bed combustor where the char is burnt to heat the sand before it is conveyed back to the rotating cone. Thus it operates as a transported bed reactor, but with transport effected by centrifugal forces in a rotating cone rather than gas. In a way it is also similar to ablative pyrolysis as part of the heat transfer takes place by the rotating wall. The system has been scaled up by the Biomass Technology Group (BTG) in the Netherlands. BTG is currently erecting a plant in Hengelo in the Netherlands.

Vacuum pyrolysis

Vacuum pyrolysis combines conditions of slow and fast pyrolysis. It is not a true fast pyrolysis in the sense that the heat transfer rate to and through the solid biomass is much slower than in the other reactor types. However, the vapour residence time is comparable and the liquid product has some similar characteristics. Coarse solids are heated relatively slowly to temperatures higher than that of slow pyrolysis, while the gas is removed from the hot temperatures by applying a reduced pressure. This vacuum leads to larger equipment and higher costs. Liquid yields are typically lower and char yields are higher than in fast pyrolysis systems. The liquid yield though is higher than in slow pyrolysis because the vapours are removed quickly which minimises secondary reactions. The technology has been developed at the University of Laval and a demonstration plant was erected in Jonquiere

Quebec (Canada). Due to operational limitations, the plant's operation ceased in 2002.

3.3.2 Oil yields and characteristics

Pyrolysis of willow is often cited to yield more or less 70 m% of pyrolysis oil, 15 m% biogas and 15 m% char on a dry feed basis. In literature however, ranges between 50 m% and 80 m% of pyrolysis oil are reported (Easterly 2002; Bridgwater 2003; Chiaramonti, Oasmaa et al. 2007). Pyrolysis oil is a dark brown liquid with a smoky odour (Lievens 2007) that approximates biomass in elemental composition (Bridgwater 2011) with a density of 1,2 kg m^{-3}. It is a "very complex mixture of oxygenated hydrocarbons with an appreciable proportion of water" (Bridgwater, Czernik et al. 2002). Because the pyrolysis liquid is formed by rapid quenching of the pyrolysis vapours and aerosols, secondary reactions are prevented so that the product has a tendency to age, i.e. to change slowly some physical and chemical characteristics over time (Bridgwater 2011).

The water in the fast pyrolysis liquid cannot easily be separated by conventional methods such as distillation (Bridgwater, Meier et al. 1999; Bridgwater, Czernik et al. 2002) and is partly the product of dehydration reactions during pyrolysis (which is called pyrolytic water), whereas the other part stems from the original water content in the feed (Demirbas 2000; Lievens 2007; Bridgwater 2011). The water content of the pyrolysis oil therefore varies over a wide range (20 – 30 % as mentioned in table 7) according to the moisture content in the feedstock and to process conditions, including the extent of secondary reaction and cracking (Cornelissen 2009). "Increasing water usually reduces viscosity, improves stability and reduces heating value" (Bridgwater and Peacocke 2000). A high water content can also lead to poor ignition (Meier, Oasmaa et al. 1999). The composition of pyrolysis oil is represented in table 7.

Component	m%
Water	20-30
Lignin fragments: insoluble pyrolytic lignin	15-30
Aldehydes	10-20
Carboxylic acids	10-15
Carbohydrates: e.g. levoglucosan	5-10
Phenols	2-5
Furfurals	1-4
Alcohols	2-5
Ketones	1-5

table 7: Composition of pyrolysis oil (Bridgwater, Czernik et al. 2002)

The calorific value (CV) of a material is an expression of its energy content, or heat value, released when burnt in air. The CV of a fuel can be expressed in two forms: the gross CV (GCV) or higher heating value (HHV), and the net CV (NCV) or lower heating value (LHV). The HHV is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapour and therefore represents the maximum amount of energy potentially recoverable from a given biomass source or fuel. The latent heat contained in the water vapour cannot be used effectively and therefore, the LHV or NCV is the appropriate value to use for the energy available for subsequent use (McKendry 2002). According to Bridgwater (2003), the gross calorific value (or high heating value, HHV) of willow derived crude pyrolysis oil ranges between 16 and 19 MJ kg^{-1} or GJ t^{-1}. Thus, the calorific value of pyrolysis oil is but is only 40 to 55 % of that of fossil diesel and petrol (Cornelissen 2005). In the base case, a LHV of 17 MJ kg^{-1} is assumed.

3.3.3 Applications of pyrolysis oil

Pyrolysis oil has as a main advantage that it can be easily stored, handled and transported economically, so that oil production and energy production can take place independently at different locations and scales (López Juste and Salvá Monfort 2000; Brammer, Bridgwater et al. 2005). It is often assumed that it can be used in *conventional boilers* with minor modifications (Vivarelli and Tondi 2004). Mohan, Pittman et al. (2006) state that pyrolysis oil can be "stored, pumped and transported in a similar matter to that of petroleum-based products and can be combusted directly in boilers, gas turbines, and slow- and medium-speed diesel engines for heat and power applications". Biomass fuels though have a very low sulphur content compared to many fossil fuels (Czernik and Bridgwater 2004). Pyrolysis oils also generate less than half of the NO_x emissions than diesel oil in a gas turbine thanks to its water content which lowers flame temperature (Moses and Bernstein 1994; López Juste and Salvá Monfort 2000; Stewart 2004; Bridgwater 2010).

According to Venderbosch, Wagenaar et al. (2004), pyrolysis oil can be used in *diesel engines* for static applications. Bridgwater (2010) confirms that medium- and slow-speed diesel engines can operate on low-grade fuels such as pyrolysis oil. The main concerns for operating diesel engines on bio-oils are difficult ignition (resulting from low heating value and high water content), corrosiveness and coking (Bridgwater 2010). Also Czernik and Bridgwater (2004) mention that difficult ignition, high viscosity, coking and corrosiveness are the most challenging characteristics to tackle for the usage of pyrolysis oils in combustion engines. Pilot-ignition engines solve the problem of difficult ignition: they use a small amount of an auxiliary fuel to ignite the main fuel (Bridgwater, Toft et al. 2002). High oxygen content results in a lower calorific value and immiscibility with other hydrocarbon fuels. A higher water content also reduces the heating value and causes ignition delay, whereas it ameliorates oil viscosity. The complex chemical composition of pyrolysis oils causes a wide range of boiling temperatures and the content of organic acids may corrode the engine materials. It is mentioned that additives (e.g. polar solvents such as methanol or acetone - see Czernik and Bridgwater, 2004) might enhance auto-ignition, that preheating might reduce ignition delays (Bridgwater 2004; Czernik and Bridgwater 2004) and that injection nozzles suffer from corrosiveness and rapid clogging due to coking. Adjusting materials for injection nozzles however is quite complex as the variability in the composition of the pyrolysis oils requires different measures to be taken. Organic acids in the oil can corrode materials and carbon deposits (e.g. char) can block or erode those materials. Chiaramonti, Oasmaa et al. (2007) confirm the need for pilot injection of diesel oil when using pyrolysis liquids in diesel engines. At room temperature pyrolysis oil is characterised by high viscosity but at slightly higher temperatures instability might occur due to secondary cracking reactions. Pyrolysis liquids thus are not very thermally stable and cannot be heated to reduce viscosity (Moses and Bernstein 1994). Also, van Tilburg, de Vries et al. (2005) state that there might be problems with using pyrolysis oils in diesel engines. Typically, pyrolysis oil has a pH value of 3 (Bridgwater, Toft et al. 2002), which explains its corrosive character. Due to the oil's corrosiveness, suppliers of diesel engines are not eager to guarantee the proper working of the engine during the total life span.

Therefore, it is certainly not usable as a transport fuel for cars as these engines are extremely vulnerable to corrosion. In addition, pyrolysis oil contains some particles that can damage small components of dynamic applications (Cornelissen 2005). If one would like to use pyrolysis oil for transport, at least hot gas filtration should be applied to upgrade the pyrolysis oil to a more pure form with less solid particles. This causes less viscosity and less aging (meaning that the pyrolysis oil will become unstable during time), however, it also diminishes oil yield by 10 % (Stals 2007). Medium and slow speed diesel engines are best suited for combustion of pyrolysis oils (Bridgwater 2004; Ringer, Putsche et al. 2006). According to Ringer et al. (2006), early results indicate that only minor modifications to engines are required for replacing conventional diesel fuel by pyrolysis oils.

They also state that difficulties with material erosion and corrosion are solvable with careful material selection and particle removal from the oils. Prins (1998) confirms that diesel engines are relatively insensitive to contaminants found in pyrolysis oils, but that larger engines are better suited because of the higher manufacturing tolerances for injection pump and nozzles in those engines. Prins (1998) underlines the need for new injection materials but indicates that improving the pyrolysis oil production process by means of hot gas filtration might enhance applicability of pyrolysis oils in diesel engines.

It is assumed that the electricity is put on the Flemish distribution network. Art. 4.5.1 of the Energy Decree states that installing a direct line outside the own site is allowed after permission by VREG (the Flemish Regulator for the Electricity and Gas market) after advice from the network administrator. So the Energy Decree does not prohibit direct sales to neighbouring industrial companies. Because the possibility of installing a direct line depends on permission by VREG, the decisions published by VREG with regard to requests for installing a direct line have been checked. VREG has published 5 anonimised decisions on its website (http://www.vreg.be/beheerders-van-directe-lijnen-en-directe-leidingen). Of these 5 decisions, 3 requests have been refused, 1 has been approved and 1 decision does not proceed to approval by VREG because it concerned a request for a direct line on one’s own site for which the Energy Decree states that this is allowed without explicit approval by VREG. One of these decisions refused the installation of a direct line between two adjacent parcels because of inefficient use of the existing distribution network, and a negative impact on the tariffs for other users of the existing network. Another refusal concerned the installation of a direct line along a canal between a wind turbine and one consumer because of safety reasons and inefficient use of the existing network. One advice though concerned the installation of a biomass plant in the Northern Campine by means of a direct line to a customer on an adjacent parcel. The direct line has been approved because it concerned the installation of a direct line to an adjacent parcel, in a region (the Northern Campine) which has a congested distribution network. For the sake of this congestion, the distribution network administrator IVEKA (who administers the distribution network in 46 municipalities in the province of Antwerp) has rejected a prior request for a connection to the network. For privacy reasons, VREG did not mention the exact location of the biomass plant, but given that the relevant network administrator was IVEKA, it has been assumed that the biomass plant was located in another part of the Campine region (i.e. the part of the Belgian Campine in the province of Antwerp, whereas our case study is located in the northern part of the province of Limburg which is also a part of the Belgian Campine). From a "worst case perspective" it has been assumed though that electricity has to be put on the distribution network, as direct sales might lead to too optimistic sales prices for electricity: it depends on finding a neighbouring partner, approval by VREG, … (see also paragraph 4.3.3).

Heat is produced both in the form of hot exhaust gases and hot water. The heat exchangers that are required for cooling the engine (water jacket), the turbocharger and the lubricating oil produce hot water at a temperature between 75 and 80 °C. The exhaust gases have a temperature between 300 and 400 °C and can be used directly or indirectly by means of a recuperation boiler where the preheated water from the heat exchangers can be heated further to temperatures between 85 and 95 °C. The thermal efficiency of an internal combustion engine like this is between 44 and 51 %, half of which stems from the exhaust gas heat source and half from the heat exchangers (COGEN Vlaanderen 2006). Here it is assumed that the heat can be sold in the form of hot water to industrial companies in the direct neighbourhood, which means that no such investments for district heating are required (for transporting the heat to residential housing areas). However, if more heat is produced than can be used by the local market, heat and, thus, revenues are lost. Schematically the conversion process can be presented as shown in figure 6.

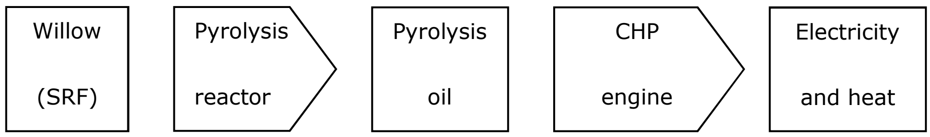

figure 6: Fast pyrolysis general conversion process outline

3.3.4 Mass and energy balance fast pyrolysis

In figure 7 the mass and energy balance of a fast pyrolysis plant for the combined production of heat and electricity has been summarised. When willow is cultivated on 2 400 hectares of farmland, it is expected that every year 19 200 t_{dm} of willow can be harvested at an average willow yield of 8 t_{dm} ha^{-1} yr^{-1}. By fast pyrolysis the willow feedstock is converted into 65 m% of pyrolysis oil, 23 m% pyrolysis gas and 12 m% of pyrolysis char. The char needs to be landfilled due to the content of heavy metals, whereas the pyrolysis gases are usually used for internal energy provision. It is assumed that the pyrolysis oil can be combusted in an internal combustion engine especially designed for the combustion of bio-oil for combined heat and power production, with an electric efficiency of 43 % and a thermal efficiency of 37 % (Stroobandt 2007).

The fast pyrolysis plant requires electricity, heat for drying the biomass to a moisture content of 7 % and heat for setting the right process temperature. Power requirements for a fast pyrolysis plant of 40 kWh t_{dm}^{-1} are estimated by Toft (1996) and Bridgwater, Toft et al. (2002). Toft (1996) and Bridgwater (2009) refer to Diebold (1993) who suggests 120 kWh t_{dm}^{-1} for an integrated biomass to gasoline plant incorporating feed drying, fast pyrolysis, zeolite cracking and refining. Toft (1996) assumes that a pyrolysis plant consumes a third of the power, resulting in a power consumption of 40 kWh t_{dm}^{-1}. This has been deducted from the gross power production by the combined heat and power engine, in order to obtain the net power production that can be sold to the electricity network afterwards.

Pyrolysis feasibility studies often presume that the internal process energy requirement for rapidly heating the willow feedstock to temperatures between 400 and 500 °C can be met by combustion of the off-gas (pyrolysis gas) and the char (Toft 1996; Bridgwater, Toft et al. 2002; Voets, Kuppens et al. 2011). The latter however contains cadmium and cannot be used for internal energy provision. So remains the question whether the pyrolysis gas contains sufficient energy to supply the pyrolysis process. Bridgwater (2009) states that "the pyrolysis process requires 15% of the energy in the feed material, and that the byproduct char contains 25% and the byproduct gas contains around 5% of the energy in the feed material, so the gas is insufficient without supplementation such as with natural gas". In table 8 we calculate the annual internal energy requirements for drying the biomass and for providing the enthalpy for pyrolysis and check whether combustion of the pyrolysis gases contains sufficient energy for providing this enthalpy, following the method proposed by Rogers and Brammer (2012a).

Heat is required for drying the incoming biomass to a moisture content of 7 m%. It is assumed that freshly harvested biomass has a moisture content of more or less 55 m% (García Cidad, Mathijs et al. 2003; Meiresonne 2007). It is assumed that the willow biomass can be naturally dried on the field to a remaining moisture content of 25 m% (García Cidad, Mathijs et al. 2003). We then assume that the waste heat recovered from the pyrolysis reactor can be used for drying the willow chips further to a final moisture content of 7 m%. This means that the 8 tonnes of dry wood yield per hectare per year enter the pyrolysis plant with a moisture content of 25 m%, or in other words that the actual mass of the entering 'wet' biomass feedstock equals 10,7 t ha^{-1} yr^{-1} (including 2,7 t water or 25 m% of the total biomass). After drying the actual mass of the annual yield of one hectare of willow equals 8,6 t consisting of 8 t dry matter and 0,6 t water. In other words 2,1 tonnes of water should be evaporated during the drying process.

The evaporation enthalpy of water (H_2O) equals 2,26 MJ kg^{-1} or GJ t^{-1} (INAV 1996). Biomass drying typically requires about 50 % more energy than the evaporation enthalpy (Wright, Satrio et al. 2010) because energy is required to heat the biomass and due to heat losses to the environment. In table 8 one can follow that the annual energy requirement for drying equals 16,8 TJ yr^{-1}.

The enthalpy for pyrolysis is defined as the energy required to raise biomass from room temperature to its pyrolysis temperature and to convert the solid biomass into the reaction products of gas, liquids and char (Daugaard and Brown 2003). It is the total energy consumed by the biomass during pyrolysis, including sensible enthalpy (i.e. the energy absorbed by the biomass to raise its temperature) and the enthalpy of reaction (i.e. the energy required to drive the pyrolysis reactions). The average value for the enthalpy of pyrolysis is approximately 1,5 MJ kg_{dm}^{-1} (or GJ t_{dm}^{-1}) for biomasses with typical moisture contents between 8 % and 10 % (Daugaard and Brown 2003). Besides, Rogers and Brammer (2012a) state that a generic bubbling fluidised bed reactor also requires 0,3 MJ kg^{-1} of feed for evaporating any residual moisture in the biomass, another 0,6 MJ kg^{-1} for raising the fluidising gas up to 500 °C from the 50 °C quench temperature and an allowance of 3 % of heat input to the pyrolysis reactor to cover heat losses. They also state that the gas heating the process has a significant heat content that can supply some of the other thermal loads. The heat requirement for the pyrolysis process equals 47,5 TJ yr^{-1}.

Next, Rogers and Brammer (2012a) subtract the energy content of the secondary pyrolysis products (char and gas) which they expressed in MJ (LHV) per kg of dry biomass feed in function of the ash content of the feed. Stals (2011) measured an ash content of 2 % in the willow clones in the Belgian Campine. When the char and gas can be burnt, 131,5 TJ yr^{-1} of energy would be available, which is double the internal energy requirement. Taking into account the Cd content of the char however, we can only use the gas as a secondary pyrolysis product. Combustion of the gas would yield only 18,0 TJ yr^{-1} whereas 47,5 TJ yr^{-1} is required. This energy requirement is subtracted from the heat sales, because it is assumed that oil will have to be combusted to provide this energy. These assumptions form the base for the economic calculations in chapter 4.

Energy requirement for drying		
Quantity of evaporated water	t_{H2O} ha^{-1} yr^{-1}	2,1
Evaporation enthalpy of water	GJ t_{H2O}^{-1}	2,26
Available farmland	ha yr^{-1}	2.400,00
Yearly energy use for drying	GJ yr^{-1}	16.796,90
Energy requirement for pyrolysis		
Pyrolysis enthalpy	GJ t_{dm}^{-1}	1,50
Moisture evaporation	GJ t_{dm}^{-1}	0,30
Fluid gas heating	GJ t_{dm}^{-1}	0,60
Total heat per dry ton of feed	GJ t_{dm}^{-1}	2,40
Allowance for heat loss		3%
Annual feedstock	t_{dm} yr^{-1}	19.200,00
Annual energy requirement for pyrolysis	GJ yr^{-1}	47.462,40
Total internal energy requirement	GJ yr^{-1}	64.259,30
Energy available in the secondary pyrolysis products		
Energy in the secondary pyrolysis products		
Char	GJ t_{dm}^{-1}	5,91
Gas	GJ t_{dm}^{-1}	0,94
Energy available (char + gas)	GJ yr^{-1}	131.520,00
Energy available (gas only)	GJ yr^{-1}	18.048,00

table 8: Internal energy requirement versus annual energy provision

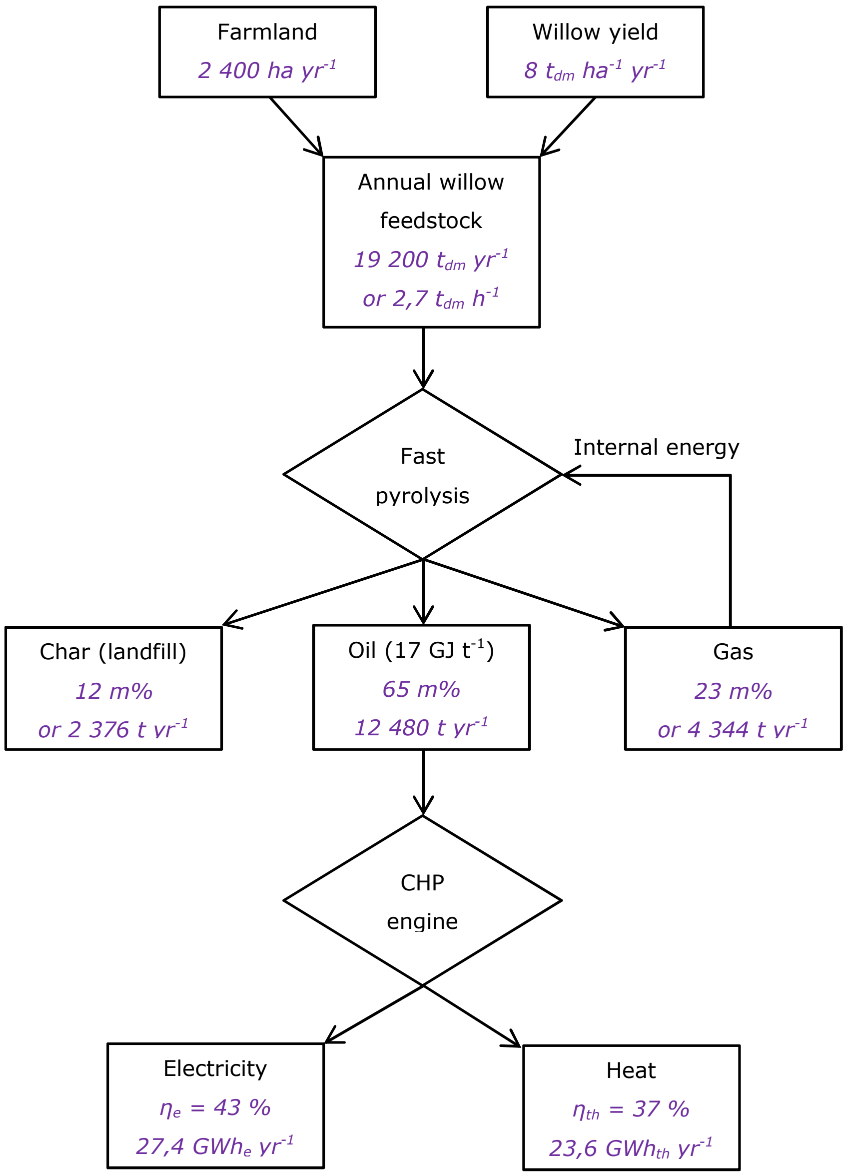

figure 7: Simplified mass and energy balance of the pyrolysis base case (CHP)

The problem with combined heat and power production is that it is not sure whether the produced heat can be sold. Heat sales require the existence of heat demand in the neighbourhood of the CHP plant. Without large heat demanders in the neighbourhood, the heat can be used for district heating as an alternative. Though when residential housing areas are too far away from the CHP plant, centralised heat production is of no use (as a final alternative it can be studied whether decoupling of fast pyrolysis and decentralised heat production is profitable though this is beyond the scope of this dissertation because there were no data available of heat demand in the studied area). Therefore in chapter 4 the economics profitability of fast pyrolysis will be calculated for 3 scenarios: as a substitute for fossil fuels in boilers, as a fuel for a power plant, and as a fuel for a combined heat and power plant. According to Voets, Kuppens et al. (2011) the extra investment for combined heat production is already profitable when 50 % of the produced heat can be sold. Because of the uncertainty about the heat sales, fast pyrolysis has been compared to combustion and gasification for electricity production only.

3.4 Combustion

3.4.1 Biomass combustion systems

The burning of biomass in air, i.e. combustion, is widely used in biomass applications to convert the chemical energy stored in biomass into heat, mechanical power and/or electricity with net conversion efficiencies from 20 % to 40 % (Bridgwater, Toft et al. 2002; McKendry 2002). Combustion is the rapid reaction of fuel and oxygen to obtain thermal energy and flue gas, consisting primarily of carbon dioxide and water (Brown 2011). From scales of 10 MW_{th} input capacity, fluid bed designs are the preferred combustors for biomass applications because of their low NO_x emissions thanks to relatively low combustion temperatures of around 850 °C (Dinkelbach 2000), though the option to cofire small amounts of biomass with coal in existing coal-fired power plants has also attracted widespread interest (Hughes 2000; Tillman 2000; Bridgwater, Toft et al. 2002; Demirbas 2003; Caputo, Palumbo et al. 2005; Tharakan, Volk et al. 2005; Jenkins, Baxter et al. 2011). The stored biomass is handled to and burnt in a boiler, which typically consists of a fluid bed combustor with one or more heat exchangers that are used to make steam. Next the steam is expanded over a turbine that drives an electric generator (Demirbas 2002). The steam from the turbine exhaust is condensed and the water recirculated to the boiler through feedwater pumps. Combustion products exit the combustor, are cleaned and vented to the atmosphere (Jenkins, Baxter et al. 2011).

3.4.2 Fumes treatment

Fumes treatment consists of a dry adsorption system and a catalytic reactor for SO_x and NO_x removal together with a fabric filter for dust collection before discharge to the stack (Caputo, Palumbo et al. 2005). According to Ljung and Nordin (1997) the cadmium present in willow may be volatilised and hence separated through a hot cyclone. There is actually a discussion about whether or not extra gas filtering is required when combusting or gasifying biomass from phytoextraction. First of all, it depends on the statute that biomass from phytoextraction will receive: will it be considered as waste or not? Some state that contaminated biomass is actually a waste product from phytoextraction, though most votes go in the direction of not considering biomass on a contaminated site as waste, but as a dedicated energy crop that needs conversion. The statute of the biomass then determines the emission requirements: there is a difference between emission standards for waste incineration and emission standards for biomass incineration (the latter are of course less stringent). A master student contacted a few local biomass and waste combustors who stated that the installed standard fume gas treatment in the incineration/combustion plants is sufficient for eliminating the cadmium concentrations in the fumes from phytoextracting crops. This has been confirmed by Sas-Nowosielska (2004) who states that "Modern flue gas cleaning technology assures effective capture of the metal containing dust" after incineration of the contaminated biomass and it has also been confirmed in the research by Witters (2011) "When this willow is considered as biomass, no additional flue gas cleaning will be necessary according to legislation". Because standard fumes treatment is included in the investment cost of both the combustion and gasification plant, and in order not to overestimate the relative profitability of a fast pyrolysis plant (one can consider it as a worst case scenario for fast pyrolysis) no extra cost for fume gas treatment has been calculated in the combustion and gasification case.

3.4.3 Combustion efficiency

It is important to note that for calculating the net electric capacity of the combustion plant, one requires knowledge about the electric efficiency and the energy content of the biomass. The energy content or heating value is defined as the heat released by combustion under specific conditions. Boiler or power plant efficiency is by convention commonly reported using the lower heating value of the fuel in some countries, while in others the higher heating value is used (Jenkins, Baxter et al. 2011). The calculations of electric efficiency have been based on Caputo, Palumbo et al. (2005) who defined the plant's energy conversion efficiency based on the biomass lower heating value. The assumed lower heating value of willow has been based on measurements by Stals (2011) for willow cultivated in the Belgian Campine, i.e. 19,3 MJ t_{dm}^{-1} which corresponds to the value proposed by Bridgwater, Toft et al. (2002). The energy efficiency is dependent on scale, in a way that efficiencies increase with up-scaling (Dornburg and Faaij 2001). Electric efficiency thus is function of the electric capacity: the greater electric capacity, the higher the electric efficiency. This relationship between electric efficiency and capacity has been applied when calculating the plant's capacity and efficiency. Therefore we simulated the data from figure 8 in Caputo, Palumbo et al. (2005) into the data in table 9, calculated the average values for each capacity and finally calculated a trendline for the electric efficiency. The electric efficiency can be expressed in function of electric power as follows:

$$\eta_e^{co} = 19{,}435 \times P_{ne}^{0{,}097} \tag{3.1}$$

In the last two columns, we calculated an uncertainty ratio for each power capacity with regard to electric efficiency: at a capacity of 5 MW_e for instance, the lowest efficiency estimate (Bridgwater's) is 79 % of the average estimated efficiency while the highest estimate (Dornburg's) is 14 % higher than the average. Uncertainty lowers when capacity increases. These values will be used for an uncertainty dummy (*efficiency dummy*) in the chapter on risk analysis.

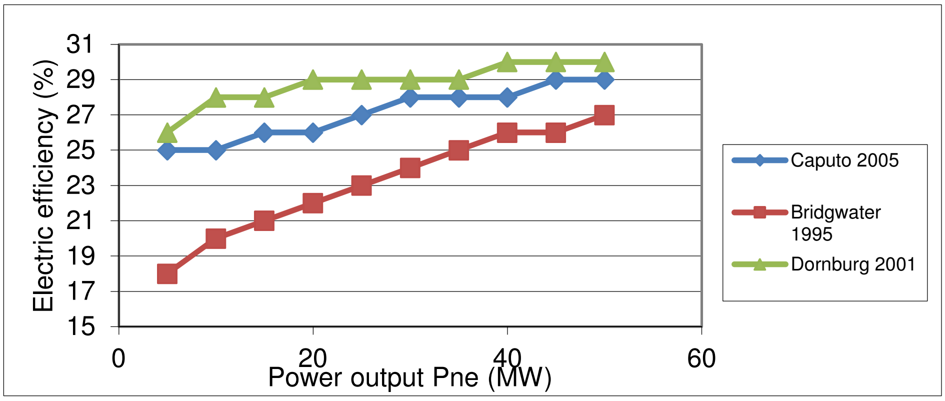

figure 8: Electric efficiency of a biomass combustion plant in function of electric power (Caputo, Palumbo et al. 2005)

P_{ne}	Electric efficiency				Uncertainty ratio	
MW_e	Caputo 2005	Bridgwater 1995	Dornburg 2001	Avg	Low	High
5	25	18	26	23	0,79	1,14
10	25	20	28	24	0,82	1,15
15	26	21	28	25	0,83	1,11
20	26	22	29	26	0,85	1,12
25	27	23	29	26	0,87	1,09
30	28	24	29	27	0,89	1,07
35	28	25	29	27	0,91	1,06
40	28	26	30	28	0,94	1,08
45	29	26	30	28	0,92	1,07
50	29	27	30	29	0,95	1,06

table 9: Average electric efficiency of a biomass combustion plant in function of electric power

Later on, the equipment costs have been parameterized in function of the combustion plant's net electric power output P_{ne}, which is a function of the biomass flow rate Φ_{co}^{h}, the lower heating value of the short rotation coppice (LHV_{SRC}) and the electric efficiency of the combustor (η_e^{co}):

$$P_{ne} = \frac{\Phi_{co}^{h} \times \eta_e^{co} \times LHV_{SRC}}{3\,600 \times OH} \quad (3.2)$$

Besides, internal power consumption has been based on Bridgwater, Toft et al. (2002) who used a value of 2 % of thermal input for the auxiliary power consumption for the combustor and 4 % for the steam cycle. The results of the base case calculations with respect to process capacity and efficiency based on the assumptions above are presented in the next table.

Variable	**Assumption**
Farmland dedicated to phytoremediation	2 400 ha yr^{-1}
Willow yield	8 t_{dm} ha^{-1} yr^{-1}
Willow calorific value	19,3 GJ t_{dm}^{-1}
Combustion service hours	8 000 h yr^{-1}
Thermal input (at combustor entrance)	12,9 MW_{th}
Thermal input (minus 2 % of thermal input for combustor)	12,6 MW_{th}
Electric efficiency	21 %
Net electric capacity	2,6 MW_e
Expected electricity production	20,7 GWh yr^{-1}

table 10: Technical assumptions combustion plant for electricity production

3.5 Gasification

3.5.1 Gasification systems

Gasification converts biomass by partial oxidation at elevated temperature into a combustible gas energy carrier (syngas) consisting of permanent non-condensable gases (Bridgwater, Toft et al. 2002). These gases are a flammable low molecular gas mixture of carbon monoxide (CO), hydrogen and methane, nitrogen, carbon dioxide and smaller quantities of hydrocarbons characterised by a low calorific value, and can be burnt to produce heat and steam, or used in gas turbine cycles to obtain electricity (Caputo, Palumbo et al. 2005; Brown 2011). Conversion efficiencies up to 50 % may be reached if biomass integrated/combined gas-steam cycles are utilised. Gasifiers have been designed in various configurations, with downdraft (co-current), updraft (counter-current), bubbling and circulating fluid beds as the main options (Bridgwater, Toft et al. 2002). One of the most attractive features of gasification is its flexibility of application, including thermal power generation, hydrogen production, and synthesis of fuels and chemicals which allows the prospect of gasification based energy refineries. The simplest application of gasification is production of heat for kilns or boilers (Brown 2011). Only fluid bed configurations are being considered in applications that generate over 1 MW_e (Bridgwater, Toft et al. 2002). According to Caputo, Palumbo et al. (2005) fluid bed gasification, followed by a combined gas-steam cycle represents a typical plant architecture for power generation. Though Bridgwater, Toft et al. (2002) distinguish between atmospheric gasification followed by a dual fuel gas engine for smaller scale applications, and pressurised gasification followed by a gas turbine combined cycle for larger scale applications. They calculated that capital costs for atmospheric gasification with gas engines are the lowest up to capacities of 4 MW_e, whereas pressurised gasification with a gas turbine combined cycle is cheaper for capacities higher than 6 MW_e. Between 4 and 6 MW_e the capital costs for both technologies are very close.

The assumed plant configuration is composed by a storage and handling section analogous to that of the combustion case, followed by a heat recovery dryer for the biomass in order to obtain a suitable moisture content (more or less 20 % on a wet basis). The obtained dry biomass is then fed into a fluid bed gasifier with the aim to produce a gas stream having a low heating value of 5,4 MJ/Nm^3. The produced gas stream is then fed into a hot gas filtration section in order to collect the contained dust, and is subsequently used as a fuel into the combined gas-steam cycle for the electric power generation. An air pollution control system comparable to the one described for the combustion solution assures fumes depuration before discharge to the stack.

3.5.2 Gas treatment

Gasification results in the production of two important ash streams: bulk ash which can be captured in cyclones and a smaller stream of fly ashes to be captured by means of filters (Vermeulen, Harmsen et al. 1998). According to Vermeulen, Harmsen et al. (1998) the heavy metals from the biomass are concentrated in the lower volume of fly ash streams during gasification. They explain this by stating that the largest part of the volatile metals (e.g. Cd) is in the gas phase when passing the cyclone, so that the fly ash should be enriched with the heavy metals. The discussion on extra gas cleaning is the same as for combustion.

3.5.3 Gasification efficiency

The net electric capacity of the gasification plant has been calculated in the same way as for the combustion plant. Electric efficiency, however, is higher than for combustion, but also here it is true that electric efficiency is a function of the electric capacity. Again, a trendline has been calculated for the average electric efficiency found in Caputo, Palumbo et al. (2005):

$$\eta_e^{ga} = 29{,}227 \times P_{ne}^{0{,}1104} \qquad (4.42)$$

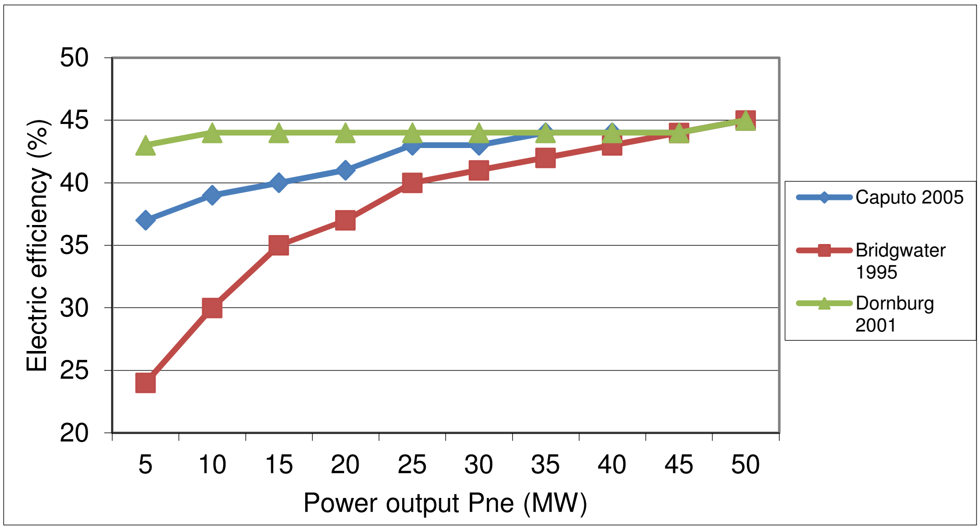

figure 9: Electric efficiency of a biomass gasification plant in function of electric power (Caputo, Palumbo et al. 2005)

In the last two columns of the following table we also calculated an uncertainty range for the electric efficiency by expressing the lowest estimate as a fraction of the average and by calculating the ratio of the highest estimate over the average estimate. Just like with combustion, we see that the uncertainty declines when capacity increases. The range almost converges to a ratio of 1 for high capacities. For high capacities uncertainty is lower than in the case of combustion. At small capacities however, uncertainty is higher compared to combustion.

P_{ne}	Electric efficiency				Uncertainty ratio	
MW	Caputo 2005	Bridgwater 1995	Dornburg 2001	Avg	Low	High
5	37	24	43	35	0,69	1,23
10	39	30	44	38	0,80	1,17
15	40	35	44	40	0,89	1,12
20	41	37	44	41	0,91	1,08
25	43	40	44	42	0,96	1,06
30	43	41	44	43	0,96	1,03
35	44	42	44	43	0,97	1,02
40	44	43	44	44	0,98	1,00
45	44	44	44	44	0,99	1,00
50	45	45	45	45	0,99	1,00

table 11: Average electric efficiency of a biomass gasification plant in function of electric power

Later on, the equipment costs have been parameterised in function of the power generated specifically by the gas turbine (P_{gt}), the power generated by the steam cycle (P_{st}), the biomass flow rate (Φ^h_{ga} measured in kg h^{-1}), and the steam flow rate produced by the heat-recovery steam generator (Φ^h_{hrsg} also expressed in kg h^{-1}). On average, the gas turbine has the largest share of total net electric capacity of a gasification combined cycle plant. P_{gt} is on average 67 % of P_{ne} of a gasification plant and the other 33 % stems from the power supplied by the combined steam cycle (AMPERE 2000; SPE 2003; Voets and Bloemen 2009; Renewable Energy Institute s.d.). The calculation of the biomass flow rate is similar to the one of combustion: it is the annual available amount of biomass divided by the amount of operational hours, which is 8 000 hours for both gasification and combustion (compare to 7 000 operational hours for a fast pyrolysis plant).

The gasification plant's net electric power output P_{ne} is a function of the biomass flow rate $\Phi_{ga}{}^{h}$, the lower heating value of the short rotation coppice (LHV_{SRC}) and the electric efficiency of the gasification plant ($\eta_e{}^{ga}$):

$$P_{ne} = \frac{\Phi_{ga}^{h} \times \eta_{e}^{ga} \times LHV_{SRC}}{3\,600\ \times OH} \quad (3.2)$$

The results of the base case calculations with respect to process capacity and efficiency based on the assumptions above are presented in the next table.

Variable	Assumption
Farmland dedicated to phytoremediation	2 400 ha yr^{-1}
Willow yield	8 t_{dm} ha^{-1} yr^{-1}
Yearly feedstock	19 200 t_{dm} yr^{-1}
Willow calorific value	19,3 GJ $t_{dm}{}^{-1}$
Combustion service hours	8 000 h yr^{-1}
Hourly biomass flow rate ($\Phi^{h}{}_{ga}$)	2 400 kg h^{-1}
Thermal input (at gasifier entrance)	12,9 MW_{th}
Electric efficiency	34 %
Power generated in gas turbine (P_{gt})	3,0 MW_e
Power generated in steam turbine (P_{st})	1,5 MW_e
Total net electric power capacity	4,5 MW_e
Expected electricity production	35,5 GWh_e yr^{-1}

table 12: Technical assumptions gasification plant for electricity production

3.6 Conclusion

As willow mainly consists of lignin, cellulosis, and hemi-cellulosis, it cannot be converted by digestion or fermentation because the microorganisms responsible for the conversion in these processes are not capable of decomposing lignin. Therefore, willow needs to be transformed into energy by thermal conversion. Three thermal conversion techniques can be distinguished depending on the available amount of oxygen (O_2): combustion, gasification, and pyrolysis. For the conversion of phytoextracting willow, pyrolysis might be the preferred conversion technology because of its moderate process temperature compared to combustion and gasification. Both combustion and gasification typically happen at higher temperatures than pyrolysis. Metals (especially Cd, which is the most problematic in the area studied) appear to volatilise more easily at higher temperatures. Research shows that the metals remain in the residual char that results from the pyrolysis process, so that the metals are concentrated from a large polluted area to the willow biomass and finally end up in a smaller volume. Combustion and gasification might require costly fume gas treatment, whereas the char from fast pyrolysis should be disposed of at a landfill. Fast pyrolysis is also preferred to slow pyrolysis because the latter is directed at char production whereas fast pyrolysis yields more pyrolysis oil. Several reactor types exist for fast pyrolysis such as bubbling and circulating fluidised beds, rotating cone, ablative, vacuum and entrained flow pyrolysis. Bubbling and circulating fluidised beds are the most prevalent reactor types resulting in typical product yields of 65 m% (some sources mention 70 m%) of pyrolysis oil, 23 m% pyrolysis gas and 12 m% of pyrolysis char. Pyrolysis oil can easily be used as a substitute for fossil fuels in boilers, because these need less modification. Though it might be interesting to convert the oil into electricity and power in a diesel engine or an internal combustion engine that has been modified for the corrosive properties of the oil, so that the investor can enjoy green power and combined heat and power certificates (see chapter 4). The oil's characteristics though make it unsuitable for dynamic applications (as a substitute for transport fuels). Also for combustion fluid bed designs are the preferred combustors for biomass applications from scales of 10 MW_{th} input capacity because of their low NO_x emissions thanks to relatively low combustion temperatures of around 850 °C. The expected net electric efficiency is 21 %, resulting in a yearly electricity production of 20,7 GWh_e. The main reactor types for gasification are updraft, downdraft, bubbling and circulating fluid bed reactors. Only fluid bed applications are considered for capacities over 1 MW_e, though power is generated most often by means of gas engines at low scales (up to 4 MW_e) and by means of combined gas steam cycles at higher scales (from 6 MW_e). Between 4 and 6 MW_e capital costs of gas engines and combined gas steam cycles are comparable. The electric efficiency is higher for combined cycles, with 34 % in the base case resulting in a yearly estimated electricity production of 35,5 $GWh_{e.}$ From an electric efficiency viewpoint, gasification thus is preferred above fast pyrolysis and fast pyrolysis is preferred above combustion for electricity production. Gasification thus will result in higher revenues and has the potential to be a preferred technology for willow valorisation. In chapter 4 it has been calculated whether these higher revenues outweigh capital costs.

Fast pyrolysis though has the advantage of metal control. There is actually a discussion about whether or not extra gas filtering is required when combusting or gasifying biomass from phytoextraction. It depends on the statute that biomass from phytoextraction will receive: it determines the emission requirements. Some local biomass and waste combustors stated that the installed standard fume gas treatment in the incineration/combustion plants is sufficient for eliminating the cadmium concentrations in the fumes from phytoextracting crops which has been confirmed in the research by Witters (2011). Because standard fumes treatment is included in the investment cost of both the combustion and gasification plant, and in order not to overestimate the relative profitability of a fast pyrolysis plant (one can consider it as a worst case scenario for fast pyrolysis) we chose not to add an extra cost for fume gas treatment in the combustion and gasification step.

4 Discounted cash flow analysis

4.1 Introduction

In chapter 2 it has been stated that the techno-economic potential of fast pyrolysis will be studied from an investor's point of view. Next, in chapter 3 it has been concluded that gasification is energetically the most efficient technology, whereas fast pyrolysis has the advantage of lower process temperatures so that the heavy metals do not volatilise. Therefore, a discounted cash flow model has been developed for the three thermochemical conversion technologies considered. A discounted cash flow model requires estimation of the initial investment expenditure at the start of the project, and identification and estimation of the relevant revenues and expenditure items throughout the expected operational lifetime of the investment. The chapter starts with a meta-analysis of the capital cost for an investment in fast pyrolysis in paragraph 4.2.

Following the analysis and estimation of the capital cost, the technical data of chapter 3 are translated into their economic consequences. This means that inputs and outputs should be priced. The assumptions with regard to the required amount of inputs and produced amount of outputs have been reported together with their corresponding prices and sources. Finally, incentives issued by the government for producing renewable energy and combined heat and power are relevant from an investor's point of view. The result of the discounted cash flow model for fast pyrolysis of willow followed by a CHP plant for the production has been presented at the end of paragraph 4.3.

Combined heat and power production however is only relevant when there is sufficient demand for heat. Ideally this heat demand is mapped during a micro-screening of the region, which might include an extensive investigation of the required heat by industry, residential housing, healthcare, swimming pools and agriculture, amongst others, by means of geographic information systems (GIS). The latter is beyond the scope of this dissertation so that the heat demand cannot yet be assured. Therefore, in paragraph 4.4, a discounted cash flow model has also been built for fast pyrolysis of willow for electricity production only. Although fast pyrolysis might be a promising option for the conversion of contaminated willow from the viewpoint of metal control, its economics should be compared to the profitability of combustion and gasification, because finding a conversion technology that yields a higher sales price for the biomass is in the interest of farmers growing short rotation coppice. Therefore, paragraphs 4.5 and 4.6 reflect the net present value of an investment in respectively combustion and gasification for electricity production. Chapter 4 concludes with a comparison of fast pyrolysis, combustion and gasification in paragraph 4.7 and discusses the cost difference with converting clean biomass and the required revenue from green power certificates.

4.2 Meta-analysis of capital investments in pyrolysis

As pyrolysis is a new technology, there are not a lot of cost data available (Rogers and Brammer 2012a). Moreover, cost data for pyrolysis plants vary significantly (Uslu, Faaij et al. 2008), which is illustrated later in this text. The capital cost of processes that have not been built hence are very uncertain (Bridgwater 2009). Therefore this section reviews existing estimates for the capital cost of a pyrolysis plant and integrates them by performing a **meta-analysis**. First, the general methods for capital investment estimation are explained. Next, existing estimates for the capital costs of pyrolysis plants are inventoried. The found capital costs can be either point estimates for a specific case or equations that are a function of the plant’s scale which already aggregate existing data on capital cost estimates. First, the equations are applied to the relevant scales of the Campine case. Next, the point estimates have been analysed. Finally, all data have been joint to come to a final equation that can be used for preliminary plant cost estimations.

4.2.1 Defining the total capital investment

"Capital investment is the total amount of money needed to supply the necessary plant and manufacturing facilities plus the amount of money required as working capital for operation of the facilities" (Peters, Timmerhaus et al. 2004). The **total capital investment** (TCI) of an industrial plant thus comprises the fixed capital investment in the plant and equipment (fixed assets) on the one hand, and the working capital with which expenses can be paid before sales revenues become available (current assets) on the other hand (see figure 10 for an overview). The *fixed capital investment* (FCI) includes both direct or manufacturing and indirect or nonmanufacturing fixed costs. Manufacturing or *direct costs* consist of the capital required for the purchase of construction items for the plant, i.e. property, all process equipment and materials. Nonmanufacturing or *indirect costs* include construction services such as overheads, supervision and engineering expenses, legal expenses (e.g. for permits), contractor's fees and contingencies (i.e. provisions for possible future events or problems) (Whitesides 2007).

The fixed capital investment should also include land costs. *Working capital* is required to cope with the irregular, non-coinciding time character of incoming cash from sales and outgoing cash for the payment of operational costs. It is the difference between current assets and current liabilities (Mercken 2004; Peters, Timmerhaus et al. 2004; Horngren, Bhimani et al. 2005). At the end of the project lifetime, the working capital and the land costs can be recovered. It is generally assumed that the amount in euros spent on working capital and land at the beginning of the project can be fully recovered at the end of the project lifetime (Peters, Timmerhaus et al. 2004). Besides, land costs are often excluded because they are site specific. Although fully recoverable, the amount of working capital has an important negative influence on the net present value (NPV) of the investment project due to the time cost of money and should not be neglected (Mercken 2004).

However, it is not always clear whether and how much of the total capital investment other authors have dedicated to working capital.

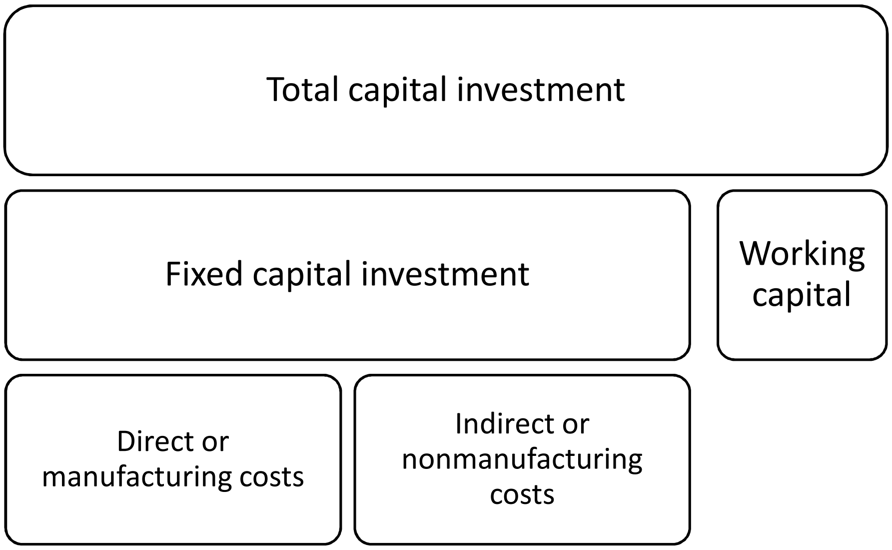

figure 10: Components of the total capital investment

4.2.2 Methods for capital investment estimation

a) <u>Cost estimate classification system</u>

Capital cost estimates can be classified according to the project detail or completeness of engineering which determines the amount of information available for estimation purposes and the expected accuracy of the capital cost estimation. Logically, the accuracy range can be narrowed by increasing the level of engineering detail (Peters, Timmerhaus et al. 2004).

Various organisations, such as the Association of Cost Engineers in the United Kingdom and the Norwegian Project Management Association, have been classifying capital cost estimates into comparable categories. Here the Cost Estimate Classification System developed by the Association for the

Advancement of Cost Engineering (AACE International, i.e. the former American Association of Cost Engineering) is briefly presented, consisting of five classes of cost estimates, based on the degree of project definition. The classes are distinguished from another by five characteristics: degree of project definition (primary characteristic), end use of the estimate, estimating methodology, accuracy and effort required to prepare the estimate (secondary characteristics) (Dysert 2003; Christensen and Dysert 2005). The five classes of cost estimates can be summarised as (Peters, Timmerhaus et al. 2004; Christensen and Dysert 2005):

- *Class 5 - Order of magnitude estimate:*
  based on very limited general information of project data and previous cost data with typical accuracy ranges of –20 % to -50 % on the low side and +30 % to +100 % on the high side.
- *Class 4 - Study estimate:*
  based on knowledge of the major equipment; accuracy ranges between –15 % to -30 % (low side) and +20 % to +30% (high side).
- *Class 3 - Preliminary estimate:*
  prepared for budget authorisation which requires that most of the process data are defined and that at least some preliminary work has been done on engineering deliverables; accuracy ranges between -10 % to -20 % and +10 % to +30 %.
- *Class 2 – Definitive estimate:*
  based on almost complete data but before full completion of engineering drawings and specifications; accuracy between -5 % to -15 % and +5 to +20 %.
- *Class 1 – Detailed estimate:*
  based on complete drawings and specifications; accuracy between -3 % to -10 % and +3 % to +15%.

Capital cost estimates at this stage of development of a phytoremediation project in the Belgian Campine are intended to compare the economic feasibility of different conversion technologies. The estimates are typically predesign estimates based on previous cost data and knowledge of the major components of the process equipment. There are no detailed engineering drawings and specifications available at this stage of the project, so that probable accuracy of the capital cost estimates is between ± -20 % and ± +30 %.

b) Methods for estimating capital investment

Several methods exist for capital cost estimation. The choice depends on the adequacy of product and process definition, the disposable information, the desired level of accuracy and detail and time constraints (Long 2000; Dysert 2003; Peters, Timmerhaus et al. 2004). A summary of the methods described by Peters, Timmerhaus and West (Peters, Timmerhaus et al. 2004) and Dysert (2003) is given below.

Detailed item estimates

For a detailed item capital cost estimate a list of the specific equipment items, materials and personnel for construction and installation required by the process is needed along with information about the size or capacity of the items. Equipment and material needs are determined by complete engineering drawings and specifications. In early stages of a process or product development, this information is often difficult to obtain or incomplete because some needs or specific requirements only become apparent later in the development process. Capital cost estimation methods that require less information are indispensable at early stages of process and product development (Anderson 2009).

Percentage of delivered equipment cost

This method is typically applied during the feasibility stage of a project. The first step is to estimate the cost of each piece of process equipment. All other costs are calculated as a percentage of the delivered equipment cost. This method has been introduced by Lang (Lang 1947; Lang 1948) and sometimes the applied percentages are referred to as *Lang factors.* At the time of preliminary and study estimates, one might not have an exhaustive list of all equipment items, because some requirements become only visible at the moment of construction. Therefore, it is important to assume a cost percentage for auxiliary equipment that has not yet been identified (Dysert 2003). The method has been adopted by Bridgwater for determining the total capital investment or *total plant cost* (TPC) of a fast pyrolysis plant (Bridgwater, Toft et al. 2002). The factors applied for a fast pyrolysis plant can be found in Bridgwater et al. (2002) whereas Peters et al. (2004) give a general overview of factors when one wants to calculate the cost of total direct plant cost if the delivered equipment cost is known.

Capacity factored estimates

This relatively quick method also known as the *six-tenth rule* is often applied for feasibility or order-of-magnitude estimates and can be used to estimate the cost of a whole processing unit or battery of units, but also for estimating the cost of individual equipment items. Williams was the first to mention the rule of six-tenths in 1947 in his article "Six-tenths Factor Aids in Approximating Costs" in the Chemical Engineering magazine of December 1947. It relates the fixed capital investment (FCI) of a new process plant to the FCI of similar previously constructed plants with a known capacity by an exponential ratio relying on the nonlinear relationship between plant capacity and plant cost:

$$Cost\ plant\ A = Cost\ plant\ B\ \times \left(\frac{Capacity\ plant\ A}{Capacity\ plant\ B}\right)^{y} \qquad (4.1)$$

The exponent y typically is on average between 0,6 and 0,7 – hence the name six-tenth rule - for many process facilities (Peters, Timmerhaus et al. 2004), but can be as low as 0,5 or as high as 0,85 for some specific types of plants or equipment (Dysert 2003). An exponent smaller than 1, indicates the presence of scales of economies so that plant costs increase with a smaller percentage than the plant's capacity increase. Strictly speaking the exponent y is not constant, i.e. the exponent tends to increase with increasing plant capacity because there are limits to technology. When the exponent reaches the value of 1, it becomes more economical to build two smaller plants than one large plant (Dysert 2003).

As predesign estimates are mainly based on historical cost data from the past, these cost data should be updated to current prices and economic conditions. This can be done by multiplying the past cost item with the ratio of the present value of the cost index to the value of in the index at the time that the previous cost estimate has been made (Peters, Timmerhaus et al. 2004; Sinnott 2005):

$$Cost\ in\ year\ A = Cost\ in\ year\ B\ \times \left(\frac{Cost\ index\ in\ year\ A}{Cost\ index\ in\ year\ B}\right) \qquad (4.2)$$

One can get fairly accurate cost estimates if the bridged period is no longer than 10 years (Peters, Timmerhaus et al. 2004). The two most cited indices are the *Chemical Engineering Plant Cost Index (CEPCI)* and the *Marshall and Swift equipment cost index (M & S Index)*. The annual values of the CEPCI and the Marshall and Swift equipment cost index are presented in table 13. They are published monthly in the Chemical Engineering[1] magazine. The CEPCI provides values for overall plants on the basis of various types of

[1] see www.che.com

equipment, building, construction labour and engineering fees whereas the Marshall & Swift equipment index only provides equipment cost indices in accordance to process industry (e.g. cement, chemicals, glass, petroleum products, electrical power, etc.). Calculations in this work are based on the CEPCI because the index refers to overall plant costs (whereas the M & S index only refers to equipment costs).

Year	CEPCI	Marshall & Swift
2001	394,3	1093,9
2002	395,6	1104,2
2003	402,0	1123,6
2004	444,2	1178,5
2005	468,2	1244,5
2006	499,6	1302,3
2007	525,4	1373,3
2008	575,4	1449,3
2009	521,8	1468,6
2010	550,8	1457,4
2011	582,8	-

table 13: CEPCI and Marshall & Swift Equipment Cost Index

Parametric cost estimation

A parametric cost estimation "is a mathematical representation of cost relationships that provide a logical and predictable correlation between the physical or functional characteristics of a plant and its resultant cost." (Dysert 2003). It relates cost as a dependent variable to one or more independent variables or *cost drivers* (Dysert 2008).

The approach that has been followed here is a combination of the aforementioned methods and has been based on Bridgwater, Toft et al. (2002); Siemons (2002); Brammer, Bridgwater et al. (2005); Uslu (2005); Bridgwater (2009); Bridgwater (2012) and Rogers and Brammer (2012a).

The resultant cost equation typically depends of the amount of output and is of the functional form (Caputo, Palumbo et al. 2005; Dysert 2005):

$$C = aQ^d \qquad (4.3)$$

with: C = the total plant cost in function of scale Q;
Q = indicator of the plant’s scale;
a = the theoretical cost of the smallest scale;
d = a constant reflecting economies of scale.

This implies that the cost per unit declines by some constant percentage as the plant’s scale doubles.

4.2.3 Analysis of existing pyrolysis investment equations

Several authors already developed an investment equation for estimating the total capital investment of a fast pyrolysis plant. Each of these equations will be briefly described below. Next they are used and applied for estimating the capital cost of a fast pyrolysis plant in the Belgian Campine. Before doing that, the expected scale of the plant should be calculated, i.e. the size of the pyrolysis plant which is dependent on the amount of biomass to be processed. The amount of biomass can be calculated by multiplying the biomass yield in dry tonnes per hectare and per year, with the available farmland for phytoremediation in the Belgian and Dutch Campine. After the minimal, probable and maximal scales of operation are known, one can calculate the expected capital cost according to the referred authors. For purposes of comparison the different estimated capital costs are normalised whenever possible, at least in terms of currency by means of exchange rates and time by means of the annual Chemical Engineering Plant Cost Index (CEPCI).

a) Scale of operation

Schreurs, Voets and Thewys (2011) estimated the biomass potential from phytoremediation of contaminated farmland in the Campine region in Belgium by means of geographic information systems (GIS). First they predicted the contamination in the region. Then they determined the amount of agricultural land that can be committed to energy crop cultivation for phytoremediation. First of all, not all contaminated land is farmland; some land is industrial land, other land is used for residential housing or nature. After subtracting the surface dedicated to other land use from the total contaminated area, the amount of contaminated agricultural land is left. However, not all the polluted farmland can be remediated by means of phytoremediation: degraded soils that are only moderately contaminated can be remediated by plants. A third condition for calculating the biomass potential is that the time span of phytoremediation (i.e. the time needed for remediation of the soils by means of the plants) is restricted to reasonable time frames to enhance phytoremediation adoption by farmers. Here it is assumed that two rotations of short rotation coppice, or in other words 42 years, is an acceptable time frame for phytoextraction (Schreurs, Voets et al. 2011).

Voets (2011a) calculated that more or less 1 300 ha of farmland in the Belgian part of the Campine (i.e. in the municipalities of Lommel, Balen, Mol, Overpelt, Neerpelt, Hamont-Achel and Hechtel-Eksel) possess a cadmium concentration above the land remediation standard of 2 mg Cd per kg soil (see also table 4 in chapter 1). It is expected that 650 ha is the absolute minimum amount of farmland that has to be phytoextracted. However if government would decide to phytoremediate all farmland that exceeds the guide value of 1,2 mg Cd per kg soil, then a total of 2 383 ha of farmland can be remediated with willow within 42 years. When no limit is put on the time frame for phytoextraction, then a maximum area of 3 015 ha of agricultural land can be dedicated to energy crops in the Belgian Campine.

In order not to overestimate the biomass potential we only consider the amount of agricultural land available in the Belgian part of the Campine region. Besides, when one wants to calculate the potential operational scale of a fast pyrolysis plant in the Belgian Campine, one also needs information about the potential biomass yield on its sandy soils. According to Ruttens (2008) a minimal annual biomass production of 4,7 ton dry matter (t_{dm}) per hectare was achievable on an experimental plantation in the municipality of Lommel with willow trees of the type "Belgisch Rood". This implies that with a minimal area of 650 ha at least 3 055 ton dry willow can be produced annually in the Belgian Campine. The most probable annual biomass production of willow however is 8 ton dry matter per hectare per year according to Vangronsveld, Herzig et al. (2009), although even annual yields of 15,6 ton dry matter have been obtained for some willow clones. Annual biomass yield in the Belgian Campine is expected to reach a maximum potential of 50 000 ton dry willow[2]. In table 14 these potential amounts of biomass yield are translated into scales of operation for a fast pyrolysis plant in the Belgian Campine in terms of hourly ingoing willow feedstock (t_{dm} h^{-1}), taking into account that a fast pyrolysis plant is operational 80 % of the time, i.e. during 7 000 hours per year.

[2] Multiplying the maximal biomass yield of 15,6 t_{dm} ha^{-1} yr^{-1} with a maximum area of 3 000 ha equals 46 800 t_{dm} yr^{-1} or 50 000 t_{dm} round.

Annual biomass yield (t_{dm} yr^{-1})	**Hourly feedstock flow (t_{dm} h^{-1})**
5 000	0,7
10 000	1,4
15 000	2,1
20 000	2,9
25 000	3,6
30 000	4,3
35 000	5,0
40 000	5,7
45 000	6,4
50 000	7,1

table 14: Potential scales of operation for a fast pyrolysis plant in the Belgian Campine

The most probable scale of operation expected in the Belgian Campine is the product of the most probable amount of 2 400 ha of available farmland for phytoextraction and the most probable biomass yield of 8 t_{dm} ha^{-1} yr^{-1} and hence equals a yearly amount of processed biomass of 19 200 t_{dm} yr^{-1} which is close to 20 000 t_{dm} yr^{-1}. The latter annual biomass yield will be referred to as the *base case* value in the remainder of this paragraph on the meta-analysis of the capital cost of a fast pyrolysis plant.

b) Literature review of investment cost equations

Very recently Rogers and Brammer (2012a) reviewed a number of techno-economic analyses of bio-oil production. The capital cost of the overall plant is expressed as the total plant cost to have the plant designed, built and commissioned. The total plant cost excludes site purchase (land costs), ground clearance (the removal of unwanted elements in or on the site such as vegetation, stones, pollutants amongst others), site access and permission/consenting costs because they are function of the specific site rather than the employed technology. Their total plant cost covers the pyrolysis reactor and the bio-oil collection system, is expressed in £ prices of 2009 and depends on the daily processed feedstock (Φ^{d}_{py}) in t_{dm} per day[3]:

$$TPC_{Py}^{Rog12} = \left(2583{,}8 \times \ln \Phi_{py}^{d} - 6958{,}8\right) \times 10^{3} \quad (4.4)$$

We calculated the daily processed feedstock by first dividing the annual biomass yield by the amount of service hours of a fast pyrolysis plant (7 000 hours per year) and then multiplying the result with 24 hours per day, expressed the TPC in 2011 EUR values by applying the exchange rate and the CEPCI. Bridgwater (2012) represents the total installed capital cost of a fast pyrolysis sytem from prepared and dried feed material to liquid bio-oil product in storage tanks in function of the flow of dry tonnes of willow feedstock per hour (Φ_{py}^{h}) and can be found in column 3 of table 15:

$$TPC_{Py}^{Bri12} = 6{,}98 \times 10^{6} \times \left(\Phi_{py}^{h}\right)^{0{,}67} \quad (4.5)$$

Two years earlier Bridgwater (2009) analysed several pyrolysis plants around the world and estimated the capital cost of a fast pyrolysis plant including all design, equipment, construction, civils and commissioning in euros of 2008:

$$TPC_{Py}^{Bri09} = 6{,}03 \times \left(\Phi_{py}^{h}\right)^{0{,}67} \quad (4.6)$$

Brammer, Bridgwater et al. (2005) estimated the investment cost for a pyrolysis unit (fluidised bed system) as a function of the mass input flow of

[3] The superscripts that have been added to TPC refer to the reference. The first three letters refer to the author and the last two figures refer to the year of the publication.

willow in kilogrammes per second. It comprises reception, feed storage, drying, communition, pyrolysis and oil storage. Here the costs of the drying stage are excluded because other authors also exclude them from the total plant cost of a pyrolysis plant unit. They include costs of the drying stage either as a separate unit of or as a part of the operational costs. Investment costs are brought to a final or total plant cost basis, meaning that costs of installation, ancillary equipment, commissioning and a contingency of 10 % are included, assuming the 10th installation. The investment cost of the pyrolysis unit equals:

$$TPC_{Py}^{Bra05} = 4\,744 \times 10^3 \times \left(\Phi_{py}^{s} + 0{,}0921\right)^{0{,}504} \qquad (4.7)$$

The ingoing willow feedstock (Φ_{py}^{s}) is measured in kg_{dm} per second. The remaining plant items for stocking the pyrolysis liquid etc. should also be accounted for:

$$TPC_{Re}^{Bra05} = \left[1\,074 \times \Phi_{py}^{s} \times (1+w) + 824\right] \times 10^3 \qquad (4.8)$$

The remaining plant items not only depend of the incoming willow feedstock but also on the moisture content of the willow in percentages of dry willow. Another capital cost equation has been found in Uslu (2005). They produced a capital investment curve based on five data points, excluding a drying system. The total capital investment is a function of the dry feedstock flow of willow in the pyrolysis plant and equals:

$$TPC_{Py}^{Usl05} = 94\,126 \times \left(\Phi_{py}^{h} \times 10^3\right)^{0{,}4316} \qquad (4.9)$$

This equation renders the total plant cost in euros of 2004. The calculated total capital investment updated to euros of 2011 with the CEPCI of 3,83 MEUR for the base case can be found in the bold row in column 6 of table 15. This is the lowest estimate for the capital cost of the base scale so far, which is probably due to the very limited (five) number of data points used by Uslu (2005). Another equation for the capital cost estimate can be found in

Siemons (2002). This estimate is somehow different as it is a function of the annual energetic capacity (P_{oil}) of the produced bio-oil expressed in thermal megawatt (MW_{th}). It is thus not only dependent on the amount of processed biomass, but is actually also a function of the process efficiency:

$$P_{oil} = \frac{\Phi_{py}^{yr} \times \eta_{oil}^{py} \times LHV_{oil}}{OH_{py} \times 3\,600\, s.h^{-1}} \tag{4.10}$$

with: Φ_{py}^{yr} = yearly processed feedstock in a fast pyrolysis plant (t_{dm} yr^{-1})

η_{oil}^{py} = oil yield as a weight percentage of dry biomass

LHV_{oil} = lower heating value of pyrolysis oil (MJ t^{-1})

OH_{py} = number of operation hours per year of a fast pyrolysis plant

The corresponding capital cost following Siemons (2002) equals:

$$TPC_{Py}^{Sie02} = 691\,453 \times P_{oil}^{0{,}76} \tag{4.11}$$

These costs include a biomass feed dryer, installation and commission, but they exclude land. The latter is consistent with Rogers and Brammer (2012a), although all other sources do not include a biomass feed dryer. Because Siemons does not mention the share of the dryer in the total capital investment, and because the costs according to Siemons are 2nd lowest, we do not correct for the presence of the dryer in the total cost. Bridgwater, Toft et al. (2002) determined the cost of the fast pyrolysis reactor and the liquid storage tank separately. The capital cost of the fast pyrolysis unit is based on 14 data points and equals (in euros of 2000):

$$TPC_{Py}^{Bri02} = 40\,804 \times \left(10^3 \times \Phi_{py}^{h}\right)^{0{,}6194} \tag{4.12}$$

The total installed capital cost of the pyrolysis liquid storage tank can be calculated by equation 4.13:

$$TPC_{Li}^{Bri02} = 119 \times 10^3 \times \left(\eta_{oil}^{py} \times \Phi_{py}^{h}\right)^{0{,}4045} \tag{4.13}$$

(1) Scale $kt_{dm}\ yr^{-1}$	(2) Rogers 2012	(3) Bridgw. 2012	(4) Bridgw. 2009	(5) Bram. 2005	(6) Uslu 2005	(7) Siemons 2002	(8) Bridgw. 2002
5	1,44	5,57	4,87	4,48	2,11	1,85	3,66
10	3,92	8,86	7,76	5,71	2,84	3,13	5,60
15	5,37	11,63	10,18	6,77	3,38	4,26	7,18
20	***6,40***	***14,10***	***12,34***	***7,72***	***3,83***	***5,30***	***8,57***
25	7,20	16,38	14,33	8,59	4,22	6,29	9,82
30	7,86	18,51	16,19	9,42	4,56	7,22	10,99
35	8,41	20,52	17,95	10,21	4,88	8,12	12,08
40	8,89	22,44	19,63	10,96	5,17	8,98	13,11
45	9,31	24,28	21,25	11,69	5,44	9,82	14,10
50	9,68	26,06	22,80	12,40	5,69	10,64	15,04

(1) Scale $kt_{dm}\ yr^{-1}$	(9) Avg	(10) Median	(11) Stdv	(12) Cov
5	3,43	3,66	1,51	44%
10	5,40	5,60	2,12	39%
15	6,97	6,77	2,80	40%
20	***8,32***	***7,72***	***3,44***	***41%***
25	9,55	8,59	4,05	42%
30	10,68	9,42	4,64	43%
35	11,74	10,21	5,20	44%
40	12,74	10,96	6,01	47%
45	13,70	11,69	6,54	48%
50	14,62	12,40	7,05	48%

table 15: Meta-analysis of the literature review of equations for estimating the capital cost of a fast pyrolysis plant expressed in million euros (MEUR) of 2011

c) Meta-analysis of the literature review of investment cost equations

In table 15 one can compare eight capital cost equations for an investment in a fast pyrolysis plant. The average and median capital cost can be found in column 9 and 10 respectively. In column 11 the standard deviation has been calculated for each scale of operation. In column 12 one can see the coefficient of variation, which is the ratio of the standard deviation over the average capital cost. The coefficient of variation is between 39 % and 45 %, which confirms that the accuracy range of *order-of-magnitude estimates* (or so called *ratio estimates*) based on previous cost data can be over ± 30 % as stated by Peters, Timmerhaus and West (Peters, Timmerhaus et al. 2004).

One can see that the estimated total plant cost for the base case scale of operation of a fast pyrolysis plant in the Belgian Campine is somewhere between 3,83 and 14,10 MEUR. The lowest estimate has been based on the investment equation of Uslu (2005) which in turn is based on only five data points most of which from the early 90s. It is not clear why the latest estimate of Bridgwater (2012) is significantly higher than the other estimates. All estimates of table 15 are plotted in figure 11. On the horizontal axis the hourly flow of processed willow is represented whereas on the vertical axis the estimated capital cost in millions of euros of 2011 are plotted. The average estimate has also been plotted for each of the possible scales of operation. For the average cost a trendline has been calculated (in the form of equation 4.3):

$$TPC_{Py}^{Kup12a} = 4\,285\,788\ \times \left(\Phi_{py}^{h}\right)^{0.6272} \qquad (4.14)$$

The exponent of the average total plant cost is somewhat higher than 0,6 (cf. six-tenths rule). It is only natural that the average total plant cost exhibits economies of scale, because the original TPC equations on which it has been based all assume the presence of economies of scale by an exponent that is smaller than 1. If there would be no economies of scale, doubling the plant's size should lead to a doubling of the total plant cost or an increase of the TPC with 100 %. An exponent of 0,6272 implies that doubling the size of the pyrolysis plant augments the total plant cost with only 54 %.

We do not dispose of sufficient information to explain all differences found in the literature review of investment cost equations. Local differences in the value of land have been avoided as much as possible by excluding the costs of land. Other costs however are still a function of local conditions: wages can differ from country to country and from region to region. Besides, certain types of equipment might be purchased at prices lower than the prevailing market prices. This has been affirmed during conversations with the managers of Nettenergy (mobile pyrolysis) in Boskoop (the Netherlands) and Bio-Oil Tessenderlo (Belgium). The latter fast pyrolysis plant in Belgium however went bankrupt in the course of 2011.

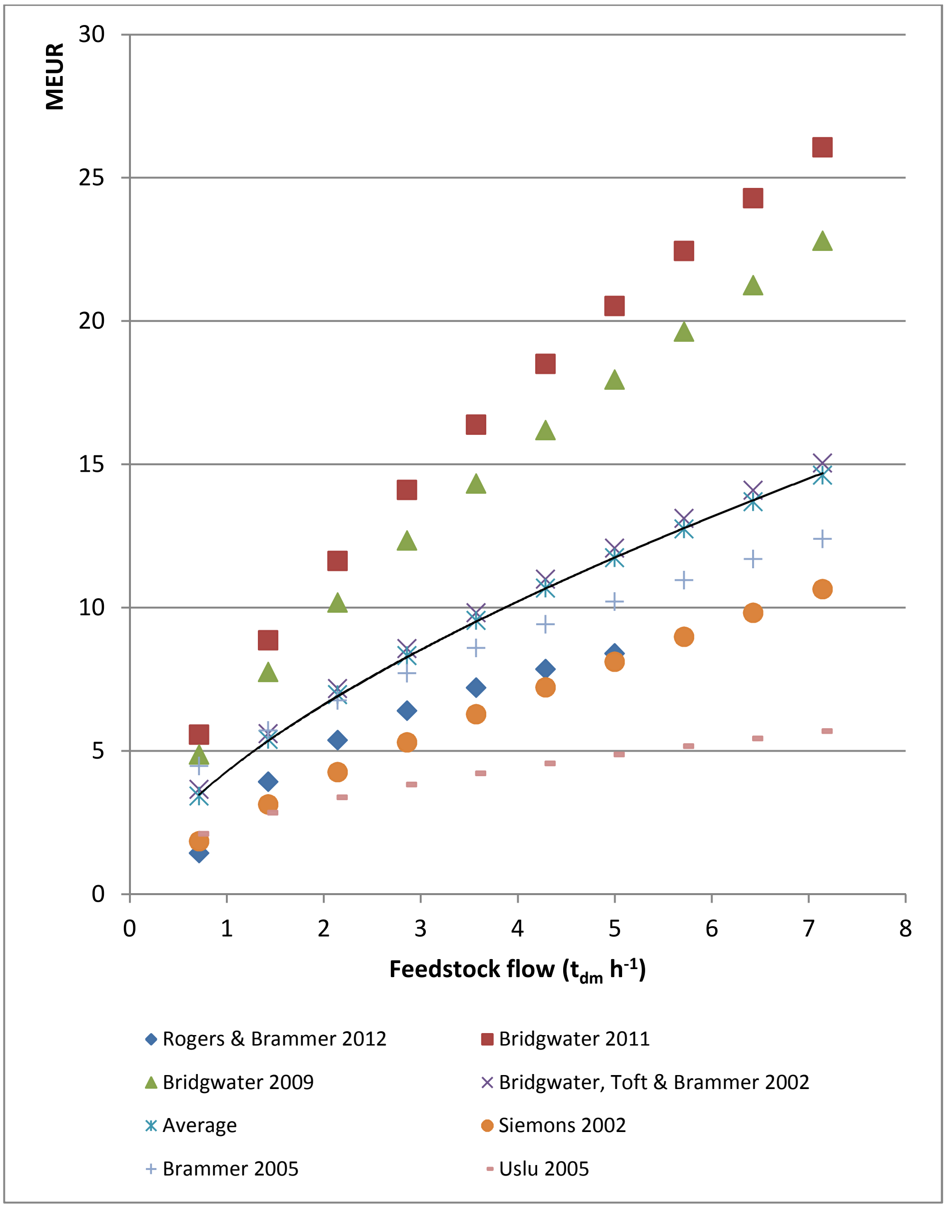

figure 11: Estimated capital cost for a fast pyrolysis plant in the Belgian Campine based on a literature review of capital cost equations

d) Point estimates of total plant costs of fast pyrolysis plants

Next to capital cost equations, a lot of point estimates have been found in several sources. In the next section, these point estimates have been inventoried and updated to 2011 values by multiplication of the Chemical Engineering Plant Cost Index. Some sources mentioned capital costs in other currencies than the EUR: it is assumed that the equipment is produced and thus should be bought in the country where this currency is used. The correct method is then to first update the plant cost with the CEPCI in its own currency, and next to apply the most recent exchange rate (in our case 2011) (Rogers 2012b). The time of application of the exchange rate is important because the exchange rates vary in time.

Another problem is that not all estimates are expressed in the same unit when it comes to scale of operation. Most of the sources mention the scale of operation in terms of processed amounts of biomass per hour. Some sources mention the processed amount of biomass on a daily or annual basis or in terms of energy output of oil (as a thermal capacity in MW_{th}). These amounts can be converted in terms of hourly biomass input flows by applying equation 4.10.

In table 16 all the point estimates that have been used are summed up. The cost estimates have been selected based on the fluid bed technology as this is the most cited technology that is believed the first to become commercially available. Some references differentiate between bubbling and circulating fluid bed. References that refer to other, very special technologies such as vacuum pyrolysis, ablative pyrolysis or BTG's rotating cone technology have not been taken into account. Other references however did not explicitly mention the technology for which the capital cost estimate has been made, but because they are most often based on generic accepted literature on fast pyrolysis we assumed that they probably represent a capital cost for the fluid bed technology. Because the information about the specific technology was often vague or not present, we were not able to take account of technology as a parameter in developing a cost equation.

From the table one can learn that the expected maximal processing capacity for a fast pyrolysis plant of biomass is about 45 t_{dm} h^{-1} or 315 000 t_{dm} of biomass annually. 36 of the 53 point estimates, or 68 % refer to scales of operation smaller than 10 t_{dm} h^{-1}. Half of the citations, more specifically 49 % of the cited references refer to plant scales up to 5 t_{dm} h^{-1}. One can clearly see that there is an upward trend in capital cost as plant scale increases, although great differences for the same scale of operation appear to be present.

The data in table 16 have been visually presented in figure 12. The trendline clearly shows the non-linear upward trend, representing economies of scale (as is illustrated by the exponent of 0,77). In figure 13, only the point estimates corresponding to scales of operation in the Belgian Campine have been selected. One can see clearly the big differences between point estimates for the same scales of operation. The trendline without the larger scales however has more or less the same characteristics. The trendline corresponding to the 36 data points relevant for the Belgian Campine equals:

$$TPC_{Py}^{Kup12b} = 2\,697\,334 \times \left(\Phi_{py}^{h}\right)^{0,7799} \tag{4.15}$$

We can now compare this equation with equation 4.14. The constant of the equation, i.e. the cost of a fast pyrolysis plant that converts 1 t_{dm} h^{-1}, is significantly lower, whereas the exponent is higher. The lower constant might be clarified by the fact that some of the point estimates correspond to quotations obtained from suppliers of pyrolysis plants. These quotations might not represent total plant costs, but rather a factored equipment cost that does not take into account all direct and indirect costs involved in constructing a fast pyrolysis plant. Another explanation is that there is a difference between costs when the investor himself can build the pyrolysis plant or when the investor has to buy the equipment from a supplier.

Reference	Scale Φ^{h}_{py} (t_{dm} h^{-1})	TPC (MEUR 2011)
Islam and Ani (2000)	0,0003	2,15 x 10^{-3}
Islam and Ani (2000)	0,10	69,94 x 10^{-3}
Uslu (2005)	0,20	0,98
Peacocke, Bridgwater et al. (2006)	0,25	3,20
Peacocke, Bridgwater et al. (2006)	0,50	3,70
Peacocke, Bridgwater et al. (2006)	1,00	4,44
Islam and Ani (2000)	1,00	0,28
Uslu (2005)	1,04	1,87
Peacocke, Bridgwater et al. (2006)	2,00	6,16
Rogers (2009)	2,00	6,43
Rogers (2009)	2,00	6,81
Uslu (2005)	2,00	3,34
Siemons (2005)	2,00	2,16
Ringer, Putsche et al. (2006)	2,29	7,70
Rogers (2009)	2,50	8,48
Rogers (2009)	2,50	7,68
Solantausta (s.d.)	2,96	11,01
Van de Velden, Baeyens et al. (2008)	3,40	5,37
Solantausta (s.d.)	3,52	15,45
Uslu (2005)	4,00	5,98
Zeevalking and van Ree (2000)	4,24	9,87
Ringer, Putsche et al. (2006)	4,58	10,26
Peacocke, Bridgwater et al. (2006)	5,00	9,12
Rogers (2009)	5,00	11,30
Rogers (2009)	5,00	12,06
van Stijn (2009)	5,00	9,00
Solantausta (s.d.)	5,93	15,34
van Stijn (2009)	6,00	5,08
Westerhout, Van Koningsbruggen et al. (1998)	6,25	11,05
Westerhout, Van Koningsbruggen et	6,25	13,98

al. (1998)		
Westerhout, Van Koningsbruggen et al. (1998)	6,25	9,77
Peacocke, Bridgwater et al. (2006)	6,77	11,09
Uslu (2005)	7,50	10,58
Magalhães, Petrovic et al. (2009)	8,33	8,91
Sorenson (2010)	8,33	15,87
Ringer, Putsche et al. (2006)	9,17	16,33
Peacocke, Bridgwater et al. (2006)	10,00	12,82
Rogers (2009)	10,00	18,37
Rogers (2009)	10,00	16,21
Uslu (2005)	10,00	8,88
Ringer, Putsche et al. (2006)	10,42	10,36
Solantausta (s.d.)	12,02	16,10
Solantausta (s.d.)	13,59	20,86
Solantausta (s.d.)	14,50	27,52
Solantausta (s.d.)	15,67	25,79
Solantausta (s.d.)	17,07	31,13
Solantausta (s.d.)	18,15	44,95
Solantausta (s.d.)	19,55	47,57
Ringer, Putsche et al. (2006)	22,92	35,72
Solantausta (s.d.)	40,89	52,97
Ringer, Putsche et al. (2006)	41,06	34,03
Ringer, Putsche et al. (2006)	41,67	27,37
Solantausta (s.d.)	44,73	30,12

table 16: Literature review of point estimates for the capital cost of a fast pyrolysis plant

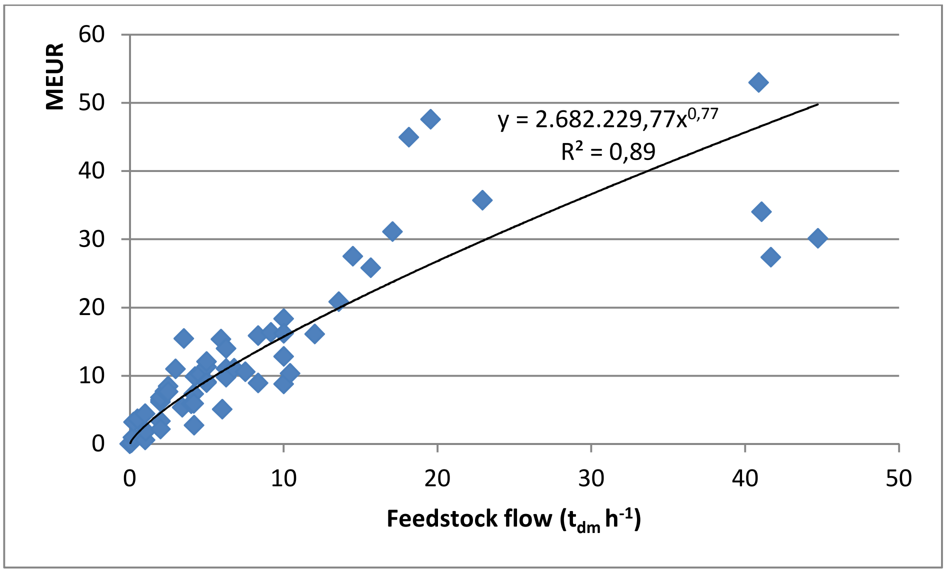

figure 12: Literature review of point estimates for capital cost estimates of fast pyrolysis plants

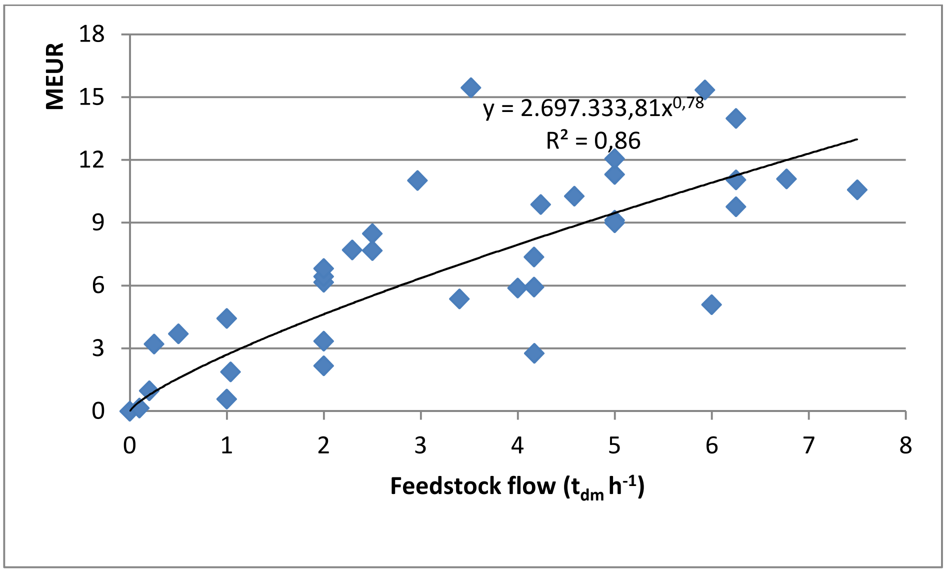

figure 13: Point estimates of capital costs of a fast pyrolysis plant with a scale of operation relevant for the Belgian Campine

In table 17 one can see that equations 4.14 and 4.15 yield a greater difference in estimates for small scales than for larger scales. This can be seen from the last column where the deviation of equation 4.14 and 4.15 from its average has been calculated. The percentage deviation from the average becomes smaller when scale increases, although the absolute difference in terms of MEUR is more or less constant (or even slightly increases with increasing scale). When one wants to apply uncertainty on the capital cost in terms of percentages (e.g. by means of a dummy variable with which the investment cost is multiplied), it is advised to apply higher percentages (up to 25 %) at smaller scales and smaller percentages for higher scales (up to 10 %).

Annual feedstock	Hourly feedstock	Max (4.14)	Min (4.15)	Avg	Deviation
5000	0,7	3,47	2,07	2,77	25%
7000	1,0	4,29	2,70	3,49	23%
10000	1,4	5,36	3,56	4,46	20%
14000	2,0	6,62	4,63	5,62	18%
20000	2,9	8,27	6,12	7,20	15%
21000	3,0	8,53	6,35	7,44	15%
28000	4,0	10,22	7,95	9,08	12%
29000	4,1	10,44	8,17	9,13	12%
30000	4,3	10,67	8,39	9,53	12%
35000	5,0	11,75	9,46	10,61	11%
42000	6,0	13,17	10,91	12,04	9%
49000	7,0	14,51	12,30	13,41	8%
50000	7,1	14,69	12,50	13,60	8%

table 17: Maximum, base case and minimum capital cost estimates for a fast pyrolysis plant in the Belgian Campine

Finally, the average capital cost has been plotted in function of the hourly feedstock flow and the corresponding trendline is represented in equation 4.16. This average corresponds the best to the estimates calculated with the equation of Rogers and Brammer (2012a).

$$TPC_{Py}^{Kup12c} = 3\,486\,567 \times \left(\Phi_{py}^{h}\right)^{0{,}6914} \quad (4.16)$$

4.3 Fast pyrolysis for CHP

4.3.1 Initial investment (I_0)

The initial investment for energy conversion consists of two large parts: investment in the pyrolysis process (including a buffer storage unit for the pyrolysis oil) and investment in an internal combustion engine for combined heat and power (CHP) production (including connection to the network).

$$I_0 = I_{py} + I_{CHP} \quad (4.17)$$

The initial investment I_0 is, thus, the sum of the total investment for the pyrolysis plant and the total investment for the combustion engine. On the basis of paragraph 4.2 "Meta-analysis of capital investments in pyrolysis", equation 4.16 (which is repeated below) has been applied for calculating the cost of the pyrolysis reactor and the storage unit for pyrolysis oil as a function of hourly feedstock input (Φ^{h}_{py}):

$$I_{py} = TPC_{Kup12c} = 3\,486\,567 \times \left(\Phi_{py}^{h}\right)^{0{,}6914} \quad (4.18)$$

The mass flow of dried willow feedstock (in t_{dm} h^{-1}) is represented by Φ_{py}^{h}. I_{py} thus represents the "total plant cost" in EUR of the fast pyrolysis reactor, the feeding system, and liquids recovery. It includes the costs of basic equipment, buildings, design, erection, piping, etc. It also includes the buffer needed to store pyrolysis oil so that heat and electricity production are still possible when the pyrolysis reactor unexpectedly shuts down.

The total capital cost of a combined heat and power plant consists of the cost of the internal combustion engine and the $DeNO_x$ for emissions control. The investment cost of CHP installations usually is expressed as a "specific investment cost" (p_{CHP}) per kilowatt (electric) or megawatt, which is then multiplied with its electrical power (P_e) or, thus, the number of kilowatts (electric) or megawatts the CHP can produce at maximum. Thus, I_{CHP} equals (Stroobandt 2007):

$$I_{CHP} = p_{CHP} \times P_e + I_{DeNOx} \tag{4.19}$$

As economies of scale play an important role in the magnitude of this specific investment cost, p_{CHP} is also a function of electrical capacity (P_e). According to Stroobandt (2007) the specific investment cost expressed in EUR kW^{-1} equals:

$$p_{CHP} = [991{,}53 - 93{,}709 \times \ln(P_e)] \times 2 \tag{4.20}$$

According to Stroobandt (2007) the investment cost of a $DeNO_x$ installation for a CHP engine on bio-oil of 1 500 kW_e equals 110 000 EUR. Stroobandt (2007) states that the investment cost of the $DeNO_x$ of a CHP engine with another electric capacity can be calculated with:

$$I_{DeNOx} = \frac{110\ 000}{1\ 500} \times P_e \times 1{,}05 \tag{4.21}$$

Filling in equations 4.20 and 4.21 in equation 4.19 yields:

$$I_{CHP} = [991{,}53 - 93{,}709 \times \ln(P_e)] \times 2 \times P_e + \frac{110\ 000}{1\ 500} \times P_e \times 1{,}05 \tag{4.22}$$

Or:

$$I_{CHP} = P_e \times \left[\left(991{,}53 - 93{,}709 \times \ln(P_e) \right) \times 2 + \frac{110\ 000}{1\ 500} \times 1{,}05 \right] \qquad (4.23)$$

The electrical capacity of the CHP engine (P_e) can also be written in function of Φ^h_{py} and the lower heating value of 1 ton of pyrolysis oil (LHV_{oil}) in GJ t^{-1}:

$$P_e = \frac{\eta_e^{CHP} \times LHV_{oil} \times \eta_{oil}^{py} \times \Phi_{py}^h}{3\ 600\ 000} \qquad (4.24)$$

By substituting equation 4.24 in equation 4.23 and adding it to equation 4.18 the total initial investment in a fast pyrolysis plant for the production of combined heat and electricity production can be totally expressed in function of Φ_{py}^h. Thus, the total investment depends on the amount of willow that will be converted into pyrolysis oil. The CHP engine is expected to be operational only during 5 000 hours per year (or more or less 60 % of the time) due to required maintenance time.

4.3.2 Expenditure (E)

Expenditure consists of yearly interest payments (assuming the investment is financed by means of a loan) and operational costs, which can be fixed or variable. Fixed costs cover costs for maintenance and overheads. Variable costs depend on the level of production or the amount of processed biomass. Variable costs that have to be faced are costs for biomass purchase, transport of the biomass to the central pyrolysis reactor, pre-treatment costs for drying and shredding, and labour. The interest payments have not been included in the cash flows: they are accounted for in the discount rate. This implies that when the NPV of the cash flows is greater than zero, that the investment is profitable even after interest payments. The resulting NPV then is the amount of money that the investor holds after interest payments.

a) Fixed operational costs

Fixed annual operational costs represent overheads, maintenance (labour and materials), insurance, etc., generally expressed as a percentage of the initial investment (Wright, Satrio et al. 2010). For the fast pyrolysis reactor, these fixed operational costs are included separately in the yearly outgoing cash flow as a percentage of the total plant cost. For the combined heat and power engine, this kind of costs has not been separately included, but has been accounted for in the "maintenance and operational" costs.

Excluding maintenance labour, Islam and Ani (2000) count 8 % for fixed operational costs. Bridgwater, Toft et al. (2002) count plant maintenance costs at 2,5 % of the total plant cost and plant overhead costs at 2,0 % of the total plant cost, or thus a total of 4,5 % fixed operational costs. Peacocke, Bridgwater et al. (2006) set a "typical value" of 4 % of the total plant cost per annum for both maintenance and overheads (or 8 % in total). Magalhães, Petrovic et al. (2009) expect a maintenance cost of 3 % of total capital investment and an insurance cost of 1 % of annual depreciation or 0,05 % of the total capital cost assuming linear depreciation over the 20 year lifetime of the pyrolysis plant. In Wright, Satrio et al. (2010) annual maintenance materials are 2 % of the total installed equipment cost. For general overhead they apply a factor of 60 % to the total salaries which corresponds more or less to 2 % of our estimate of the total capital cost of a fast pyrolysis plant. Insurance and taxes are considered as 1,5 % of the total installed equipment cost. Wright, Satrio et al. (2010) thus count more or less 5,5 % of total capital investment for fixed operational costs. Some sources do not separately mention insurance costs, but include them in the overheads. Here, the maintenance costs for the fast pyrolysis reactor are set at 3 % and overhead (including insurance) costs are set at 2 % of the total plant cost. Total fixed operational costs thus amount 5 % of the total plant cost, with a minimum of 3 % and a maximum of 8 %.

b) *Biomass purchase*

According to Koppejan and de Boer-Meulman (2005) the price for energy coppice might be as high as 80 EUR t_{dm}^{-1}. Bridgwater, Toft et al. (2002) mention an average cost of 70 EUR t_{dm}^{-1} in Europe. Prins (1998) expects a breakeven price for biomass feedstock to be 45 EUR t_{dm}^{-1} (without subsidies). Siemons (2005) expects a cost of 35 EUR t_{dm}^{-1} for biomass with a moisture content of 5 %. However, negative prices may be claimed for the treatment of contaminated willow. van Stijn (2007), the owner of a pyrolysis factory in the Belgian municipality of Tessenderlo, wants to convert biomass only if it is delivered for free. For the treatment of municipality waste, he will even *receive* 40 EUR t^{-1}. Here the cost for biomass purchase has been based on the cultivation and harvest costs in the Belgian Campine (see paragraph 5.2.1), i.e. 50 EUR t_{dm}^{-1}.

c) *Pre-treatment costs*

A high water content in pyrolysis oil causes aging during storage of the liquid before it is transformed into electricity and/or heat. To avoid aging of the pyrolysis oil, the oil should be used within the first year after production (Bridgwater, Toft et al. 2002; Cornelissen 2005). However, some moisture is needed in order to lower viscosity (Bridgwater, Toft et al. 2002). According to Bridgwater, Toft et al. (2002) a “7% moisture content is preferred” for the biomass feedstock (on a wet basis). Staged condensation is an alternative to control the water content in the pyrolysis oil, especially in a biorefinery where the production of high value chemicals is pursued (of which the techno-economics are beyond the scope of this dissertation). Particle size should be in the range of 2 to 5 mm in order to avoid secondary reactions of the pyrolysis vapours (before condensation) with the formed char (Bridgwater, Toft et al. 2002). Koppejan and de Boer-Meulman (2005) state that cutting the willow in small particles costs 10 EUR per fresh ton of willow. Energy use for the drying process has been reported in paragraph 3.3.4.

d) Staffing costs

First of all, we need to know how much manpower (L) is needed to operate both the pyrolysis and CHP plant. Bridgwater, Toft et al. (2002) calculate the labour requirements per shift for the pyrolysis unit and power unit seperately, add them together and multiply their manning with four (four shifts in rotation). This method however ignores the fact that labour is also required for plant management and administration, and that health and safety restrictions do not allow single man operation (Thornley, Rogers et al. 2008). The latter calculated the potential for job creation based on several bioenergy systems, by summing direct staffing for plant operation and management, staffing for agricultural activities and staffing for transporting the biomass for several thermal conversion technologies and scales. Process plants with an electrical output of 5 MW_e require 11 full time equivalents of staff (regardless of power production only or combined heat and power production), where plants with an electrical output of 2 MW_e require at least 3 full time equivalents of staffing level. These staffing levels have been adopted by linear extrapolation and rounding the number of employees for levels between 2 and 5 MW_e. This staffing level however includes staff for the CHP plant, while the labour cost of the CHP unit is incorporated in the "maintenance and operational cost of the CHP engine" (see further). In order to avoid double counting of labour costs, we deduced 40 % of the total staff (based on Bridgwater, Toft et al. (2002) total staffing of a fast pyrolysis plant consists for 60 % of staff for operating the reactor, whereas 40 % is dedicated to the engine).

Once the staffing level is known, it can be multiplied by the cost of one employee. The most recent quadrennial labour cost survey of 2008 contains the monthly wages of one person employed in the industrial sector in

Belgium: the labour cost of one full time equivalent was 4 479 EUR per month or 53 784 EUR annually (FOD Economie 2008). In 2011 terms, this annual labour cost can be updated by using the index of the conventional wages per sector. For NACEBEL sector E, i.e. production and distribution of electricity, gas and water, the index was 127,38 at the end of 2008 and increased to 134,00 at the end of 2012 implying an increase gross wages with 5,20 % (FOD WASO 2012). Therefore the wages are expected to be around 56 500 EUR yr^{-1} in the sector of bioenergy production.

e) <u>Transport costs</u>

Before short rotation willow can be pyrolysed, it should be transported to the pyrolysis plant. The transport costs for energy crops (miscanthus and willow) for use in pyrolysis plant networks have been studied by Rogers and Brammer (2009). Most of the studies into the economics of pyrolysis have used a simple distance rate based on commercial freight rates to analyse transport costs. Rogers and Brammer (2009) were the first to examine the cost structure for truck operations and concluded that the use of distance alone does not lead to accurate representation of the transport cost, because the trucks needed between biomass field stores and the pyrolysis plant will spend a considerable portion of their time being loaded and unloaded and travel on slower rural roads. They developed a method using transport zones while taking into account biomass availability. They found that the transport cost for willow is between 0,20 and 0,40 £ GJ^{-1} (or between 5 and 10 EUR t_{dm}^{-1}). In a recent study (Voets, Neven et al. 2012) (yet to be published) the economically optimal location for a fast pyrolysis plant in the Belgian Campine has been determined by means of a geographical information system (GIS). The study took into account the spatial distribution of the contaminated locations (instead of a uniform biomass distribution). Distances to three potential locations have been calculated using the existing road network. Voets et al. (2012) have built a transport cost model consisting of distance fixed and distance dependent transport costs assuming transport movements by means of a tractor-trailer. The study though did not consider loading as a transport operation because the use of a Claas harvester implies that willow is loaded into the tractor-trailer during the harvesting process. As this cost is already comprised in the cultivation and harvesting cost, only three remaining transport operations have been distinguished in the study: a loaded outward journey, unloading and an unloaded return trip. Of the identified locations, the Overpelt Fabriek site results in the lowest biomass transport distance and costs. The average transport cost according to this study is expected to be around 6,5 and 7,5 EUR t_{dm}^{-1}. Here transport costs are set at 7 EUR t_{dm}^{-1}.

f) *Landfill costs of char*

Almost all metals present in the phytoextracting biomass remain in the char during fast pyrolysis (Koppolu, Agblevor et al. 2003; Koppolu and Clements 2003; Koppolu, Prasas et al. 2004; Cornelissen 2009; Lievens, Carleer et al. 2009; Stals, Thijssen et al. 2009; Shackley and Sohi 2010). The metals thus are mainly concentrated in a smaller volume, or 15 m% of the original biomass. Because the char is contaminated with heavy metals, it is not attractive for incineration (Inguanzo, Domínguez et al. 2002). As it is not clear whether there exist useful, environmentally sound applications for the char due to the high concentration of heavy metals (it can certainly not be used as a soil amendment), it is assumed that the char can be disposed of by landfilling in accordance with the Materials Decree (Flemish Parliament 2012) of the Flemish Region and the Flemish regulation concerning sustainable management of material cycles and waste (Flemish Government 2012). It is not sure currently whether the char should be landfilled or combusted. In Flanders, there is a landfill ban on non-recyclable combustible municipal waste and waste that can be burnt because combustion yields useful energy (see art. 4.5.1 of the VLAREMA concerning landfill and incineration bans). Due to the environmental risks associated with the combustion of waste containing heavy metals, however, it is expected that it should be deposited in a category II landfill.

The amount that should be paid to waste processing companies is the sum of the processing fee and the environmental tax (Kuppens, Umans et al. 2011). In 2009 the landfill tariff was 41 EUR t^{-1} and the environmental tax was 79,36 EUR t^{-1}, so that the total landfill cost for industrial waste on a landfill of category II equalled more or less 122 EUR t^{-1} (Kuppens, Umans et al. 2011).

g) <u>Energy consumption</u>

The fast pyrolysis plant requires electricity, heat for drying the biomass and heat for setting the right process temperature. Energy consumption has been calculated in paragraph 3.3.4. Power requirements have been deducted from the gross power production by the combined heat and power engine, in order to obtain the net power production that can be sold to the electricity network afterwards.

Internal process energy requirement for rapidly heating the willow feedstock to temperatures between 400 and 500 °C can be met by combustion of the off-gas (pyrolysis gas) and the char (Toft 1996; Bridgwater, Toft et al. 2002; Voets, Kuppens et al. 2011). The latter however contains cadmium and cannot be used for internal energy provision. Combustion of the gas would yield only 18,0 TJ yr^{-1} whereas 47,5 TJ yr^{-1} is required. This energy requirement is subtracted from the heat sales, because it is assumed that oil will have to be combusted to provide this energy.

h) Water consumption

Cooling water is required for rapid quenching of the hot pyrolysis gases in the condensing heat exchangers, so that part of the gas can be condensed to form pyrolysis oil. Bridgwater (2002) calculated the average of the water consumption as suggested by Black (1986), Beckman and Graham (1993), Diebold (1993) and Cottam (1995). He found an average of 18,5 m³ cooling water per oven dry tonne (t_{dm}) of feedstock. Later, in 2009, Bridgwater stated that 20 m³ of cooling water is required per dry tonne of biomass processed. This cooling water however can be recycled. The make-up water (the loss of cooling water through evaporation that should be replenished) required however have negligible costs (Ringer, Putsche et al. 2006). Here water utilities consumed are based on a techno-economic evaluation of a bubbling fluidised bed pyrolysis unit for mixed plastic waste: 4 722 tonnes of water are yearly required for pyrolysis of 50 000 tonnes of waste per year, or thus make up water consumption equals 0,1 tonne of water per tonne of feedstock (Westerhout, Van Koningsbruggen et al. 1998). The price that is charged for cooling water is 1,5 EUR per tonne of water according to Bridgwater, Toft et al. (2002), whereas Peacocke, Bridgwater et al. (2006) state a water price of 1,25 EUR m^{-3} (which is also 1,25 EUR t^{-1} because the mass of 1 m³ is 1 000 kg or 1 t). The latter was taken from the tariff of a water utility in the United Kingdom. Because we think that cooling water does not require the purity of drinking water, and that instead industrial waste water (effluent) can be used, we contacted Aquafin NV to obtain the cost price for effluent. Weemaes (2011), research coordinator at Aquafin NV, states that the cost of effluent is roughly 40 times lower (0,04 EUR m^{-3} if a water utility would charge a price of 1,50 EUR m^{-3}), but that the price depends of several factors and that one should also account for costs of water treatment (e.g. disinfection) which varies from application to application. For precautionary reasons, we assumed a water price of 0,77 EUR m^{-3} in the base case, which is right in the middle of the interval 0,04 and 1,50 EUR m^{-3}.

i) Maintenance and operational costs of the CHP engine

The maintenance and operational costs of the CHP engine have been modeled by Stroobandt (2007). They consist of the maintenance and operational costs of the engine itself and the maintenance and operational cost of the urea gas treatment. Urea is used as a selective catalyst for the conversion of nitric oxides emitted during combustion of bio-oil and diesel into nitrogen and water. Both costs are expressed in EUR MWh^{-1} and are a function of the electric capacity in kW_e:

$$C_{CHP} = 65{,}347 \times P_e^{-0{,}1544} \times 0{,}9 \tag{4.25}$$

$$C_{urea} = 26{,}209 \times P_e^{-0{,}1112} \tag{4.26}$$

4.3.3 Revenues (R)

The CHP engine produces electricity and heat. It would be nice if the produced heat and electricity could be used to foresee the electricity and heat demand of agricultural farms in the Campine area; however, this is impossible since CHP production takes place centrally and heat cannot be transported. It is indeed true that electricity can be transported, but this would mean we have to invest in an independent electricity grid from the central CHP engine to the farmers spread in the contaminated area. Therefore, we consider electricity and heat savings or sales that are possible on-site by the investing company. Heat might be delivered to neighbouring industrial companies. To make production of energy profitable, it is important the produced heat can be sold to a local community and/or large industrial consumer in the neighbourhood.

a) Savings and sales of electricity and heat

There are two options for marketing your electricity output: you either have to deliver it to the distribution network (the transmission network is for large scale power production only) or you can sell your electricity to a neighbouring facility by installing a direct line. Article 4.5.1 of the Energy Decree (Flemish Parliament 2012) states that installing a direct line is allowed on one's own site and when one wants to install a direct line outside the own site, approval of the Flemish regulator VREG is required. VREG has published 5 anonimised decisions on its website. Of these 5 decisions, 3 requests have been refused, 1 has been approved and 1 decision does not proceed to approval by VREG because it concerned a request for a direct line on one's own site for which the Energy Decree states that this is allowed without explicit approval by VREG. One of these decisions refused the installation of a direct line between two adjacent parcels because of inefficient use of the existing distribution network, and a negative impact on the tariffs for other users of the existing network. Another refusal concerned the installation of a direct line along a canal between a wind turbine and one consumer because of safety reasons and inefficient use of the existing network. The third refusal concerned the installation of a direct line between a photovoltaic solar installation and a consumer for which the line should cross the public domain which raised safety issues. One advice though concerned the installation of a biomass plant in the Northern Campine by means of a direct line to a customer on an adjacent parcel. The direct line has been approved because it concerned the installation of a direct line to an adjacent parcel, in a region (the Northern Campine) which has a congested distribution network. For the sake of this congestion, the distribution network administrator IVEKA (who administers the distribution network in 46 municipalities in the province of Antwerp) has rejected a prior request for a connection to the network.

The price received for electricity put on the network is lower than the price for electricity sold to a neighbour. The price of electricity consists of (VREG 2010):

- the energy price (including the cost of green electricity and CHP);
- the network tariff (distribution and transmission network);
- the taxes imposed by government

The total electricity invoice for small professional customers with an average electricity consumption of 50 MWh was more or less 7 500 EUR in July 2010. The total average cost of electricity thus was 150 EUR MWh^{-1} of which 52 % represents the share of the energy price, 39 % represents the share of the cost of the distribution network with another 8 % for the costs of the transmission network and 1 % taxes. The energy price alone thus was on average 80 EUR MWh^{-1} (VREG 2010). However, a case study with respect to the deliverance to the network of electricity produced by a landfill gas engine in Belgium has been set at 57,14 EUR MWh_e^{-1} (Van Dael 2012).

It is important to note that electricity used locally has another value compared to the remaining electricity sold to an electricity supplier. When electricity can be used locally, it replaces the quantity of electric energy that normally is bought from an electricity supplier via the electricity grid. The avoided purchase cost than corresponds to the price of electricity sold from the grid, which includes network tariffs and taxes. When a surplus of electricity, i.e. the amount of electricity that cannot be used locally, is supplied to the electricity grid, it should be bought by an electricity supplier at a price which will be lower than the avoided purchase cost, because the producer of electricity than cannot count the costs for the transmission or distribution network (Stroobandt 2007). Here, the worst case scenario has been adopted and it has been assumed that electricity can be put on the grid for a price of 70 EUR MWh^{-1} (which is between 57 and 80 EUR MWh^{-1}).

The heat from the engine is expected to substitute heat from natural gas, so that the heat savings will only be worth more or less 20 EUR MWh^{-1} based on the lower calorific value of the gas (Fiala, Pellizzi et al. 1997; De Paepe and Mertens 2007; Stroobandt 2007; Nuon 2010).

Total electricity and heat energy production (E_e and E_{th} expressed in MWh_e and MWh_{th} respectively) can be calculated by applying the following equations:

$$E_e = P_e \times OH_{CHP} = \left(\frac{\eta_e^{CHP} \times LHV_{oil} \times \eta_{oil}^{py} \times \Phi_{py}^h}{3\ 600\ 000}\right) \times OH_{CHP} \quad (4.27)$$

$$E_{th} = P_{th} \times OH_{CHP} = \left(\frac{\eta_{th}^{CHP} \times LHV_{oil} \times \eta_{oil}^{py} \times \Phi_{py}^h}{3\ 600\ 000}\right) \times OH_{CHP} \quad (4.28)$$

with:
- E_e = electricity production (MWh_e)
- E_{th} = heat production (MWh_{th})
- P_e = electrical capacity (MW_e)
- P_{th} = thermal capacity (MW_{th})
- OH_{CHP} = number of operating hours per year of a CHP engine (5 000 h yr^{-1})
- $\eta^{CHP}{}_e$ = electric efficiency of the CHP engine
- $\eta^{CHP}{}_{th}$ = thermal efficiency of the CHP engine
- LHV_{oil} = lower heating value of the pyrolysis oil (17 GJ t^{-1})
- $\eta^{py}{}_{oil}$ = pyrolysis oil yield (65 m%)
- $\Phi^h{}_{py}$ = hourly processed feedstock in the pyrolysis plant (t_{dm} h^{-1})

They basically are the product of the electric or thermal capacity (P_e or P_{th} expressed in MW_e or MW_{th}) and the number of operating hours of the combustion engine (OH_{CHP}), i.e 5 000 hours which is quite low due to maintenance time. Both equations differ only with respect to the electric/thermal energy efficiency of the CHP engine.

b) <u>Subsidies</u>

There are two important categories of subsidies for which people can apply: subsidies that lower the investment capital and subsidies during exploitation. Possible investment subsidies are investment tax allowance and ecology premium. Exploitation support consists of green power certificates (GPC) and combined heat and power certificates (HPC).

Investment allowance

Companies that invest in energy saving or environmental friendly research and development can get a federal subsidy of the Belgian state on their investment capital in the form of a deduction of the company's profit, which diminishes due taxes. The amount of money that can be deducted is calculated as a percentage of the investment cost of fixed assets. The basic deduction is based on the consumer price index and lies between 3,5 % and 10,5 %. Investments made in the year 2011 can count on the minimum percentage of 3,5 %. Investors in innovative technologies with the aim of lowering environmental damage are entitled to receive an extra investment deduction of 10 %. The total investment deduction for our case study amounts up to 13,5 % (see art. 69 of the Law on the Income Tax).

Ecology premium

The ecology premium is a subsidy issued by the regional Flemish government for energy investments. Until 31st January 2011, all SMEs investing in technologies that appear on a limited list of technologies are qualified for a premium of 20 % of the extra cost of the investment compared to regular investments in energy. Large enterprises can recover 10 % of the additional cost. "Production of energy (CHP/electricity) by pyrolysis of biomass" is on the list and the presumed extra cost is set at

50 %. This means that SMEs (which we expect the pyrolysis investor to be) are eligible for a premium of 10 % on the total investment in the pyrolysis and CHP engine. However, in the old system, this premium was guaranteed and its height was set on 35 % for SMEs and 25 % for large companies. This system, however, was discontinued as of May 2007. Beginning in September 2007, a call system for which the budget is fixed was installed.

As from 1st February 2011 the conditions for the ecology premium have changed again. The ecology premium now has been called the "Ecology Premium Plus" and is only intended for investments that do not qualify for green power certificates or combined heat and power certificates. Because the investment in the Campine will probably qualify for receiving GPC and HPC, we do not take into account the possibility of receiving an ecology premium. Besides, the premium is subject to so many changes and the pyrolysis plant in Tessenderlo also did not receive an ecology premium from the Flemish Government.

Green power certificates

The Flemish Government encourages the production of electricity from renewable energy sources by means of the system of green power certificates, which for existing installations consists of two parts:

- On the one hand, producers of electricity receive a green power certificate for every megawatt hour or 1 000 kWh of electricity produced on the basis of solar energy, wind energy, water power, or even organic biomass from the Flemish Regulation Entity for the Electricity and Gas market (VREG);
- Suppliers of electricity on the other hand are bound to deliver each year a certain amount of green power certificates that they have earned themselves or they can buy from other green current producers.

The producer of renewable electricity can sell the green power certificates on the bilateral certificate market (i.e. VREG's GPC database), the Green Certificate Exchange of BelPEx or at the minimal support price that the distribution network administrator is obliged to pay. Most of the certificates however, are sold by the bilateral certificate market. The most recent average market prices for a green power certificate were 103,30 EUR MWh^{-1} and 98,99 EUR MWh^{-1} in respectively March and February 2012. The minimal price at which a GPC can be sold fluctuates around 80 EUR MWh^{-1} and the highest price that can be obtained for one GPC is more or less 120 EUR MWh^{-1} (VREG 2012).

The existing system however has been criticised, especially due to the over subsidisation of solar energy. As a consequence of the success of the green power certificates, the supply of green power certificates was higher than the demand so that investors in renewable energy risked that they could not sell their certificates. Therefore the Flemish Government announced in May 2012 to drastically alter the existing system, based on the following principles:

- increase the production of green power in Flanders;
- eliminate over subsidisation;
- stabilisation of the market value of a green power certificate;
- redistribution of the costs of green power between all users.

These principles have been fixed in the Decree of 13th July 2012 concerning the alteration of the Energy Decree of 8th May 2009 with regard to environment friendly energy production (i.e. art. 7.1.1 and next of the Energy Decree). As from January 2013 every technology will receive the support it requires to be profitable, and only that. An observatory will be installed within the Flemish Energy Agency (VEA) for continuously monitoring the ever changing conditions in the renewable energy market. One certificate will no longer correspond to the production of 1 MWh_e but will depend on the required support to render the plant profitable. Besides, the support will be limited in time: when current installations receive support as long as it is operational, the support will be limited to the depreciation period of the plant (i.e. 10 or 15 years depending on the technology) (Govaert 2012).

The number of green power certificates thus will be awarded in function of the profitability of a green power plant. For this purpose the observatory will calculate the "unprofitable top" for every technology which is a function of the depreciation period, the electricity price, the fuel costs, and the scale of the project (amongst others). The unprofitable top determines the *banding factors* that will be applied. The banding factor determines the amount of green power certificates that a production plant will receive per MWh_e of green power it produces. For instance, suppose that in the new system one green power certificate will have a market value of 97 EUR. When a green power producer requires 97 EUR MWh_e^{-1} to be profitable, i.e. the unprofitable top is 97 EUR MWh_e^{-1}, the producer will be awarded 1 green power certificate per MWh_e. However, when the technology is more profitable and requires only 48,5 EUR MWh_e^{-1}, the producer will receive only half a certificate per MWh_e, i.e. the banding factor equals 0,5. When the electricity price changes and the plant becomes even more profitable, the amount of awarded green power certificates will be adjusted so that the plant renders just profitable again. The banding factor can never be higher than 1,25 and the minimum support for one green power certificate will be at least 93 EUR.

The methodological framework for calculating the unprofitable top and banding factors has been added as an annex to the Decision of the Flemish Government amending the Energy decision of 19th November 2010, with regard to the green power certificates, the heat and power certificates and the guarantees of origin. The unprofitable top is defined as the amount of support required to set the net present value of the operational cash flows to zero. This is to some extent comparable with the discounted cash flow model that has been developed here, but there are a lot of differing assumptions. For instance, it is not stated which depreciation period will be applied for biomass, and whether a time limit will be applied in practice because it is adviced by VREG that implementing a time limit for support is not desirable for technologies with high operational costs such as biomass installations (VREG s.d.). Besides stakeholders reported that the presented system will not promote a healthy mix of technologies, but instead will they expect it will result in a one-sided technology choice. Another discussion is about the applied discount rate. In our case study a discount rate of 9 % has been applied because it is a standard value for a private discount rate for enterprises (Ochelen and Putzeijs 2008), though the proposed discount rate for category 4 (combustion of solid biomass, cf. infra) equals 8 % and the discount rate of category 5 (combustion of fluid biomass, cf. infra) equals 12 %. Most of the other assumptions have not been fixed yet (such as the expected increase in the electricity price, interest rates, etc.), and only the method has been referred to in the decision.

In the same decision, art. 6.2/1.1 states that the Flemish Energy Agency (VEA) calculates the unprofitable top and banding factors based on the most cost efficient and performing reference installations for several representative project categories:

1. solar energy;
2. wind energy on land;
3. biogas installations (digestion technology);
4. installations for the incineration of solid biomass;
5. installations for the incineration of fluid biomass;
6. installations for the incineration of biomass waste;
7. installations for the incineration of municipal household waste or industrial waste

For solar energy, unprofitable tops will be calculated for installations with a maximal alternating current capacity of 750 kW, for wind energy unprofitable tops will be calculated for capacities up to 4 MW_e per turbine, whereas the unprofitable top and banding factors for the other installations will be based on a maximal power capacity of 20 MW_e. One can clearly see that (fast) pyrolysis and gasification do not appear in the list of representative categories, though they produce green power. One might think that combustion of the pyrolysis oil in a diesel engine can be categorised under the incineration of fluid biomass, but what about gasification? When the combustion of oil is categorised in category 5 with a depreciation period of 10 years, this might even be advantageous for fast pyrolysis compared to combustion and gasification, because it is assumed that the engine should be replaced every 10 years, so that a new request can be made to VREG after the first 10 years.

Given the uncertainties, it is not possible at this moment to calculate the impact of the new system on the profitability of the fast pyrolysis plant. Besides the observatory will publish its banding factors the earliest in December 2012 after which they should be approved by the Flemish Government. The Flemish Energy Agency even announced on its website (www.energiesparen.be) that for technologies that are currently not applied on a commercial scale (e.g. fast pyrolysis and gasification) the calculations for the unprofitable top and banding factors will be postponed until April 2013. The old system has still been applied, and at the end of this chapter the required minimal support for fast pyrolysis under applicable assumptions has been discussed.

Combined heat and power certificates

A comparable system exists for combined heat and power. It will also be changed from January 2013 based on the main principles as for the green power certificates. Because of the uncertainties and the publication date of the banding factors by VEA, it is not possible to calculate the impact of the new certificate system. Therefore calculations are based on the current system. Currently, one combined heat and power certificate is awarded by VREG for every MWh of primary energy savings produced by a *qualitative* combined heat and power installation. A CHP engine is qualitative if the relative primary energy saving (RPES) is at least 10 % as defined by the European Directive 2004/8/EG concerning combined heat and power production. The RPES has been defined as:

$$RPES = \left(1 - \frac{1}{\frac{\eta_{th}}{\alpha_{th}} + \frac{\eta_e}{\alpha_e}}\right) \times 100\% \tag{4.29}$$

with: η_{th} = thermal efficiency of the combined heat and power engine;
η_e = electric efficiency of the combined heat and power engine;
α_{th} = reference efficiency of separate heat production;
α_e = reference efficiency of separate electricity production.

The reference efficiencies have been determined on a European level. When oil is used as a fuel, the European reference efficiency for electricity production equals 44,2 % when the plant is constructed between 2006 and 2011. The thermal reference efficiency equals 89 % (COGEN Vlaanderen 2006). The amount of primary energy savings in MWh can be calculated by:

$$PES = E \times \left(\frac{1}{\alpha_e} + \frac{\eta_{th}}{\eta_e \alpha_{th}} - \frac{1}{\eta_e}\right) \tag{4.30}$$

with E the amount of produced electricity by the combined heat and power engine. During the first four years of operation, one can hand in all certificates for sale. As from month 49 or the fifth year, only a fraction X of the certificates is accepted. This fraction X depends on RPES, so that combined heat and power installations that save relatively much fuel, can benefit from the combined heat and power certificates. The fraction X equals:

$$X = \frac{RPES - 0{,}2 \times (T - 48)}{RPES} \tag{4.31}$$

with T the time in months after commissioning of the CHP engine. The price of one combined heat and power certificate equals more or less 35 EUR MWh^{-1} which is close to the minimal support of 31 EUR MWh^{-1} guaranteed by the government for installations commissioned after 1st January 2012. The highest price obtained for a HPC equals more or less 45 EUR MWh^{-1}.

Also in the system of the heat and power certificates, things will change, based on the same principles as the green power certificates. Heat and power certificates were already limited in time, but the degressivity of equation 4.31 will be abolished.

4.3.4 Base case results

In table 18 the base case assumptions as described in paragraphs 4.2 and 4.3 have been summarised.

Variable	Assumption
Farmland dedicated to phytoextraction	2 400 ha yr^{-1}
Willow yield	8 t_{dm} ha^{-1} yr^{-1}
Oil yield	65 m%
LHV pyrolysis oil	17 GJ t^{-1}
Pyrolysis investment constant	3 486 567
Pyrolysis investment exponent	0,6914
Pyrolysis operational hours	7 000 h yr^{-1}
Fixed operational cost	5 % of total plant cost
Dummy uncertainty CHP maintenance	1
Purchase price of willow	50 EUR t_{dm}^{-1}
Purchase price of water	0,77 EUR m^{-3}
Annual wage of 1 employee	56 500 EUR yr^{-1}
Landfill cost of char	122 EUR t^{-1}
Sales price GPC	100 EUR MWh_e^{-1}
Sales price HPC	35 EUR MWh_{pes}^{-1}
Sales price electricity	70 EUR MWh_e^{-1}
Sales price heat	20 EUR MWh_{th}^{-1}

table 18: Base case assumption fast pyrolysis of willow for combined heat and power

The share of the different expenditure and revenue items in relation to the discounted total revenues over the 20 years life time of the pyrolysis reactor have been represented in table 19.

Cash flow	Discounted sum (EUR)	%
	Revenues	
Investment allowance	628 160	1
Electricity sales	17 015 267	34
Heat sales	1 960 238	4
GPC	23 132 952	46
HPC	7 553 849	15
Total revenues	**50 290 466**	**100**
	Expenditure	
Investment	12 280 737	24
Fixed costs pyrolysis	3 197 005	6
Biomass purchase	8 763 404	17
Biomass transport	1 226 877	2
Biomass grinding	1 752 681	3
Labour	2 578 814	5
By-product disposal	2 645 789	5
Water consumption	13 496	0
Operational cost CHP	8 139 902	16
Pilot fuel	8 139 902	7
Total expenditure	**43 987 951**	**87**
CF before tax	6 302 516	13
CF after tax (= NPV)	**3 040 410**	**6**

table 19: Share of expenditure and revenue items in total discounted revenues, fast pyrolysis CHP base case

The last row of table 19 shows that the base case would yield a NPV of the cash flows of 3,04 MEUR at a discount rate of 9 %, which corresponds to an internal rate of return of the investment of 13 %. This result is only valid given the assumption of 100 % certainty about the values of the base case variables. The sales of the green power certificates make up the largest part (46 %) of the revenues. Together with the combined heat and power certificates and the investment allowance, all forms of subsidies (exploitation and investment subsidies) constitute 62 % of all revenues. This is a large amount, but it is not uncommon for renewable energy projects (cf. income statements of Belwind that indicate that one third of the revenues from wind turbines stems from sales of the produced electricity, whereas two thirds of the revenues stem from the sales of green power certificates). Though subsidies can be abolished or drastically changed. This dependence on green power certificates and heat and power certificates is not very promotional for the economic risk of an investment in renewable energy. If the subsidies for renewable energy and energy savings would be omitted, the investment would be very loss making with an NPV of -17,5 MEUR. In the final section of this chapter it will be indicated what the amount of green power certficates should be in order to render a fast pyrolysis plant profitable.

The greatest part of the expenditure goes to the investment (24 % compared to total revenues or 28 % of the total discounted costs), biomass purchase (17 % compared to total revenues or 20 % of total discounted expenditure) and the maintenance and operational costs of the CHP (16 % compared to total revenues or 19 % of total discounted expenditure). It is remarkable that biomass transport costs are only 2 % compared to total revenue or 3 % of total discounted expenditure. Biomass transport is often cited as one of the main problems in feasibility studies of bioenergy projects. Here the small share of transport costs is due to the phytoextraction aspect of the Campine biomass: on the one hand, the scale of operation is relatively small so that transport distances to the central pyrolysis plant are limited, on the other hand, the assumption that all contaminated area should be phytoextracted yields higher biomass concentrations in terms of agricultural land occupation compared to traditional short rotation coppice.

4.4 Fast pyrolysis for electricity production

Because we are not sure that the produced heat can be sold effectively, we focus from a precautionary perspective in the remainder of this chapter on electricity production. The profitability of fast pyrolysis for electricity production is investigated and compared to combustion and gasification of willow for electricity production. This means that we do not require the investment in a combined heat and power engine, but instead an investment in a diesel engine for electricity suffices. Besides, the income generated by heat sales and sales of the combined heat and power certificates will be lost. The changes that occur compared to combined heat and power production are explained below.

The investment cost of pyrolysis decreases because heat exchangers are no longer required to recover low-grade heat. The investment cost of the heat exchangers are expected to be 10 % of the investment costs of the internal combustion engine (Voets, Kuppens et al. 2011). Therefore the total capital investment of the CHP is decreased with 10 % in order to obtain an estimate for the investment expenditure for the internal combustion engine for electricity production only.

The operational costs for the pyrolysis reactor do not change and are the same as in the previous paragraph. The maintenance and operational costs of the CHP engine however should be replaced by the maintenance and operational costs that are relevant for power production only. The fixed operational costs are covered by the same percentage that is applied to the investment expenditure of the pyrolysis reactor. So here 5 % of the sum of the investment expenditure for the pyrolysis reactor and the diesel engine have been counted. The costs for biomass purchase, transport and pre-treatment do not change. The staffing cost however, should be adjusted for the labour requirement of the internal combustion engine. Where they were included in the maintenance and operational cost of the CHP engine, they should be added separately here. Again the staffing levels and costs have been based on a linear extrapolation of the figures in Thornley, Rogers et al.

(2008) but now without the 40 % deduction for avoiding double counting of staffing costs which was required in the CHP case.

It has been assumed that there is actually no difference between the electric efficiency of an internal combustion engine for electricity production only and for combined heat and power production. Calculation of the electric efficiency following Bridgwater, Toft et al. (2002)'s equation for a dual fuel engine for power production yields an efficiency of 42 %, which is comparable to the efficiency of 43 % of the CHP engine calculated following Stroobandt (2007). Revenues only consist of the sales of the net electricity production to the electricity network and the green power certificates. The base case economic results are presented in table 20. The important thing to note, is that the total discounted investment expenditure is slightly lower (only the internal combustion engine is 10 % cheaper), the total expenditure (investment and operational expenditure) is lowered with 3,5 MEUR, but due to the loss of heat sales and combined heat and power certificates, total revenues decrease with at least 8,9 MEUR making the NPV of the cash flows strongly negative (-1,1 MEUR). Therefore, it is really important to invest in combined heat and power production and to find potential heat consumers in the neighbourhood of the pyrolysis plant, although the latter is uncertain. Therefore, in the next paragraphs we investigate whether electricity production by willow combustion or gasification is an economic alternative.

Cash flow	Discounted sum (EUR)	%
Revenues		
Investment allowance	529 039	1
Electricity sales	16 303 210	39
GPC	24 526 872	61
Total revenues	**41 359 121**	**100**
Expenditure		
Investment	11 753 104	28
Fixed costs (total)	4 720 779	11
Biomass purchase	8 763 404	21
Biomass transport	1 226 877	3
Biomass grinding	1 752 681	4
Labour	6 189 154	15
By-product disposal	2 645 789	6
Water consumption	13 496	0
Pilot fuel	3 389 246	8
Total expenditure	**40 454 529**	**98**
CF before tax	4 720 779	11
CF after tax (= NPV)	**-1 074 639**	**-3**

table 20: Share of expenditure and revenue items in total discounted revenues, fast pyrolysis electricity base case

4.5 Combustion for electricity production

Fluid bed designs are the preferred technology for combustion. Power can be generated by a sequential steam turbine. The technological assumptions have been described in paragraph 3.4 of chapter 3.

4.5.1 Initial investment (I_0)

The estimation of the investment expenditure for *combustion* and *gasification* are based on Caputo, Palumbo et al. (2005). The "total capital investment" is expressed as the sum of all direct and indirect plant costs. Caputo et al. subdivided the total direct costs of a combustion or gasification plant into the costs of the main plant sections or the purchased equipment (power generation, biomass storage and handling and fumes treatment) and the costs of piping, the electric circuit and civil works. Those costs were estimated by summing the costs of the components of equipment for each plant section (e.g. the cost of power generation by combustion is the sum of the cost of the boiler, the steam turbine, the heat exchanger, etc.). The costs of these components were estimated by interpolating experimental and literature data resulting in correlations in function of the electric capacity of the respective component. The total equipment cost then is augmented with 87 % in order to cover for site preparation, engineering, start-up, etc. Finally Caputo et al. validated their estimations with actual plant costs in literature and found agreement between a +/- 20 % range. The capital cost has been updated with the CEPCI.

The equipment costs have been parameterised in function of the combustion plant's net electric power output P_{ne}, which is a function of the biomass flow rate Φ_{co}^{h}, the lower heating value of the short rotation coppice (LHV_{SRC}) and the electric efficiency of the combustor (η_e^{co}):

$$P_{ne} = \frac{\Phi_{co}^{h} \times \eta_{e}^{co} \times LHV_{SRC}}{3\,600\ \times OH} \tag{4.32}$$

Equipment	Cost (EUR)
Power generation	
Boiler	$1\,340\,000\ P_{ne}^{0,694}$
Steam turbine	$633\,000\ P_{ne}^{0.398}$
Condenser	$398\,000\ P_{ne}^{0.333}$
Heat exchanger (cooling water)	$51\,500\ P_{ne}^{0.5129}$
Alternator	$138\,300\ P_{ne}^{0.6107}$
Fans	$35\,300\ P_{ne}^{0.6107}$
Condensate extraction pumps	$9\,000\ P_{ne}^{0,4425}$
Feed pumps	$35\,000\ P_{ne}^{0,6107}$
Pumps	$28\,000\ P_{ne}^{0.5575}$
Biomass storage-handling	
Biomass storage	$114\,100\ P_{ne}^{0,5575}$
Biomass handling	$46\,600\ P_{ne}^{0,9554}$
Compressor and dryers	$11\,400\ P_{ne}^{0,5575}$
Emergency diesel	$36\,200\ P_{ne}^{0,1989}$
Fumes treatment	
NO_x and SO_x removal equipments	$126\,000\ P_{ne}^{0,5882}$
Fumes filtration	$66\,600\ P_{ne}^{0,7565}$
Ashes storage	$88\,300\ P_{ne}^{0,3139}$
Ashes extraction	$93\,500\ P_{ne}^{0,4425}$
Fans	$28\,500\ P_{ne}^{0,5575}$
Fumes ductworks	$51\,500\ P_{ne}^{0,5129}$
Discharge stack	$28\,500\ P_{ne}^{0,5575}$

table 21: Purchased equipment cost of a willow combustion plant (Caputo, Palumbo et al. 2005)

Besides the cost for the purchased equipment, one should sum them with piping costs, electrical costs, civil works costs, which can be found in the table 22.

Equipment	Cost (EUR)
Piping (B)	
Fire fighting tank	85 700 $P_{ne}^{0,1040}$
Fire fighting components	5 300 $P_{ne}^{0.7656}$
Fire fighting system	6 600 $P_{ne}^{0.7656}$
Industrial water tank	9 300 $P_{ne}^{0.7656}$
Tanks	10 300 $P_{ne}^{0.5129}$
Heat exchanger	34 200 $P_{ne}^{0.5575}$
Degasifier	17 100 $P_{ne}^{0,5575}$
By-pass valves	20 600 $P_{ne}^{0,5129}$
High pressure valves	28 500 $P_{ne}^{0,5575}$
Control valves	10 100 $P_{ne}^{0,6756}$
Valves	28 500 $P_{ne}^{0,5575}$
Pipes	42 300 $P_{ne}^{0,885}$
Pipe rack	12 100 $P_{ne}^{0,686}$
Electrical (C)	
Switches	13 400 $P_{ne}^{0,3672}$
Electric protections	44 700 $P_{ne}^{0,2266}$
Transformer	64 600 $P_{ne}^{0,4289}$
Auxiliary transformer	14 000 $P_{ne}^{0,4425}$
Electrical equipment	409 100 $P_{ne}^{0,6415}$
Assembling	186 900 $P_{ne}^{0,7137}$
Civil works (D)	
Buildings yard guard	70 100 $P_{ne}^{0,4425}$
Conditioning plant and ventilation	23 400 $P_{ne}^{0,6328}$
Civil works	1 337 400 $P_{ne}^{0,3672}$
Personnel of building yard	133 700 $P_{ne}^{0,3672}$
Building yard facilities	13 300 $P_{ne}^{0,7565}$
Wastewater treatment	6 900 $P_{ne}^{0,6107}$

table 22: Estimated cost of piping, electrical and civil works (Caputo, Palumbo et al. 2005)

Cost component	Factor
Total purchased equipment	A
Piping	B
Electrical works	C
Civil works	D
Direct installation cost	0,30 x A
Auxiliary services	0,15 x A
Instrumentation and controls	0,10 x A
Site preparation	0,10 x A
Total direct plant costs	*= 1,65 x A + B + C + D*
Engineering	0,12 x A
Start-up	0,10 x A
Total indirect plant costs	*= 0,22 x A*
Total plant cost	= 1,87 x A + B + C+ D

table 23: Factors applied for calculating direct and indirect plant costs (Caputo, Palumbo et al. 2005)

Finally, the estimate of the total plant cost of a willow combustion plant has been summarised in one equation, by calculating the total plant cost of a combustion plant for the relevant scales of operation in the Campine. The trendline that describes the total combustion plant cost in function of hourly feedstock equals:

$$TPC_{Co}^{Kup12} = 10\,941\,206{,}61 \times \left(\Phi_{Co}^{h}\right)^{0{,}6061} \tag{4.33}$$

Our estimate for some scales of operation can be found in table 24. Comparison with table 17 learns that the total plant cost is strongly higher than the total plant cost associated with a fast pyrolysis plant.

Annual feedstock (t_{dm} yr^{-1})	Hourly feedstock (t_{dm} h^{-1})	Net electric capacity (MW_e)	TPC combustion (MEUR)
5000	0,6	0,6	8,23
7000	0,9	0,8	10,09
10000	1,3	1,3	12,53
14000	1,8	1,8	15,36
20000	2,5	2,7	19,07
21000	2,6	2,9	19,64
28000	3,5	3,9	23,38
29000	3,6	4,1	23,88
30000	3,8	4,2	24,38
35000	4,4	5,0	26,76
42000	5,3	6,2	29,89
49000	6,1	7,3	32,82
50000	6,3	7,5	33,22

table 24: Total plant cost estimate for a willow combustion plant in the Belgian Campine

4.5.2 Expenditure (E)

a) <u>Fixed operational costs</u>

Fixed operational costs consist of maintenance costs, insurance and general overhead costs. Caputo, Palumbo et al. (2005) charge 1,5 % of the total plant cost for maintenance and 1 % for insurance and general costs. Total fixed operational costs thus equal 2,5 % of the total plant cost. Mitchell, Bridgwater et al. (1995) do not make a distinction between the financial parameter they use for maintenance and overhead costs of different biomass conversion technologies: maintenance and overhead costs both are counted as 2,5 % of the capital cost or 5 % in total. Toft (1996) also does not distinguish between the maintenance and overhead costs of thermochemical conversion technologies: he applies 4 % both for maintenance and overheads or a total of 8 % of the capital investment in order to account for fixed operational costs. An a kWh basis nevertheless, this results in a higher fixed operational cost for combustion compared to pyrolysis, due to a combination of a higher total capital investment for combustion and a low electric efficiency. Fiala, Pellizzi et al. (1997) multiply the total capital investment with a coefficient expressing the mean annual incidence of maintenance and repair operations as a percentage of the total investment for calculating the annual cost of maintenance and repair. They apply a standard maintenance factor of 3 %, with a minimum of 2 % and a maximum of 6 %. Interpreting the maintenance cost in the same way as Fiala, Pellizzi et al. (1997), i.e. the mean annual incidence of repair and taking into account the higher number of operational hours of a combustion plant (8 000 hours compared to 7 000 hours for fast pyrolysis), we set the default value for the fixed operational cost at 3 % of the total capital investment (compared to 5 % in the case of fast pyrolysis).

b) *Biomass purchase, transport and pre-treatment*

The starting point of our calculations is: which conversion technology is the most profitable for valorising the biomass potential in the Belgian Campine? The base of our calculations thus is the amount of biomass (willow) that phytoextraction in the Belgian Campine will yield. Therefore we assume the same amount of biomass for pyrolysis, combustion and gasification. This implies that biomass purchase and transport costs are the same for all three conversion technologies. There is a difference however for pre-treatment prerequisites. While pyrolysis requires that willow is comminuted to a particle size of less than 2 mm, fluid bed combustors accept a wide range of particle sizes up to 50 mm (Bridgwater 2002). Thus there is no need for further size reduction after harvest of the biomass, as it is already chipped to the right size at harvest. With regard to moisture content, Bridgwater (2002) states that a moisture content of 35 % is considered reasonable. As it has been stated in paragraph 3.3.4 that willow can be air dried to a moisture content of 25 %, we assume that there is no need for extra drying costs.

c) Staffing costs

Staff requirements are calculated according to Bridgwater (2002) who split staff requirements of the conversion (combustion) and the generation (steam cycle) step. Besides they distinguish between staff requirements for scales below and above 140 MW of energy available in the prepared feedstock. Even with the maximal scale of operation of 7 350 ha in the total Campine (Belgian and Dutch Campine), the energy available will almost certainly be lower than 140 MW_{th}. Under base case assumptions, 7 350 ha yield 58 800 t_{dm} of willow with a calorific value of 19,3 GJ t_{dm}^{-1} which corresponds to 39,4 MW_{th}[4] energy available in the input. The number of staff required by the combustion module equals:

$$L_{co} = [-0{,}0488 ln(P_{in}) + 0.3001] \times P_{in} \tag{4.34}$$

The specific labour requirement for the steam cycle then equals (Bridgwater 2002):

$$L_{st} = [0{,}1951 \ln(P_{ge}) + 0{,}9298] \times P_{ge} \tag{4.35}$$

d) Ash disposal cost

The ash flow rate is expressed as 2 % of the total annual biomass flow rate (Caputo, Palumbo et al. 2005). It needs to be landfilled in the same place as pyrolysis char at the same cost of 122 EUR t^{-1}, which is higher than the total

4 $\frac{58\,800\, t_{dm} \times 19\,300\, MJ\, t_{dm}^{-1}}{8\,000\, h \times 3\,600\, s\, h^{-1}} = 39{,}4\, MJ\, s^{-1} = 39{,}4\, MW$

ash disposal cost of 86 EUR t^{-1} (including ash transport) assumed by Caputo, Palumbo et al. (2005).

e) *Water cost*

Water is needed to supply the boiler to generate steam. This boiler feed water or make up water is required at a rate of 1,5 t MWh_e^{-1} at a cost of 0,77 EUR t^{-1} (see the pyrolysis section), which is close to the cost of 0,84 EUR t^{-1} mentioned by Bridgwater, Czernik et al. (2002)

4.5.3 Revenues (R)

Revenues are calculated in the same way as for fast pyrolysis for electricity production. With regard to the green power certificates it is assumed that certificates will be awarded for the gross production of electricity output, whereas the sales of electricity take into account internal electricity consumption by the combustion and steam cycle plant: 2 % and 4 % of gross electricity production respectively (Bridgwater, Toft et al. 2002).

4.5.4 Base case results

In table 25 the base case assumptions as described in paragraphs 4.5.1, 4.5.2 and 4.5.3 have been summarised.

Variable	Assumption
Farmland dedicated to phytoextraction	2 400 ha yr^{-1}
Willow yield	8 t_{dm} ha^{-1} yr^{-1}
Willow calorific value	19,3 GJ t_{dm}^{-1}
Combustion investment constant	10 941 206,61
Combustion investment exponent	0,6061
Combustion operational hours	8 000 h yr^{-1}
Fixed operational cost	3 % of total plant cost
Purchase price of willow	50 EUR t_{dm}^{-1}
Purchase price of make up water	0,77 EUR m^{-3}
Annual wage of 1 staff member	56 500 EUR yr^{-1}
Landfill cost of ashes	122 EUR t^{-1}
Sales price GPC	100 EUR MWh_e^{-1}
Sales price electricity	70 EUR MWh_e^{-1}

table 25: Base case assumption combustion of willow for electricity production

The share of the different expenditure and revenue items in relation to the discounted total revenues over the 20 years life time of the combustion and steam cycle plant have been represented in table 26.

Cash flow	Discounted sum (EUR)	%
	Revenues	
Investment allowance	944 693	3
Electricity sales	13 241 998	39
GPC	20 151 188	59
Total revenues	**34 337 879**	**100**
	Expenditure	
Investment	18 469 070	54
Fixed costs combustion	5 057 873	15
Biomass purchase	8 763 404	26
Biomass transport	1 226 877	4
Labour	6 475 025	19
By-product disposal	427 654	1
Water cost	23 935	0
Total expenditure	**40 628 395**	**118**
CF before tax	-6 300 516	-18
CF after tax (= NPV)	**-7 222 560**	**-21**

table 26: Share of expenditure and revenue items in total discounted revenues, willow combustion for electricity production base case

The last row of table 26 shows that a combustion plant is not profitable at all (even without taking into account potential extra costs for fume gas treatment), with a strong negative NPV of the cash flows of -7,2 MEUR at a discount rate of 9 %. The sales of the green power certificates make up the largest part (59 %) of the revenues. Together with the investment allowance, all forms of subsidies (exploitation and investment subsidies) constitute 62 % of all revenues. Both sales of electricity and green power certificates are lower than when electricity is produced by fast pyrolysis, which is due to the relatively low electric efficiency of the base case combustion plant (21 %).

The greatest part of the expenditure goes to the investment (54 % compared to total revenues or 45 % of the total discounted costs), biomass purchase (26 % compared to total revenues or 22 % of total discounted expenditure), staffing costs (19 % compared to total revenues or 16 % of total discounted expenditure). Labour costs have considerably increased compared to fast pyrolysis, whereas costs of by-product (ash) disposal are far more lower.

4.6 Gasification for electricity production

4.6.1 Initial investment (I_0)

The total capital investment for a gasification plant has also been based on Caputo, Palumbo et al. (2005). The cost equations used for estimating the cost of the purchased equipment cost for a fluid bed gasification plant, followed by a combined gas-steam cycle for power generation can be found in table 27. The equipment costs depend on the power generated specifically by the gas turbine (P_{gt}), the power generated by the steam cycle (P_{st}), the biomass flow rate (Φ^h_{ga} measured in kg h^{-1}), or the steam flow rate produced by the heat-recovery steam generator (Φ^h_{hrsg} also expressed in kg h^{-1}). On average, the gas turbine has the largest share of total net electric capacity of a gasification combined cycle plant. P_{gt} is on average 67 % of P_{ne} of a gasification plant and the other 33 % stems from the power supplied by the combined steam cycle (AMPERE 2000; SPE 2003; Voets and Bloemen 2009; Renewable Energy Institute s.d.). The calculation of the biomass flow rate is similar to the one of combustion: it is the annual available amount of biomass divided by the amount of operational hours, which is 8 000 hours for both gasification and combustion (compare to 7 000 operational hours for a fast pyrolysis plant). The costs for piping, electrical and civil works, the other direct and indirect costs are the same for combustion and gasification and can be found in the respective table 22 and table 23.

Equipment	Cost (EUR)
Power generation	
Steam turbine	633 000 $P_{st}^{0.398}$
Gasifier	1 600 $\Phi^{h}{}_{gas}^{0,917}$
Turbogas group	3 800 $P_{gt}^{0,754}$
Heat-recovery steam generator	6 540 $\Phi_{hrsg}^{0,81}$
Condenser	398 000 $P_{st}^{0.333}$
Heat exchanger (cooling water)	51 500 $P_{st}^{0.5129}$
Alternator	138 300 $P_{st}^{0.6107}$
Fans	35 300 $P_{st}^{0.6107}$
Condensate extraction pumps	9 000 $P_{st}^{0,4425}$
Feed pumps	35 000 $P_{st}^{0,6107}$
Pumps	28 000 $P_{st}^{0.5575}$
Biomass storage-handling	
Biomass storage	114 100 $P_{ne}^{0,5575}$
Biomass handling	46 600 $P_{ne}^{0,9554}$
Compressor and dryers	11 400 $P_{ne}^{0,5575}$
Emergency diesel	36 200 $P_{ne}^{0,1989}$
Heat-recovery dryer	9 600 $\Phi^{h}{}_{gas}^{0,65}$
Fumes treatment	
NO_x and SO_x removal equipments	126 000 $P_{ne}^{0,5882}$
Fumes filtration	66 600 $P_{ne}^{0,7565}$
Ashes storage	88 300 $P_{ne}^{0,3139}$
Ashes extraction	93 500 $P_{ne}^{0,4425}$
Fans	28 500 $P_{ne}^{0,5575}$
Fumes ductworks	51 500 $P_{ne}^{0,5129}$
Discharge stack	28 500 $P_{ne}^{0,5575}$

table 27: Purchased equipment cost of a willow gasification plant (Caputo, Palumbo et al. 2005)

Finally, the estimate of the total plant cost of a willow gasification plant has been summarised in one equation, by calculating the total plant cost of a gasification plant for the relevant scales of operation in the Campine. The trendline that describes the total gasification plant cost in function of hourly feedstock equals:

$$TPC_{Ga}^{Kup12} = 12\,890\,503{,}22 \times \left(\Phi_{Ga}^{h}\right)^{0{,}6773} \qquad (4.36)$$

Our estimate for some scales of operation can be found in table 28. Comparison with table 17 and table 24 learns that the total plant cost is the highest for a gasification plant and the lowest for a fast pyrolysis plant.

Annual feedstock (t_{dm} yr^{-1})	**Hourly feedstock (t_{dm} h^{-1})**	**Net electric capacity (MW_e)**	**TPC gasification (MEUR)**
5000	0,6	1,0	9,38
7000	0,9	1,4	11,78
10000	1,3	2,1	14,99
14000	1,8	3,1	18,83
20000	2,5	4,6	23,98
21000	2,6	4,9	24,78
28000	3,5	6,8	30,11
29000	3,6	7,0	30,84
30000	3,8	7,3	31,55
35000	4,4	8,7	35,03
42000	5,3	10,7	39,63
49000	6,1	12,7	43,99
50000	6,3	13,0	44,60

table 28: Total plant cost estimate for a willow gasification plant in the Belgian Campine

4.6.2 Expenditure (E)

a) <u>Fixed operational costs</u>

Fixed operational costs for maintenance, insurance and overheads have been set at 4 % of the total plant cost, following Caputo, Palumbo et al. (2005) and Voets, Kuppens et al. (2011). This seems reasonable as a gasification plant is expected to be operational during 8 000 hours per year, which is more than the 7 000 hours per year that a fast pyrolysis plant is operational. Therefore it can be expected that less maintenance is required in a gasification plant compared to the incidence of maintenance in a fast pyrolysis plant. As a consequence, we charge only 4 % of the total plant cost for a gasification plant, compared to 5 % for a fast pyrolysis plant. Although the gasification plant is assumed to be operational the same number of hours as a combustion plant, the charge for the fixed operational cost in a gasification plant has been deliberately set somehow higher than in a combustion plant: 4 % compared to 3 %. This is because gasification is more complex than combustion and given the low maturity of biomass gasification compared to biomass combustion (Caputo, Palumbo et al. 2005).

b) <u>Biomass pre-treatment</u>

Willow needs to be dried and reduced in size for the conversion in a gasification reactor. Maximal moisture contents between 10 % and 20 % and wood chip sizes of 25 mm to 30 mm are required for the well-functioning of a fluid bed gasifier (Bridgwater, Toft et al. 2002). Because the willow has already been chipped at harvest, no extra costs for diminution have been charged. Drying costs however do matter, but it is expected that there is enough process heat available for drying the biomass.

c) Labour costs

The labour requirement for the gasification reactor is calculated using the same relationships used for the fast pyrolysis plant, because the equipment required in both systems is very similar. The labour required for the gas turbine combined cycle for electricity production is based on the labour requirement for the steam cycle.

d) Other operational costs

Other costs comprise cost for disposing ashes, water and the costs for cracking the tar in the product gases. Ash disposal costs are expected to be the same for the combustion and the gasification plant (Caputo, Palumbo et al. 2005). For cracking of the tar in the product gases, 0,68 t of catalyst is required per ton dry feed input, at a cost of 30 EUR t^{-1} (Bridgwater, Toft et al. 2002). Water requirements are one third of the water requirements associated with the steam turbine in a combustion plant, because in a gas turbine – steam combined cycle the steam cycle only contributes a third of the total power produced by the total gasification plant (the other two thirds are produced by the gas turbine).

4.6.3 Revenues (R)

Revenues are calculated in the same way as for the pyrolysis and combustion systems. The amount of revenues however differs because of other energy efficiencies.

4.6.4 Base case results

In table 29 the base case assumptions as described in paragraphs 4.6.1, 4.6.2 and 4.6.3 have been summarized.

Variable	Assumption
Farmland dedicated to phytoextraction	2 400 ha yr^{-1}
Willow yield	8 t_{dm} ha^{-1} yr^{-1}
Willow calorific value	19,3 GJ t_{dm}^{-1}
Gasification investment constant	12 890 503,22
Gasification investment exponent	0,6773
Combustion operational hours	8 000 h yr^{-1}
Fixed operational cost	4 % of total plant cost
Purchase price of willow	50 EUR t_{dm}^{-1}
Purchase price of make up water	0,77 EUR m^{-3}
Annual wage of 1 staff member	56 500 EUR yr^{-1}
Landfill cost of ashes	122 EUR t^{-1}
Sales price GPC	100 EUR MWh_e^{-1}
Sales price electricity	70 EUR MWh_e^{-1}

table 29: Base case assumptions gasification of willow for electricity production

The share of the different expenditure and revenue items in relation to the discounted total revenues over the 20 years life time of the combustion and steam cycle plant have been represented in table 30.

Cash flow	Discounted sum (EUR)	%
	Revenues	
Investment allowance	1 177 534	2
Electricity sales	21 922 256	40
GPC	32 369 116	58
Total revenues	**55 468 906**	**100**
	Expenditure	
Investment	23 021 198	42
Fixed costs	8 406 002	15
Biomass purchase	8 763 404	16
Biomass transport	1 226 877	2
Labour	6 823 464	12
By-product disposal	427 654	1
Water cost	124 621	0
Tar cracking	3 575 469	6
Total expenditure	**52 368 689**	**94**
CF before tax	3 100 218	6
CF after tax	**-1 663 797**	**-3**

table 30: Share of expenditure and revenue items in total discounted revenues, willow gasification for electricity production base case

The last row of table 30 shows that willow gasification for electricity is also not profitable, with a strong negative NPV of the cash flows of -1,7 MEUR at a discount rate of 9 %. Again, the sales of the green power certificates make up the largest part (58 %) of the revenues. Although revenues are higher than when willow is combusted or pyrolysed (thanks to the high electric efficiency of the plant), the net present value of the cash flows is still negative because expenditure has also increased. The greatest part of the expenditure goes to the investment (42 %), biomass purchase (16 %), fixed costs (15 %) and the labour costs (12 %).

4.7 Conclusion

4.7.1 Comparison of electricity production

In the previous paragraphs, it became clear that fast pyrolysis of willow for the combined production of heat and electricity was the only profitable conversion route. Because it is not sure whether the heat can be sold to industrial consumers in the surroundings of the potential fast pyrolysis plant, we checked whether electricity production alone would be profitable. Because fast pyrolysis for electricity production only, is not profitable under the base case assumptions in the Belgian Campine, it has been investigated whether combustion or gasification of the willow would yield better results. Unfortunately, none of these resulted in a positive net present value. Here the main data concerning the base case for electricity production by means of fast pyrolysis, gasification and combustion have been summarized.

Variable	Combustion	Gasification	Pyrolysis
Quantity of feedstock that requires valorisation			
Willow yield		$8\ t_{dm}\ ha^{-1}\ yr^{-1}$	
Available farmland		2 400 ha	
Annual feedstock		$19\ 200\ t_{dm}\ yr^{-1}$	
Technical parameters			
Electric efficiency	21 %	34 %	24 %
P_{ne} (MW_e)	2,6 MW_e	4,5 MW_e	5,1 MW_e
Operating hours	8 000 h	8 000 h	reactor 7 000 h engine 5 000 h
Economic parameters			
I_0 constant	10 941 207	12 890 503,22	4 684 181 (including engine)
I_0 exponent	0,6061	0,6773	0,7897 (including engine)
Total plant cost	18,5 MEUR	23,0 MEUR	13,7 MEUR
Net present value	-7,22 MEUR	-1,66 MEUR	-1,07 MEUR

table 31: Base case data of combustion, gasification and pyrolysis of willow for electricity production

Profitability calculations for pyrolysis, combustion and gasification of willow have the same starting base, because it is investigated which conversion technology is best suited for valorisation of the biomass potential stemming from phytoextraction in the Belgian Campine. From a technical point of view, gasification yields the best results with regard to electricity production. Gasification has the highest total electric efficiency and combustion has the lowest efficiency. Efficiency calculations take into account internal energy consumption by the conversion reaction. Pyrolysis total process electric efficiency is the total efficiency of the pyrolysis and bio-oil engine, i.e. final electricity produced divided by the available energy in the biomass feedstock. It is less straightforward than the electric efficiency of the combustion and gasification process, because one has to take account of the oil yield, the lower heating value of the pyrolysis oil, and the combustion efficiency of the internal combustion bio-oil engine. The electric power capacity seems a bit misleading, because the pyrolysis plant appears to have the highest capacity compared to combustion and gasification. One should however notice that the pyrolysis engine is only operational during 5 000 hours per year, whereas the gasification plant is operational during 8 000 hours per year, so that final electricity production (capacity multiplied by operational hours) of course is the highest in the gasification plant. Therefore, it is better to compare the plants in terms of total process electric efficiency.

From an economic point of view, pyrolysis is the best conversion technique for the base case assumption that 2 400 hectares will be phytoextracted in the Belgian Campine. Although one should keep in mind that electricity production only is not sufficient for valorising the biomass in the Campine: even the best conversion technology (pyrolysis) is loss making (a negative NPV of -1,07 MEUR). Part of the explanation is the lower investment cost associated with fast pyrolysis. Other explanations can be found in figure 14.

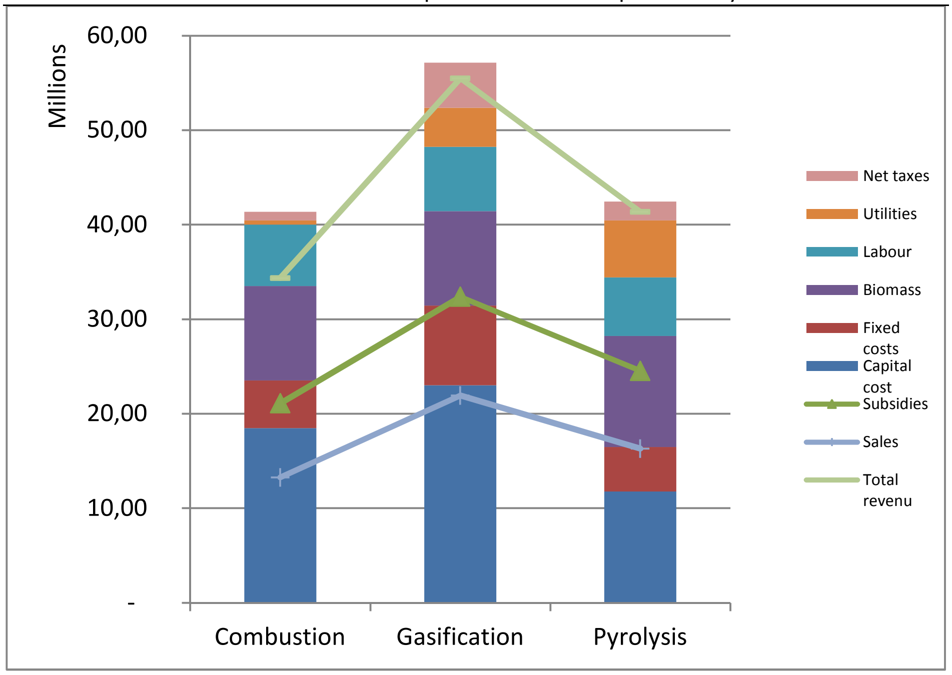

figure 14: Comparison yearly expenditure and revenues for a pyrolysis, combustion and gasification plant for electricity production in the Belgian Campine

Gasification is the most expensive technology for processing the same amount of annual feedstock, especially because of the high capital investment which also results in higher fixed costs as they are calculated as a fixed percentage of the total capital investment. When it comes to production cost per MWh of electricity, gasification is comparable to pyrolysis, whereas combustion is the most expensive technology in terms of cost per MWh_e (see table 32). This can be explained by the electric efficiency of the respective technologies: combustion has a very low overall efficiency (21 %) compared to pyrolysis (24 %) and gasification (34 %) (cf. table 31). Gasification might have a higher total cost, but it also results in higher electricity production, so that the production cost per MWh_e is comparable to the one of fast pyrolysis. The fact that gasification has a lower NPV than fast pyrolysis is due to the time aspect of the cash flows in investment analysis:

gasification has a very high initial investment in year 0 compared to fast pyrolysis, which weighs on the NPV calculation.

EUR/MWh_e	Pyrolysis	Combustion	Gasification
Excl. subsidies	173,70	214,82	167,22
Incl. subsidies	68,39	108,30	63,86

table 32: Unit cost of electricity production

The production cost of fast pyrolysis oil has also been calculated: the cost of producing 1 GJ of pyrolysis oil equals 21 EUR, which is higher than the break even selling price calculated by Rogers and Brammer (2012a) because of the extra cost of the contamination present in the willow. From their estimate (see figure 15) a break even selling price of 13 GBP GJ^{-1} (or 15,58 EUR GJ^{-1}) for a plant processing 65 tonne willow per day can be deduced. The higher cost in the Campine can be explained by the extra costs incurred for disposal of the contaminated char. Unfortunately, none of the conversion technologies has sufficient revenues to cover total costs. The above results are only valid under 100 % certainty. In the next chapter, risk analysis has been performed in order to check the influence of uncertain variables on profitability and to determine the maximum price that can be paid for willow.

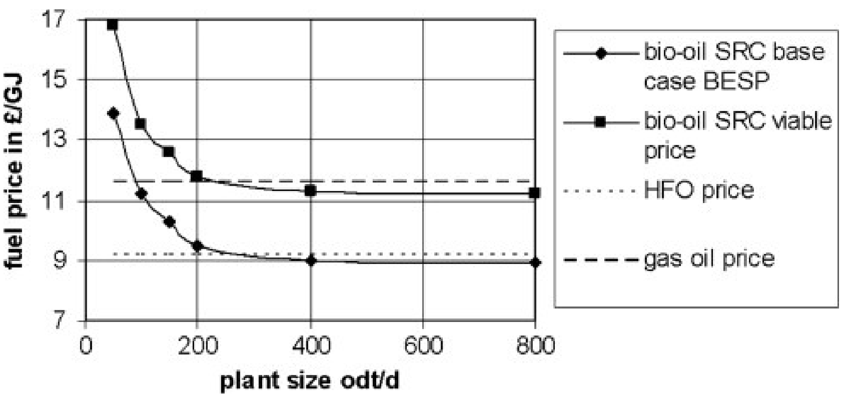

figure 15: Break even selling price for pyrolysis oil from willow (Rogers and Brammer 2012)

4.7.2 Pyrolysis oil as a substitute for heavy oil in boilers

In chapter 3 it has been stated that pyrolysis oils can easily substitute petroleum based products in boilers or furnaces. It has the advantage that it can be applied with only minor (or even no) modifications, whereas in combustion engines there is more technical uncertainty with respect to maintenance time, replacing blocked parts, ignition to name a few technical risks. In order to avoid the technical risk on blockage one can opt to use pyrolysis oil for replacing heavy fuel oil in furnaces in existing furnaces. Therefore the economic calculations have been repeated based on the following assumptions:

- fossil fuels in existing furnaces will be replaced (and sold to consumers that already dispose of a furnace), so that no investment cost for a power engine is required (nor is labour or a pilot fuel required for the engine);
- minor modifications might be required (but is not sure), therefore costs for modifications have been considered to be negligible;
- oil will be used to replace heavy fuel oil for industrial heat, so revenues consist of savings of heavy fuel oil purchase;

Oil can substitute heavy fuel oil saving between 8 and 12 EUR GJ^{-1} (Christis 2012). As indicated in the next table (where an average of 10 EUR GJ^{-1} has been assumed), though the technological risk has been reduced, the economics of substituting heavy fuel oil are very negative. Therefore it is unlikely that pyrolysis oil will be used for substituting fossil fuels in boilers and furnaces (this can change when the costs for oil production decrease, for instance when biomass waste with a negative economic value or gate fee can be processed instead). Dedicated energy crops that are supposed to yield an income for a farmer thus require the valorisation of the crops in a green power plant, a combined heat and power plant or a biorefinery for the production of chemicals/materials.

Cash flow	Discounted sum (EUR)
Revenues	
Investment allowance	358 276
Fuel savings	19 367 122
Total revenues	**19 725 398**
Expenditure	
Investment	7 004 413
Fixed costs (total)	3 197 005
Biomass purchase	8 763 404
Biomass transport	1 226 877
Biomass grinding	1 752 681
Labour	2 578 814
By-product disposal	2 645 789
Water consumption	13 496
Total expenditure	**27 182 478**
CF before tax	-7 457 080
CF after tax (= NPV)	**-6 134 457**

table 33: NPV of a fast pyrolysis plant when pyrolysis oil substitutes heavy fuel in industrial boilers or furnaces

4.7.3 Suggestions for incentives

As a conclusion, the economic information in this chapter will be used to formulate some indicative directions for incentives for phytoextraction and the amount of green power certificates. When phytoextraction with willow would be the outcome of crop choice model based on a larger cost-benefit model that incorporates external benefits and costs, investors will not be eager to use willow contaminated with heavy metals in a fast pyrolysis plant because of the costs entailed by the pollution. First of all investors can avoid the disposal costs (122 EUR per ton of char) associated with the char by choosing clean biomass (willow). Besides, when clean biomass is used the char can be combusted without a risk of metal emissions for internal energy provision, so that no oil is required for heating the pyrolysis reactor (and more heat can be sold at 20 EUR MWh_{th}^{-1}). One can even state that the remaining char can be sold (though there is not really a market). Therefore it is suggested that government might provide incentives which cover the extra costs incurred by the investor in a fast pyrolysis plant. In the next table the calculation of the incentive can be followed.

Calculation of the phytoextraction incentive	
Available farmland (ha)	2 400
Willow yield (t_{dm} ha^{-1} yr^{-1})	8
Annual willow feedstock (t_{dm} yr^{-1})	19 200
Disposal costs	
Char yield (m %)	12,4
Yearly char production (t_{dm} yr^{-1})	2 376
Disposal cost (EUR yr^{-1})	289 837
Heat sales loss	
Energy from CHP (GJ yr^{-1})	46 211
Energy from CHP (MWh yr^{-1})	12 836
Lost heat sales (EUR yr^{-1})	256 729
Total costs per year (EUR yr^{-1})	546 566
Required incentive (EUR t_{dm}^{-1} willow)	**28,47**

table 34: Calculation of the required phytoextraction incentive for willow

Pyrolysing the annual feedstock of 19 200 t_{dm} yr^{-1} results in the production of 2 376 t_{dm} yr^{-1} char that has to be disposed of at a cost of 122 EUR t_{dm}^{-1}. Besides, when char contains heavy metals and is not available for internal energy provision, the difference between the total internal energy requirement and the energy available in the gases in table 8, i.e. the energy that should be provided by the CHP, equals 46 211 GJ yr^{-1} or 12 836 MWh yr^{-1}. When char is available, this heat can be sold, so that polluted char incurs a loss of heat sales of 256 729 EUR yr^{-1}. The extra costs incurred per year by using contaminated willow instead of clean willow thus amount to 546 566 EUR yr^{-1} or 28,47 EUR per tonne of dry contaminated willow. Therefore it is suggested to provide an incentive of at least 28,47 EUR t_{dm}^{-1} for investors who are using willow cultivated for phytoextraction.

Next the unprofitable top has been simulated after incorporating the incentive for phytoextraction. The system of GPCs is a means to internalise the (positive) externalities of avoided CO_2-emissions. When the unprofitable top for GPCs would have been calculated based on polluted biomass, they not only internalise avoided CO_2 but are also covering the extra costs incurred by the contamination of the biomass. Therefore it has been chosen to calculate the unprofitable top for GPCs for several assumptions of electricity prices, assuming the inclusion of a phytoextraction incentive in the discounted cash flow model. The following table indicated the suggested unprofitable top and banding factors (assuming a market value of 1 GPC of 97 EUR MWh_e^{-1}).

Electricity price (EUR MWh_e^{-1})	Unprofitable top (EUR MWh_e^{-1})	Banding factor (dimensionless)
60	107	1,10
80	88	0,91
100	69	0,71
120	50	0,52

table 35: Possible indication for the unprofitable top and banding factor for a fast pyrolysis plant with an electric capacity of 5 MW_e

5 Risk analysis

5.1 Introduction

The value of phytoextracting crops depends on the profitability of the sequential investment in a conversion technique aimed at the economic valorisation of the plants. However, the net present value (NPV) of an investment in such an innovative technology is risky due to technical and economic uncertainties. Therefore, decision makers want to dispose of information about the probability of a positive NPV, the largest possible loss, and the crucial economic and technical parameters influencing the NPV. This chapter maps the variability in the NPV of an investment in fast pyrolysis, combustion and gasification for the production of electricity from willow cultivated for phytoextraction in the Belgian Campine. The probability of a positive NPV has been calculated by performing Monte Carlo simulations. In a next step, this information has been used to explore the price range for willow by simulating the maximum price that an investor in renewable energy from phytoextracting willow is likely to pay for the biomass. The results of these calculations can be found in paragraph 5.2.2.

The section on the price range for willow has been based on fast pyrolysis for the production of electricity only and not on combined heat and power production, because heat sales are uncertain and depend on the presence of potential industrial consumers that are located in the surroundings of a potential fast pyrolysis plant. It is just this certainty that is required when calculating maximum willow prices. Because fast pyrolysis of willow followed by the combined production of heat and power appeared to be the most profitable, the next paragraph (paragraph 5.3) focuses on the economic risks associated with this profitability. The probability of a positive NPV has been calculated by performing Monte Carlo simulations and information about possible losses has been provided by means of experimental design. Both methods are combined in order to identify the key economic and technical parameters influencing the project's profitability.

5.2 Exploration of the willow price

5.2.1 The cost of cultivating and harvesting willow

During phytoextraction, a farmer switches from traditional activities to the cultivation of metal accumulating crops. In this study, the focus is on short rotation coppice. This section therefore describes the cultivation steps that are required and the costs as they have been communicated in the CLO-project on phytoremediation by Meiresonne, researcher at the INBO (Research Institute for Nature and Forest).

Before planting the cuttings, one should first prepare the farmland. It needs to be ploughed and harrowed at a cost of 67 EUR ha^{-1} and 75 EUR ha^{-1} respectively. Next, the cuttings are planted by means of a leek planter. The rent cost of a leek planter is 450 EUR ha^{-1}. 15 000 cuttings with a length of 20 to 25 cm are planted per hectare. They are planted in double rows 75 cm apart and with the double rows spaced at 1,5 m. This double row planting of 15 000 plants per hectare has been confirmed by Volk, Abrahamson et al. (2006). In each row the cuttings are planted at 60 cm from each other (INBO 2007; Caslin, Finnan et al. 2010). The cost of one cutting is 0,08 EUR per cutting. In order to prevent damage from rabbits, it is advised to erect fences at a cost of 505,50 EUR ha^{-1}. Next, weed killing is required right after planting and harvest (i.e. every 3 years) at a cost of 50 EUR ha^{-1}. Fertiliser (e.g. NO_3, NH_4, P_2O_5, K_2O) is applied to the field at a cost of 74,25 EUR ha^{-1}. A rent cost of 39 EUR ha^{-1} yr^{-1} is assumed. According to INBO the cost of harvesting was 850 EUR ha^{-1}, but according to Pieter Verdonckt from Inagro this cost has been augmented to 1 300 EUR ha^{-1} in 2011. An overview of the expenditure is given in table 36.

Activity	Cost (EUR ha^{-1})	Years
Ploughing	67	0
Harrowing	75	0
Cuttings	1 200	0
Planting	450	0
Fencing	505	0
Weed killing	50	0, 3, 6, 9, 12, 15, 18
Fertiliser	74	0, 4, 7, 10, 13, 16, 19
Rent	39	every year
Harvesting	1 300	3, 6, 9, 12, 15, 18, 21
Stump elimination	1 500	21

table 36: Cultivation costs of short rotation willow (Meiresonne 2007)

The cost of cultivation can be represented by the levelised cost (LC) of cultivation, a concept which is often used in energy calculations (El Kasmioui and Ceulemans 2012). It is defined as:

$$LC = \frac{\sum_{t=0}^{21}(1+r)^{-t}.C_t}{\sum_{t=0}^{21}(1+r)^{-t}.q_{willow}} \tag{3.1}$$

It can be interpreted as the price at which willow cultivated in short rotation must be sold in order to break even. Assuming a willow yield of 8 t_{dm} ha^{-1} yr^{-1} the calculated levelised cost equals **51,03 EUR t_{dm}^{-1}**. This cost will be 86,86 EUR t_{dm}^{-1} if the willow yield is only 4,7 t_{dm} ha^{-1} yr^{-1} (Ruttens, Vangronsveld et al. 2008; Vangronsveld, Herzig et al. 2009) but can be as low as 26,17 EUR t_{dm}^{-1} at high willow yields of 15,6 t_{dm} ha^{-1} yr^{-1} (ranges for the willow yield have been determined on Ruttens, Vangronsveld et al. (2008); Vangronsveld, Herzig et al. (2009); Ruttens, Boulet et al. (2011); Witters (2011)).

5.2.2 Maximum price that can be paid for use as a feedstock

The expected cultivation cost of willow is thus more or less 50 EUR t_{dm}^{-1}. This cost can be considered as the minimal sales price of willow (though no profit margin for the farmer has been counted yet). The maximum unit willow price then has been defined as the price guaranteeing a 95 % chance of a positive net present value of cash flows generated by an investment in fast pyrolysis, gasification or combustion of willow for electricity production. It takes into account uncertainties with respect to the technical and economic base case assumptions. First, the uncertainties have been identified by the principles described in paragraph 2.4.2. Next the influence of the uncertainties on the variability of the net present value of the cash flows has been investigated. Uncertainties that do not have an important impact on the net present value are omitted from further analysis. The uncertainties that are left finally are used in order to calculate the maximal willow price.

The uncertain variables are identified by taking into account ranges found in literature for the several technological and economic assumptions made in chapter 4. All uncertainties are summed up and classified in table 37. The table has been arranged in a way that first general uncertainties that apply for all conversion technologies are described (e.g. the scale of the plant which is a combination of farmland and expected willow yield), next the uncertainties with regard to respectively fast pyrolysis, combustion and gasification for electricity production are mentioned. The efficiency dummy which appears in the table, reflects the uncertainty with respect to electrical efficiency as explained in figure 8/table 9 of paragraph 3.4.3 for combustion and in figure 9/table 11 of paragraph 3.5.3 for gasification.

In a next step, these uncertainties have been introduced in the Crystal Ball software.

	Min	B.C.	Max
General uncertainties			
Farmland (ha)	650	2400	3000
Willow yield (t_{dm} ha^{-1} yr^{-1})	5	8	15
Weather impact (dummy)	0,9	1	1
Willow purchase price (EUR t_{dm}^{-1})	30	50	70
Electricity price (EUR MWh_e^{-1})	60	70	80
GPC price (EUR MWh_e^{-1})	80	100	120
Landfill cost (EUR t^{-1})	114	122	130
Price make up water (EUR m^{-3})	0,04	0,77	1,5
Pyrolysis specific uncertainties			
Oil yield (m%)	60	65	70
LHV Oil (GJ t^{-1})	16	17	19
I_0 constant (x 10^3)	2 697	3 487	4 286
I_0 exponent	0,6490	0,6865	0,7407
Fixed cost	3 %	5 %	8 %
Combustion specific uncertainties			
Willow calorific value (GJ t_{dm}^{-1})	17,6	19,3	20,2
Efficiency dummy	0,79	1	1,14
I_0 dummy	0,7	1	1,3
Fixed cost	2 %	3 %	6 %
Gasification specific uncertainties			
Willow calorific value (GJ t_{dm}^{-1})	17,6	19,3	20,2
Efficiency dummy	0,69	1	1,23
I_0 dummy	0,7	1	1,3
Fixed costs	3 %	4 %	5 %

table 37: General and specific uncertainties with regard to technical and economical variables

Next, the following steps are followed in order to calculate the maximum price that an investor in a combustion, a gasification or a fast pyrolysis plant for electricity production is willing to pay for willow from the Campine:

1. calculate the **variability** of the net present value of the cash flows as a result of the **realistic uncertainties** of the variables indicated in table 37 that can take any value between its minimum and maximum value, taking into account that the base case value is more probable than the minimum and maximum value by means of a triangular distribution, and calculate the chance that the net present value is positive under these circumstances;
2. calculate the **sensitivity** of the net present value of the cash flows to the **realistic uncertainties** of the variables indicated in table 37 by computing the contribution to the variability of the net present value for each variable;
3. identification of the variables that have an impact on the variability of the NPV by simultaneously studying the results of steps 1 and 2;
4. calculation of the maximum willow prices at the relevant scales of operation in the Belgian Campine by taking into account the real uncertainties indicated in table 37 so that the chance of a positive net present value of the cash flows is at least 95 %.

Statistic	*Forecast value*		
	Combustion	***Gasification***	***Pyrolysis***
Trials	10 000	10 000	10 000
Base Case	-7.222.560,45 €	-1.663.787,32	-1.074.638,55
Mean	-8.120.650,43 €	-2.890.670,12	-1.946.772,06
Median	-8.214.310,75 €	-4.057.112,88	-2.084.010,41
St.dev.	3.072.991,14 €	6.105.479,71	2.441.589,87
Skewness	0,3345	1,11	0,5550
Minimum	-21.010.631,22 €	-20.242.915,50	-11.391.119,82
Maximum	8.291.815,51 €	31.386.219,21	12.319.419,72
P(NPV>0)	1,13 %	25,51	17,66 %

table 38: Statistics of the Monte Carlo simulations for a combustion, a gasification and a fast pyrolysis plant for the production of electricity

From table 38, some conclusions can be drawn with respect to the economic risk of the conversion technologies. The average net present value of the cash flows of the 10 000 simulation runs confirm what the base case already indicated: fast pyrolysis is likely to yield a less negative net present value compared to combustion and gasification. The means of the simulations are lower than the base case value. This can be explained by the fact that the realistic ranges sometimes are already “skew” in their assumptions. Sometimes the base case value is not in the middle of the triangular distribution, but closer to the minimum or the maximum value of the range. For instance, the base case value of 2 400 ha for the farmland available for phytoextraction, is more close to the maximum potential of farmland than to its minimum.

Another important conclusion is that the variability of the net present value of the gasification system is larger than for the combustion or the pyrolysis plant. This implies a larger extent of uncertainty with regard to the true value of the net present value of the cash flows in the gasification case. This larger degree of uncertainty is also reflected in the range width of the gasification's NPV based on the realistic range: the minimal calculated NPV during the 10 000 simulations is 51 MEUR lower than the maximum, compared to 24 and 29 MEUR both for fast pyrolysis and combustion respectively. Despite of the great range, is gasification the only conversion technology that can yield 31 MEUR, whereas the highest attainable NPVs are 8 MEUR and 11 MEUR for combustion and fast pyrolysis respectively.

In the next sections the distributions/variabilities of the NPVs based on the realistic ranges have been visually presented. After the visual presentation, a discussion of the figures follows before proceeding to the maximum willow prices.

5.2.3 Variability and sensitivity of the net present value of the cash flows of a combustion plant for the production of electricity

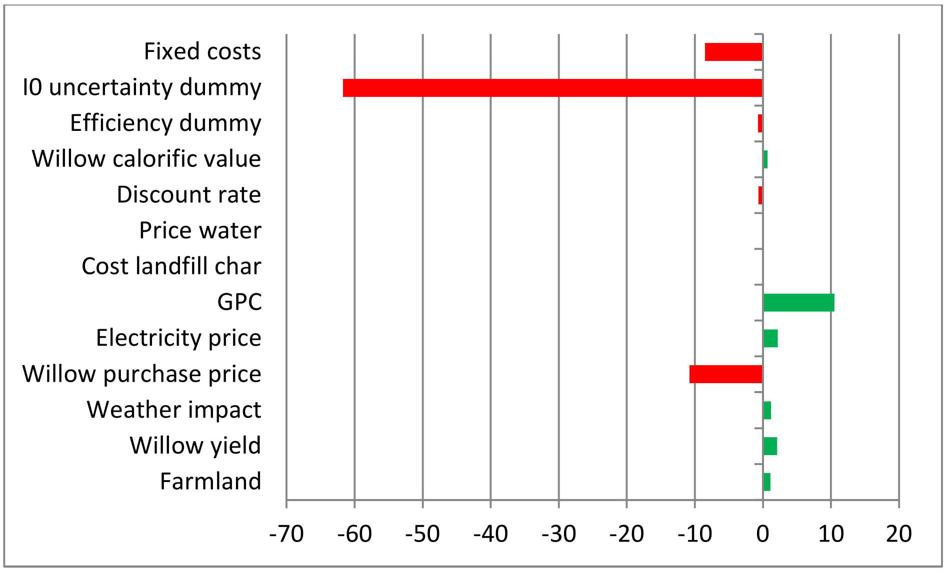

figure 16: Sensitivity chart of the net present value of the cash flows of an investment in a combustion plant based on realistic ranges for the uncertain variables

In table 38 one can see that the chance of a positive net present value is almost zero, i.e. 1,13 %. From figure 16 one can see that the most influential variable is the uncertainty with respect to the investment cost of a combustion plant. It explains more than 60 % of the variability of the net present value. Also the price of the green power certificates is important, which can be explained by the influence it has on the greatest share of total revenues. The variables that have a very low impact on the variability of the net present values are the landfill cost (that is the cost for landfilling one tonne of ashes), the price of the make up water, the uncertainty with respect to electric efficiency (i.e. the combustion's efficiency uncertainty dummy), the discount rate and the impact of bad weather. It is remarkable that the uncertainty with respect to scale of operation, which is both expressed by the available farmland and willow yield per hectare per year, contribute not much to the variability of the NPV. In the section on the prices however, it will become clear that they are important and that economies of scale do play a role in determination of the maximum willow price.

5.2.4 Variability and sensitivity of the net present value of the cash flows of a gasification plant for the production of electricity

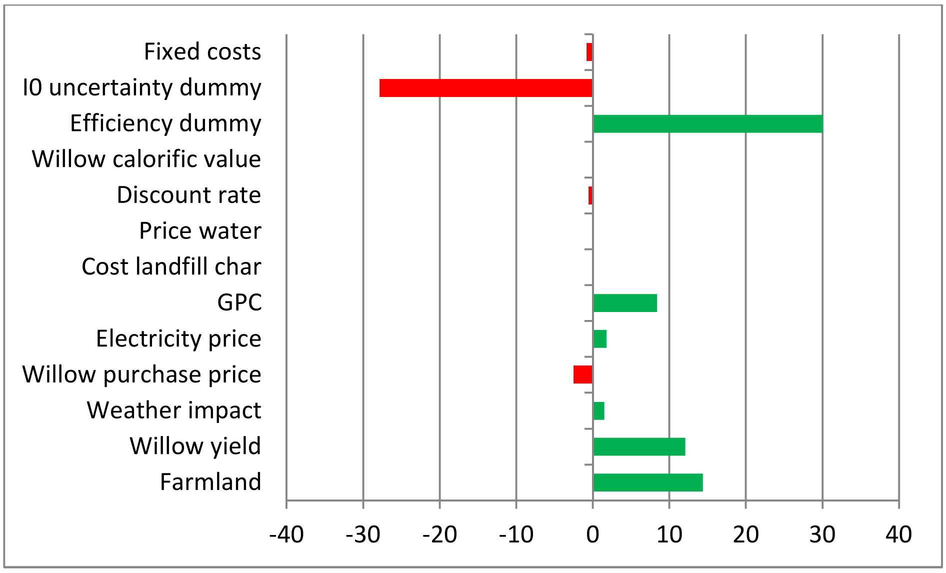

figure 17: Sensitivity chart of the net present value of the cash flows of an investment in a gasification plant based on realistic ranges for the uncertain variables

Under current assumptions and expectations with respect to the minimal, base case and maximum values of the variables, there is a chance of 25 % that the NPV of the cash flows will be positive. The uncertainty with regard to the landfill cost of the ashes and the price of make up water, as well as the discount rate and the weather impact are unimportant in explaining the variability of the gasification plant's NPV. Under realistic expectations, again the uncertainty about the height of the investment cost explains a very high share (27,9 %) of the variability of the NPV. The minus sign indicates that an increase of the dummy, for example from 1 to 1,30 decreases the NPV of the gasification plant. Unlike in the combustion plant, the uncertainty about the gasification plant's electric efficiency does play an important role in explaining the variability of the net present value. The same is true for the indicators for the scale of operation: uncertainty about the available farmland and the willow yield explain 14,4 % or 12,1 % (or

26,5 % in total) of the variability in the NPV of the gasification plant. Notwithstanding the impact of the investment cost, the fixed cost is quite unimportant.

5.2.5 Variability and sensitivity of the net present value of the cash flows of a fast pyrolysis plant for the production of electricity

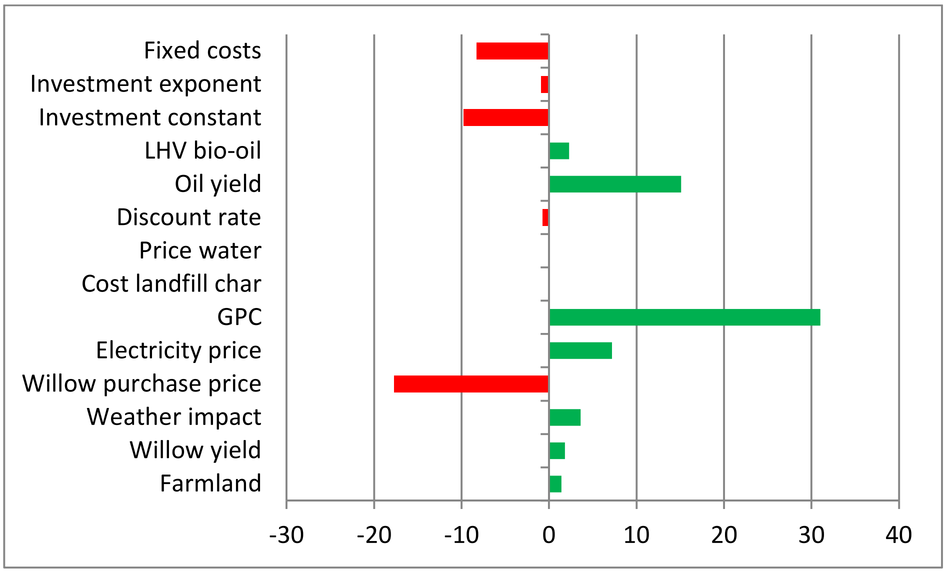

figure 18: Sensitivity chart of the net present value of the cash flows of an investment in a fast pyrolysis plant based on realistic ranges for the uncertain variables

From table 25 it can be concluded that the probability that an investment of a fast pyrolysis plant for electricity production is profitable, is 17 %. An important difference with combustion and gasification is that the uncertainty of the investment cost is split into uncertainty with respect to extent of economies of scale (represented by the value of the exponent in the investment function) and the equipment cost of the pyrolysis plant (which is included in the constant of the investment function). The uncertainty with respect to the investment exponent, so whether the exponent is 0,6490 or 0,7407 is not important. More important is the equipment cost, although less important than in the combustion and gasification case. This might be explained by the fact that the uncertainty with regard to the constant is smaller: the constant is only allowed to deviate more or less 13 % above or below the base case value. This is thanks to the detailed study of the investment cost of a fast pyrolysis plant. Even though the landfill costs of the char comprise 6 % of total costs of a fast pyrolysis plant, it has only a small influence on the variability of the NPV. Therefore the uncertainty about the landfill cost will be omitted when calculating maximum prices. Especially the value of the green power certificates (which is changeing), the willow purchase price and the oil yield are important variables for determining the NPV.

5.2.6 Maximum willow prices

After analysis of the NPV's sensitivity for the values of the uncertain variables and the importance of the uncertainty of these variables in explaining the NPV's variability, some variables can be omitted from further analysis. For instance, the uncertainty with respect to the landfill costs of char and ashes has been omitted when calculating the maximum willow prices in the next section. During calculation of the maximum prices for a gasification plant, the uncertainty about the price of the make up water and the fixed costs of the gasification plant have also been omitted by setting both variables at its base case value. The same has been done for the investment exponent during calculation of the maximum prices that are valid in a fast pyrolysis plant. When the maximum prices for a combustion plant were calculated, the available farmland, the willow yield, the price of make up water and the efficiency uncertainty dummy have been set at their base case values too. (We checked whether inclusion or exclusion of these variables had an impact on the calculated maximum prices, and there was only a slight difference on the results). In table 39 one can follow the calculation of the maximum willow price. In column 1 one can see the scales of operation for which the maximum prices have been calculated. These scales of operation are the same as the ones that have been used in the meta-analysis of the capital cost of a fast pyrolysis plant. In columns 2, 3 and 4 one can read the maximum willow price that an investor in combustion, gasification or fast pyrolysis is willing to pay to convert the annual feedstock of willow so that the probability that his investment is profitable (i.e. NPV > 0) is at least 95 %.

Scale	Estimated maximum price that an investor might be willing to pay (EUR t_{dm}^{-1})			p_{willow}	Conversion	p_{willow}-c_{willow}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
ha	*Combustion*	*Gasification*	*Pyrolysis*	*Max*	*Choice*	*Price-cost*
500	-298	-305	-37	-37	Pyrolysis	-87
1000	-179	-170	-20	-20	Pyrolysis	-70
1500	-123	-108	-10	-10	Pyrolysis	-60
2000	-89	-70	-1	-1	Pyrolysis	-51
2500	-64	-40	6	6	Pyrolysis	-44
3000	-45	-20	11	11	Pyrolysis	-39
3500	-31	-3	17	17	Pyrolysis	-33
4000	-18	11	22	22	Pyrolysis	-28
4500	-8	24	26	26	Pyrolysis	-24
5000	1	34	30	30	Pyrolysis	-20
5500	9	43	33	43	Gasification	-7
6000	16	50	37	50	Gasification	0

table 39: Maximum willow price in function of the scale of operation

One can see that the prices that correspond to the combustion plant are the lowest and that the prices corresponding to the fast pyrolysis plant are the highest until willow is available from 5 000 hectares of farmland. The highest attainable price mentioned in column 5 is the maximum of the prices mentioned in columns 2, 3 and 4. In column 6 it has been mentioned to which of the three conversion technologies the highest attainable price belongs. Fast pyrolysis clearly is the most economical technology for all potential scales of operation in the Belgian Campine. However, one should note that pyrolysis becomes competitive with gasification at higher scales, i.e. when willow can be supplied from a larger area. At small scales, all prices are negative, which implies that the investor is only willing to convert the wood if a *gate fee* is paid by the farmer to the bioenergy plant. In column 7 the difference between the price that can be paid and the cultivation and harvest cost of willow (c_{willow} see paragraph 5.2.1) of 50 EUR t_{dm}^{-1} has been calculated. Only when 6 000 hectares of farmland are dedicated to willow cultivation, the conversion plant's scale is large enough to recuperate the cultivation cost of 50 EUR t_{dm}^{-1}, which implies that the price an investing company is willing to pay is always lower than the cultivation and harvest cost borne by the farmer. Finally, the data in columns 2, 3, 4 and 5 are represented in figure 19. As can be seen from the figure, the highest attainable price curve almost completely falls together with the maximum price curve of a fast pyrolysis plant, whereas it converges with the gasification curve at the highest scales. When high amounts of biomass are available, gasification is more economical than fast pyrolysis. Fast pyrolysis is especially the most appropriate technology at small scales, whereas gasification is more advantageous at high scales.

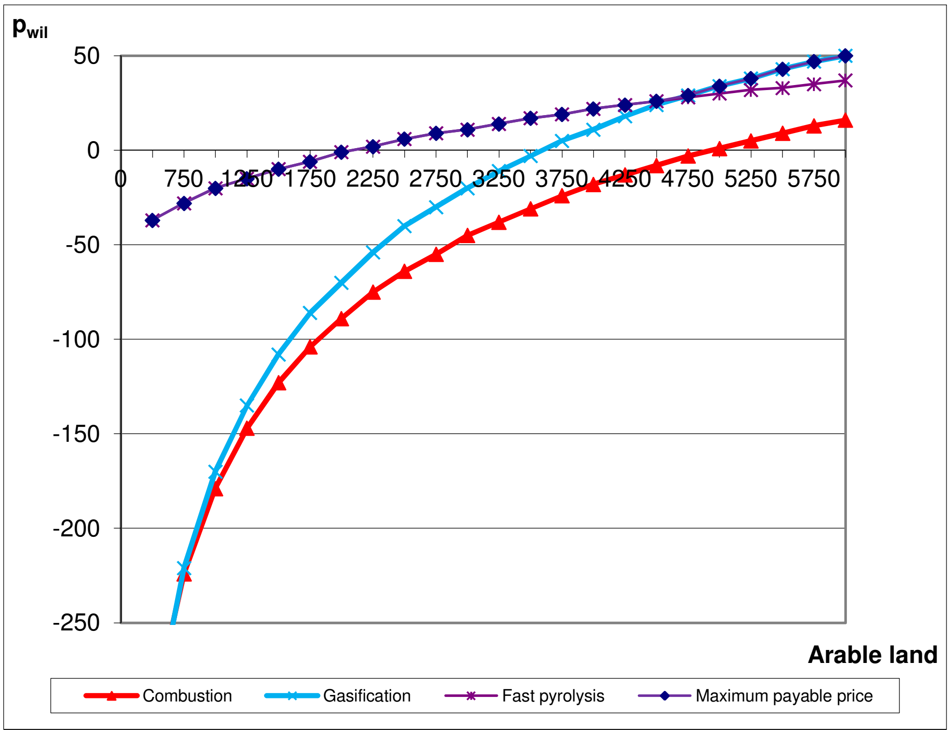

figure 19: Maximum attainable willow prices for a combustion, gasification or fast pyrolysis plant for electricity production

5.3 Risk analysis of fast pyrolysis for combined heat and power production

In chapter 4 it has been illustrated that fast pyrolysis of willow for the combined production of heat and power (CHP) is expected to be a profitable investment, on the condition that all heat can be sold locally. The alternatives, for which this condition does not hold, do not seem profitable at all. Combustion, gasification or fast pyrolysis of willow for electricity production only all appear loss making. Of these three alternatives, fast pyrolysis was the less loss making conversion technology for the expected conversion scales in the Belgian Campine, whereas at higher scales gasification might be more appropriate. Because CHP production by means of fast pyrolysis is the only profitable conversion route so far, we come back to this technology in order to fully grasp and study its economic risk.

5.3.1 Recap of the base case

In the Belgian Campine at least 2 041 ha of farmland hold Cd concentrations exceeding guide values (i.e. the Cd concentration of 1,2 mg per kg soil that should be achieved once it is decided to remediate the soil) set by the Flemish Government (Schreurs, Voets et al. 2011) while it is believed that some 2 400 ha can be dedicated to the cultivation of phytoextracting crops. If the contaminated land across the Dutch-Belgian border will also be remediated, metal accumulating willow can be grown on a maximum of 6 420 ha of agricultural land. In the Belgian part of the Campine, an annual production of 19,2 kton of dry biomass per year is attainable given an average biomass yield of 8 ton dry matter per hectare per year. This means that a fast pyrolysis plant that is operational during 7 000 hours per year, will convert 2,74 ton dry biomass per hour. The total capital cost of such a fast pyrolysis plant for the combined production of heat and power is recapitulized in table 40.

Processing capacity	2,74 t_{dm} h^{-1}
Gross electric power	5,5 MW_e
Capital cost pyrolysis reactor	7,00 MEUR
Capital cost CHP engine	3,71 MEUR
Total plant cost (year 1)	10,71 MEUR

table 40: Recap of the total plant cost of the base case fast pyrolysis plant for the combined production of heat and electricity

The cash flows generated by an investment of 10,71 MEUR for a fast pyrolysis plant that converts willow at 2,74 t_{dm} h^{-1} for the combined production of electricity and heat with a gross electric capacity of 5,5 MW_e, results in a positive NPV over 20 years of 3,04 MEUR, i.e. for the base-case assumptions the investment in a fast pyrolysis plant for the valorisation of phytoextracting crops appears to be profitable with an internal rate of return of 13 %. The expected cash flows for year 1 are reproduced in table 41. The structure is more or less the same as in table 19, which could also been used for identifying important variables. The difference is that table 41 only represents the cash flows in year 1, whereas table 19 adds all cash flows over a period of 20 years at a discount rate of 9 %. The latter is not merely a multiplication of the cash flows of year 1 by 20, because especially for the combined heat and power certificates, cash flows might differ from year to year. Here the cash flows for year 1 are chosen because they have a larger impact as they are only discounted 1 year.

Expenditure/revenue item	Amount (EUR)	Share of total expenditure/revenue (%)
Total expenditure	***4 818 725***	***100 %***
Capital cost	1 345 311	28 %
Maintenance & operational cost CHP	891 698	19 %
Fixed costs pyrolysis	350 221	7 %
Biomass purchase	960 000	20 %
Biomass transport	134 400	3 %
Biomass pre-treatment	192 000	4 %
Staff cost	282 500	6 %
Char landfill cost	289 837	6 %
Water consumption	1 478	0 %
Pilot fuel	371 280	8 %
Total revenues	***5 545 241***	***100 %***
Electricity sales	1 863 963	34 %
Heat sales	214 737	4 %
Green power certificates	2 534 133	46 %
Combined heat and power certificates	932 408	15 %

table 41: Expected cash flows in year 1 for a fast pyrolysis plant in the Belgian Campine converting 2,74 t_{dm} h^{-1}

5.3.2 Monte Carlo simulations

Although the base case consists of the most probable assumptions, it is uncertain that the investment in the fast pyrolysis plant will yield a NPV of cash flows of 3,04 MEUR. Monte Carlo simulations have been performed in order to check the sensitivity of the NPV for changes in the values of the input variables and in order to indicate the extent to which an investor runs the risk of a negative NPV. At first, 14 variables were allowed to change according to realistic ranges (see also table 37), but the NPV was the least sensitive to the fixed operational cost of the fast pyrolysis reactor, the price of the make up water, the landfill cost per ton of char, and the price of heat. Next the uncertainty concerning the values of the 10 variables stated in table 43 were allowed to be variable during Monte Carlo simulations. The table states the 10 variables with their respective minimal, base case (i.e. most probable) and maximal values.

The result of 10 000 Monte Carlo simulations is as follows: under the above stipulated assumptions and uncertainties, there is a 87 % chance of a positive NPV (see table 42). The mean NPV is close to the base-case NPV of 3,04 MEUR. The standard deviation equals 3,1 MEUR. A summary of the Monte Carlo statistics can be found in table 42.

Statistic	***Forecast value***
Trials	10 000
Base Case	3.040.409,66 €
Mean	3.213.061,58 €
Median	2.662.135,42 €
St.dev.	3.130.605,29 €
Skewness	0,9352
Minimum	-3.821.515,86 €
Maximum	20.840.215,54 €
P(NPV>0)	87 %

table 42: Summary statistics of the Monte Carlo simulations on the net present value of the cash flows of a fast pyrolysis plant for the combined production of heat and power

Variable		***Values***		
		Minimal	***Base-case***	***Maximal***
Farmland	x_{ha}	650 ha	2 400 ha	3 000 ha
Willow yield	x_{tdm}	5 t_{dm} ha^{-1} yr^{-1}	8 t_{dm} ha^{-1} yr^{-1}	15 t_{dm} ha^{-1} yr^{-1}
Oil yield	$x_{oil\%}$	60 %	65 %	70 %
Sales price GPC	x_{GPC}	80 EUR MWh_e^{-1}	100 EUR MWh_e^{-1}	120 EUR MWh_e^{-1}
Sales price HPC	x_{HPC}	31 EUR MWh_{PEB}^{-1}	35 EUR MWh_{PEB}^{-1}	45 EUR MWh_{PEB}^{-1}
Sales of electricity	x_{elec}	60 EUR MWh_e^{-1}	70 EUR MWh_e^{-1}	80 EUR MWh_e^{-1}
Willow purchase cost	x_{wilpur}	30 EUR t_{dm}^{-1}	50 EUR t_{dm}^{-1}	70 EUR t_{dm}^{-1}
LHV of pyrolysis oil	x_{LHV}	16 GJ t^{-1}	17 GJ t^{-1}	18 GJ t^{-1}
Investment constant	x_{cst}	2 697 333,81	3 486 567,30	4 285 787,76
Investment exponent	x_{exp}	0,6267	0,6914	0,7799

table 43: Uncertainty ranges for Monte Carlo simulations on the net present value of the cash flows of a fast pyrolysis plant for the combined production of heat and power

In figure 20 one can see the contribution of the uncertainty of each variable to the variance of the NPV. A green bar indicates that an increase in the value of a variable augments the NPV and hence increases the profitability of the investment. A negative contribution is indicated by the red bars. For example, if more farmland is available for phytoextraction, economies of scale come into play. Here the presence of economies of scale is confirmed because of the positive relationship between available farmland and the NPV. The investment exponent (which equals 0,6914) has a slightly negative influence on the NPV: a higher exponent increases the investment cost and hence lowers the NPV. A higher investment exponent also reflects less economies of scale. The most important variables influencing the NPV are: available farmland (i.e. the scale of operation), the willow biomass yield, the product yield (oil yield), the market prices of the green power certificates, the willow purchase cost and the electricity price. Together the uncertainty of the first four variables explains more than 70 % of the total NPV variance.

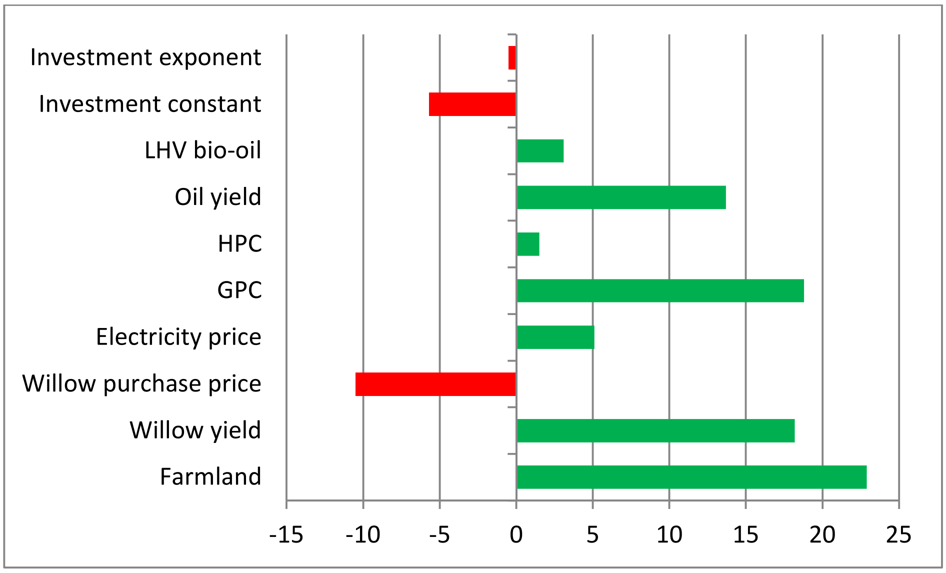

figure 20: Sensitivity analysis – contribution to variance of the NPV of the cash flows of a fast pyrolysis plant for the combined production of heat and power

Comparing figure 20 with figure 18, i.e. comparing the sensitivity of the NPV of an investment of fast pyrolysis for combined heat and power production with the sensitivity of the NPV of an investment in fast pyrolysis for electricity production only, one can conclude that the uncertainty about the revenues from the support mechanism of the green power certificates is less important when heat and power are combinedly produced. When only electricity is produced the revenues generated by the green power certificates are more important for rendering the investment profitable. If the system of the green power certificates alters, the economic risk of electricity production only is higher. When both heat and electricity are produced, economies of scale should be taken account of in reducing economic risk. Both the uncertainty about the available farmland and the willow yield explained more or less 5 % of the variability of the NPV in case of electricity production only, where they account for 40 % of the variability of the NPV when both heat and power are produced.

In the next table one can find the maximum willow prices that have been calculated for an investment in a fast pyrolysis plant for the combined production of heat and power, analogous to the calculations in table 39. At 2 500 ha (comparable to the base case) the cultivation and harvest cost of the short rotation willow can be recuperated.

Scale		**Maximum possible willow price (EUR t_{dm}^{-1})**		**p_{willow} - c_{willow}**
(1)	(2)	(3)	(4)	(5)
ha	***kt_{dm} yr^{-1}***	***Electricity production only***	***Combined heat and power***	***Price/cost difference***
500	4	-37	-2	-52
1000	8	-20	26	-24
1500	12	-10	38	-12
2000	16	-1	46	-4
2500	20	6	51	1
3000	24	11	56	6
3500	28	17	60	10
4000	32	22	63	13
4500	36	26	66	16
5000	40	30	68	18
5500	44	33	70	20
6000	48	37	71	21

table 44: Maximum willow price in function of the scale of operation for a fast pyrolysis plant for combined heat and power production

Finally, the numerical values for the input variables in the Monte Carlo simulations (drawn at random from their assumed probability distributions) are inserted into an meta-regression model resulting in equation 5.1. The legend of the symbols can be found in table 43.

$$\begin{aligned} NPV = & -7{,}8\,.\,10^{7} + 2{,}9\,.\,10^{3}x_{ha} - 1{,}1\,.\,10^{5}x_{wilpur} - 2{,}2x_{cst} \\ & - 7{,}6\,.\,10^{6}x_{exp} + 1{,}3\,.\;10^{3}x_{LHV} \\ & + 1{,}6.\,10^{5}x_{elec} + 1{,}5\,.\,10^{5}\,x_{GCC} \\ & + 1{,}4\,.\,10^{5}x_{HPC} + 6{,}4\,.\,10^{5}\,x_{tdm} \\ & + 5{,}2\,.\,10^{7}x_{oil\%} \end{aligned} \tag{5.1}$$

This equation can now be used to estimate the NPV of a specific scenario. For example if one wants to calculate the NPV for the base-case, just fill out the base-case values of table 43. The signs of the coefficients correspond to the signs of the contribution of each variable to the variance of the NPV illustrated in figure 20. In table 45 the coefficients of the regression analysis can be found. All coefficients are statistically significantly different from zero (see column significance) at a 5 % significance level and the ranking of the variables according to their standardised coefficients corresponds to the ranking from figure 20.

Symbol	*Unstandardised coefficient*	*Standardised coefficient*	*Significance*
(constant)	-77 793 759,83		0.000
x_{ha}	2 911,15	0,460	0.000
x_{wilpur}	-114 346,07	-0,299	0.000
x_{cst}	-2,21	-0,228	0.000
x_{exp}	-7 608 214,81	-0,076	0.000
x_{LHV}	1 299,43	0,171	0.000
x_{elec}	156 955,56	0,205	0.000
x_{GPC}	153 622,95	0,403	0.000
x_{HPC}	141 866,01	0,133	0.000
x_{tdm}	640 138,27	0,425	0.000
$x_{oil\%}$	52 617 305,83	0,347	0.000

table 45: Coefficients of the regression analysis based on the Monte Carlo simulations

5.3.3 Design of experiments

The same uncertainties have been investigated by means of Plackett-Burman designs. For the 10 uncertain variables, 12 Plackett-Burman designs and 12 Box-Wilson foldover designs have been simulated. The results of the design are represented in table 46. In each run, a variable can take its base-case value (indicated by a plus sign) or its extreme value that has a negative impact on the NPV (indicated by a minus sign). This will be the minimal value in table 43 if a lower value has a negative impact on the NPV (e.g. a lower calorific value which decreases energy production and hence sales of electricity); it is the maximal value in table 43 for variables that have a negative impact on the NPV if an increase in their value impacts negatively on the NPV (e.g. the investment exponent). The Box-Wilson foldover is the opposite of the Plackett-Burman run: i.e. when the available farmland takes its base case value in the first run of the Plackett-Burman design (as indicated by the plus sign in column "P1" in table 46), it will take a minus sign in the first run of the opposing Box-Wilson foldover. This means that in the 12th run of the Box-Wilson foldover every variable takes its base case value, and hence the NPV of this 12th run corresponds to the NPV of the base-case of 3,0 MEUR. As explained in paragraph 2.4.3 "Plackett-Burman designs" every run (except the 12th Box-Wilson run) has half of the variables at their extreme value negatively impacting the NPV. Hence it is clear that all results are lower than the base-case result. The meta-regression model of these 24 runs is represented by equation 5.2 (the symbols of the variables correspond to the ones mentioned in table 46):

$$\begin{aligned} NPV = \; & -2{,}8\,.\,10^{6} - 8{,}7\,.\,10^{5} y_{ha} + 6{,}3\,.\,10^{5} y_{wilpur} \\ & + 5{,}5\,.\,10^{5} y_{cst} + 5{,}9\,.\,10^{4} y_{exp} + 3{,}2.\,10^{5} y_{LHV} \\ & + 4{,}7\,.\,10^{5} y_{elec} + 8{,}0\,.\,10^{5} y_{GCC} \\ & + 2{,}3\,.\,10^{5} y_{HPC} - 3{,}2\,.\,10^{5} y_{tdm} \\ & + 6{,}9\,.\,10^{5} y_{oil\%} \end{aligned} \qquad (5.2)$$

	P1	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*	*P11*	*P12*
y_{ha}	+	+	-	+	+	+	-	-	-	+	-	-
y_{wilpur}	-	+	+	-	+	+	+	-	-	-	+	-
y_{cst}	+	-	+	+	-	+	+	+	-	-	-	-
y_{exp}	-	+	-	+	+	-	+	+	+	-	-	-
y_{LHV}	-	-	+	-	+	+	-	+	+	+	-	-
y_{elec}	-	-	-	+	-	+	+	-	+	+	+	-
y_{GPC}	+	-	-	-	+	-	+	+	-	+	+	-
y_{HPC}	+	+	-	-	-	+	-	+	+	-	+	-
y_{tdm}	+	+	+	-	-	-	+	-	+	+	-	-
$y_{oil\%}$	-	+	+	+	-	-	-	+	-	+	+	-
NPV PB	-5,3	-4,6	-1,8	-3,5	-3,3	-2,8	-1,7	-1,5	-3,3	-2,5	-0,7	-2,3
NPV BW	-2,0	-1,0	-4,3	-2,2	-2,1	-2,7	-5,0	-6,7	-1,7	-1,5	-7,0	+3,0

table 46: Results of the Plackett-Burman design and Box-Wilson foldover

The details of the regression equation can be found in table 47. The variables in this equation should be interpreted somewhat differently: if a variable takes its base case value, it gets the value +1, if it takes its extreme value with a negative impact on the NPV, the variable takes the value -1. Equation 5.2 leads to somewhat other conclusions. Although van Groenendaal and Kleijnen state that the application of the Box-Wilson foldover leads to unbiased estimators of the main effects, there are some important differences to note. The first thing to note is that the sign of the estimator of the main effect of the available farmland does not correspond to the sign reflected by one-factor-at-a-time sensitivity analysis or to the sign this variable has in equation 5.1. If the willow yield increases from 5 t_{dm} ha^{-1} yr^{-1} to 8 t_{dm} ha^{-1} yr^{-1} equation 5.2 states that the NPV on average in the 24 runs lowers the NPV with 318 238 EUR. However, this variable is not significantly different from zero at the 10 % significance level (see significance in table 47 = 0,321). The order of importance differs from the ranking of the variables according to the Monte Carlo simulations although the standardised coefficients in table 47 are in the same order of magnitude of the ones in table 45, except the standardised coefficient of the willow yield. The willow yield is the second most important variable according to the Monte Carlo simulations, but according to the Plackett-Burman its coefficient comes on the 7th place, although that coefficient has a significance of only 0,321 so it is probably incorrect. The difference in sign is correct for the willow purchase cost, the investment constant and the investment exponent: as the Plackett-Burman simulations measure the effect of changing y_{wilpur} from +1 to -1, i.e. from the base case value of 50 EUR t_{dm}^{-1} to the extreme value negatively impacting the NPV or the maximal value of 70 EUR t_{dm}^{-1}. The NPV should be higher if y_{wilpur} equals +1 compared to -1, and that corresponds to the positive sign of the standardised coefficient of 0,303 in table 47. This appears to contrast with the negative sign of the standardised coefficient of -0,299 in table 45 but it is not: the effect of the unit willow purchase cost is measured differently during Monte Carlo simulations by means of the variable x_{wilpur}. In the base case x_{wilpur} takes the value of 50 EUR t_{dm}^{-1}: when the purchase cost increases, i.e. when x_{wilpur} augments, this higher purchase cost results in a lower NPV as indicated by the minus sign of -0,299 in table 45. Although the signs differ in both tables, it (counter-intuitively) represents the same effect. The only thing that stays somehow unclear, is the negative sign of the available farmland in the Plackett-Burman designs. It is expected though that it can be explained by the huge difference in available farmland that the -1 value represents compared to the +1 value: when x_{ha} equals -1 it actually represents a case where the minimal farmland is 650 ha, compared to 2 400 ha. When there is only 650 ha of farmland available, the scale of the plant might be too low in order to be realistic and hence the effect of the available farmland might not be representative for realistic cases.

Symbol	*Unstandardised coefficient*	*Standardised coefficient*	*Significance*
(constant)	-2 776 261,83		0.000
y_{ha}	-869 991,40	-0,420	0,014
y_{wilpur}	627 176,98	0,303	0,063
y_{cst}	546 064,11	0,264	0,100
y_{exp}	59 127,00	0,029	0,851
y_{LHV}	317 356,80	0,153	0,322
y_{elec}	467 979,00	0,226	0,153
y_{GPC}	797 135,41	0,385	0,023
y_{HPC}	230 059,96	0,111	0,469
y_{tdm}	-318 238,37	-0,154	0,321
$y_{oil\%}$	696 530,53	0,337	0,042

table 47: Coefficients of the regression analysis based on the Plackett-Burman and Box-Wilson simulations

5.4 Conclusion about the economic risk of fast pyrolysis

In the first part of this chapter, it has been proved that fast pyrolysis is not only the least loss making conversion technology compared to combustion and gasification, but that its standard deviation is also the lowest when real uncertainties are taken into account (even though that the maximum possible NPV is the highest for gasification). Therefore, in the next part of the chapter, the focus was on the exploration of the economic risk of fast pyrolysis combined with CHP, which is profitable on the condition that there is a neighbouring heat consumer at the pyrolysis plant.

In table 48 the data about the sensitivity of the NPV throughout this chapter have been summarized. Although not always perfectly comparable due to measurement differences (e.g. the difference in the measurement of the uncertainty about the initial investment expenditure), some important conclusions can be put forward. The scale of the plant plays an important role in a fast pyrolysis plant with a CHP engine, and also in a gasification plant. Both the willow yield and the available farmland explain a large part of the NPV's uncertainty in both cases. When it comes to technical uncertainties, the uncertainty about the electric efficiency is extremely important in the gasification case. This uncertainty can be reduced by increasing scale, as indicated by figure 9 where it is illustrated that efficiency estimates converge at larger plants with a higher electric capacity. The uncertainty about the exact investment cost on the other hand is less important for pyrolysis than for combustion and gasification. Especially for an investment in a combustion plant, it is extremely important that detailed engineering plans are developed, in order to reduce the uncertainty about the investment expenditure as it explains more than 60 % of the variability of the combustion plant's NPV. The uncertainty about economic variables which influence the operational costs and revenues are the least important for a gasification plant. With regard to the changes in the green power certificates system, it is expected that it will have the heaviest impact on fast pyrolysis for electricity production.

Sensitivity NPV	Combustion (electricity)	Gasification (electricity)	Pyrolysis (electricity)	Pyrolysis (CHP)
Scale uncertainty				
Willow odt ha yr	2,1 %	12,1 %	1,8 %	18,2 %
Agriland ha	1,1 %	14,4 %	1,4 %	22,9 %
Technological uncertainty				
Efficiency uncert.	-0,7 %	30 %		
LHV willow	0,7 %	0 %		
LHV oil			2,3 %	3,1 %
Oil yield			15,1 %	13,7 %
Investment uncertainty				
I_0 uncert. dummy	-61,7 %	-27,9 %		
I_0 constant			-9,8 %	-5,7 %
I_0 exponent			-0,9 %	-0,5 %
Operational expenditure uncertainty				
Willow cost	-10,8 %	-2,5 %	-17,7 %	-10,5 %
Fixed cost	-8,5 %	-0,8 %	-8,3 %	unimportant
Cost water	-	-	0 %	unimportant
Operational revenues uncertainty				
Price GPC	10,5 %	8,4 %	31 %	18,8 %
Price electricity	2,2 %	1,8 %	7,2 %	5,1 %

table 48: Comparison of the sensitivity of the NPV for combustion, gasification and fast pyrolysis of willow

The base case economic model indicated that the NPV of an investment in fast pyrolysis for the combined production of heat and power is positive, which means that the revenues are high enough to recuperate the production cost of 180,96 EUR MWh^{-1} of electricity (= the total yearly expenditure of 5 545 241 EUR – see table 41- divided by the product of the gross electric capacity of 5,5 MWe and the 5 000 operation hours of the CHP engine). The base case values however are highly uncertain. First, these uncertainties have been studied by Monte Carlo simulations. Under current knowledge there is a 87 % chance of a positive NPV. The problem with Monte Carlo simulations is that the assumed probability distributions are often unknown and hence represent the best guess of the expert. Therefore it has been argued that the results of Monte Carlo simulations might have a level of uncertainty, because the assumed distributions might differ from reality.

The Plackett-Burman design and its Box-Wilson foldover are suggested as an alternative for estimating risk. The problem with the Plackett-Burman design is that they are more difficult to interpret: as the variables either take a value of +1 or -1, the estimator of the main effect is not comparable to the estimator found during Monte Carlo simulations. The standardised coefficients however have more or less the same magnitude, although the order of importance differs. Another problem is that the Plackett-Burman technique only focuses on the extreme values of the ranges found in literature. This information is relevant for decision makers, but the combination of extreme values in the runs of the Plackett-Burman designs are very unlikely to occur in reality, whereas these extreme situations are possibly underrepresented during Monte-Carlo simulations. It is suggested that both Monte Carlo and Plackett-Burman simulations provide complementary information for decision makers. The focus for the Plackett-Burman design should not be on the meta-model, but on the possible outcomes of the NPV: they indicate the maximal losses an investor can run. It is believed that for the main effects the meta-model of the Monte Carlo simulations is better suited.

In our opinion, design of experiments is mainly helpful to gain a first understanding of the problem (Mavris and Bandte 1995) and does not fully grasp economic risk as these techniques are only concerned with the worst case values of the input variables of the economic model. There are two important drawbacks: only two values are being used for each variable, where they could, in fact, take any number of values; and no recognition is being given to the fact that the base case value is much more likely to occur than the extreme values having a negative impact on the NPV.

6 Risk reduction: input optimisation

6.1 Introduction

From chapter 5 it has been concluded that an investment in fast pyrolysis is very dependent on the economic scale of operation (cf. the sensitivity of the NPV for the contracted available farmland and the average willow yield that is expected in the Belgian Campine), the price of the green power certificates and the oil yield. The uncertainty with regard to these variables were the four most influencial variables for the variability of the NPV. It is important to reduce this variability by increasing the scale of operation, lower the dependence on the green power certificates (especially on the occasion of the changes in 2013), and increase the oil yield.

The scale can be increased by searching for other feedstocks that can complement the stream of willow that will be available in the Belgian Campine. One option is to set up contracts with farmers in other parts of the Campine (e.g. the Dutch Campine), or in the province of Limburg or Antwerp. Though it is expected that merely augmenting the amount of processed willow will not decrease the dependence on the green power certificates and the oil yield. One option is to find a combination of feedstocks that improves oil quality and oil yields (e.g. higher heating value, higher oil yield, lower water content). Cornelissen, Jans et al. (2009) showed that fast co-pyrolysis of willow and waste of biopolymers synergistically improves the characteristics of the pyrolysis process: e.g. reduction of the water content of the bio-oil, more bio-oil and less char production and an increase of the HHV of the oil. The impact of these synergistic effects have been investigated in the next sections.

Another opportunity to decrease the dependence from the value of the green power certificates is to search for alternative products: for instance a shift from energy production to materials production might result in more stable economic prospects. Examples to accomplish this goal are ample: extracting high value chemicals from the oil (which depends on the composition of the feedstock), upgrading of the oil into transport fuels (or other applications), valorisation of the byproducts of fast pyrolysis, change process conditions in order to obtain a different product mix. In chapter 6 the economic impact of a change in "inputs" on the economic profitability has been investigated by means of the case of fast co-pyrolysis with biopolymer waste. It is hoped that the increase in scale and the synergistic effects might enhance results. Some biopolymers might even result in the production of specialty chemicals. In chapter 7 the economic potential of valorising the "output" of char (the byproduct of fast pyrolysis) and a change in process conditions that alters the ratio of the outputs is investigated.

6.2 Co-pyrolysis with bioplastics

Fast co-pyrolysis of biomass and waste of biopolymers synergistically improves the characteristics of the pyrolysis process: e.g. reduction of the water content of the bio-oil, more bio-oil and less char production and an increase of the HHV of the oil. This section investigates the economic consequences of the synergistic effects of fast co-pyrolysis of 1:1 w/w ratio blends of willow and different biopolymer waste streams via private cost-benefit analysis (i.e. discounted cash flows) and Monte Carlo simulations taking into account uncertainties (Cornelissen, Jans et al. 2009).

Fast pyrolysis of biomass results in the production of char, gas, and a large amount of bio-oil with a relatively high water content, which is a major drawback for its use. The potential of fast co-pyrolysis of 1:1 w/w ratio blends of willow and biopolymers (PLA, corn starch, PHB, Biopearls, Eastar, Solanyl and potato starch) as an upgrading step for the production of pyrolysis oil has been investigated (Cornelissen, Jans et al. 2009). In fact, fast co-pyrolysis results in interactions that inhibit the formation of pyrolytic water. Fast co-pyrolysis of willow blended with polyhydroxybutyrate (PHB), polylactic acid (PLA), Biopearls and potato starch resulted in a synergistic decrease in the amount of pyrolytic water. In some cases however, positive effects of fast co-pyrolysis are combined with negative effects: e.g. fast co-pyrolysis of willow and corn starch yields a bio-oil with less pyrolytic water, but the amount of bio-oil produced has also been reduced compared to fast pyrolysis of pure willow (Cornelissen, Yperman et al. 2008a; Cornelissen, Jans et al. 2008b; Cornelissen 2009; Cornelissen, Jans et al. 2009).

The results are valid for willow and biopolymer blends that have been pretreated by shredding the material into small particles of 2 mm that have been dried at 105 °C (378 K) (Cornelissen 2009). The seven biopolymers are ranked according to decreasing profitability (see table 52 in paragraph 6.5). In a next step the maximum prices for collecting and transporting shredded and dried biopolymers to the pyrolysis plant have been calculated. Finally, the maximum prices for collecting and transporting biopolymers are subjected to economic uncertainties with the help of Monte Carlo sensitivity analyses.

It is illustrated that from an economic point of view, the use of biopolymer waste is preferred to pure biopolymers for fast co-pyrolysis with willow, as market prices of pure biopolymers are too high to make fast co-pyrolysis profitable. Because biopolymers make up less than 1 % of the global plastic market, they lack economies of scale and its waste streams are small and scattered. Above this, communication problems arise when setting up a dedicated waste management structure: it might be confusing for citizens to sort compostable biopolymers separately from traditional and non-compostable petrochemical plastics. This is aggravated by the fact that not all biopolymers are compostable, because they are defined either as polymers from renewable origin (but not necessarily compostable), or as polymers from petrochemical origin that are compostable. This makes managing biopolymer waste streams very complex and costly. As a solution the calculated maximum prices for collection and transportation of the biopolymers to the pyrolysis plant (including pretreatment) should be considered as the maximum prices that can be paid by a company investing in fast co-pyrolysis of willow and biopolymers to an organisation that needs to dispose of a large stream of biopolymer waste. Examples of the latter are organisers of large festivals where drinks are sold in cups made from biopolymers, or fast food chains using biopolymer boxes for serving meals resulting in large daily streams of biopolymer waste in their bins. Currently, these organisations dispose of their biopolymer waste by delivering them to a composting waste processing company at a cost of 80 EUR per ton. A company investing in fast pyrolysis thus can use the maximum prices during negotiations about the delivery of biopolymers to the pyrolysis plant with those organisations that want to dispose of large streams of biopolymer waste. These negotiations might lead to win-win situations when a company with biopolymer waste has to pay less than 80 EUR per ton to dispose of its waste, while the company investing in fast co-pyrolysis gets its biopolymer feedstock at a cost lower than the maximum payable price. Conclusively, this section investigates whether the economics of fast pyrolysis might be enhanced by using synergistic waste streams, solving at the same time the disposal problem associated with phytoextraction and providing an alternative processing technique for biopolymer waste which is expected to grow in volume in the next decade.

It is expected that phytoextraction in the Belgian Campine yields 19,2 kt_{dm} of contaminated willow per year. If willow is blended with biopolymers on a 1:1 w/w ratio, 38,4 t_{dm} yr^{-1} of feedstock needs to be co-pyrolysed which implies an increase in the scale of operation. Assuming that the pyrolysis reactor is operational during seven thousand hours per year, this means that the reactor pyrolyses 5,5 ton biomass per hour. It is assumed that the bio-oil can be burnt in an engine in order to produce combined electricity and heat (CHP) with electric and thermal efficiencies of 43 % and 37 %, respectively (Stroobandt 2007).

6.3 Assumptions with respect to the cash flows

All assumptions with regard to *economic* aspects, such as the total plant cost, expenditure and revenue items are the same as for the combined heat and power plant from paragraphs 4.3 and 5.3. Some important, specific assumptions with respect to the *technical* aspect (such as oil yield and lower heating value of the oil) are explicitly mentioned and explained in what follows.

6.3.1 Collection and transport of the biopolymers

The expense for collection, transportation and pretreatment of the bioplastic waste cannot be estimated yet, because the production of applications with biopolymers is still too low. The collection of bioplastics via organic waste or plastics, metals and cardboard waste can be considered, but the amount of biopolymers in these waste streams is still too low in order to economically separate the biopolymers from the other waste fractions. Therefore, the calculation of the maximum price for collection and transportation (including pretreatment) of each biopolymer waste stream to the pyrolysis plant is one of the central topics in this chapter.

6.3.2 Revenues from crotonic acid

Besides bio-oil, crystals of crotonic acid (which are a source of value added chemicals) are formed during co-pyrolysis of willow with PHB. These crystals can be easily separated so that the costs involved during partitioning are negligible. Prices for very small quantities of very high quality crotonic acid (98 to 99% purity) used in laboratories can be looked up in online supplier's catalogues. Prices for bulk quantities however are dependent on the amount of crotonic acid ordered which in turn determine quantity discounts granted by suppliers. As a consequence bulk prices are not mentioned on suppliers' and manufacturers' websites and can only be retrieved by directly contacting the supplier. According to Belgian distributors, dividing the market prices found for lab quantities and qualities by a factor 5 to 10 is deemed to correct for the large quantities and the possible lower quality of the crotonic acid obtained by fast copyrolysis of willow and PHB. According to distributors' online catalogues 500 g of crotonic acid is worth 20 to 25 EUR. Applying the factor 5 to 10, this means that crotonic acid can be sold at a price of 5 to 10 EUR kg^{-1}. In the base case, the sales price is set, pessimistically, at 5 EUR kg^{-1}. Because crotonic acid has several appellations like trans-2-butenoic acid or beta-methylacrylic acid, its Chemical Abstracts Service (CAS) registry number (107-93-7) has been used to retrieve prices and to avoid mistakes.

6.3.3 Combined heat and power production from bioplastics

The CHP engine produces electricity and heat. Electric and thermal efficiencies are expected to be 43 % and 37%, respectively. By combusting the bio-oil, 43 % of its lower heating value (LHV) is converted into electricity and 37 % of its LHV is converted into heat. Taking the higher heating value (HHV) would lead to an overestimation of electricity and heat generation, because this assumes that the heat in the water vapour released during combustion can be recovered. As it is not possible to measure the LHV of the pyrolysis oils, an estimation of the LHV based on the HHV and the water content of the bio-oil has been made via pairwise regression analysis of existing literature data (Chang, Chang et al. 1997; Faaij, van Doorn et al. 1997; Bridgwater and Peacocke 2000; Huang, McMulland et al. 2000; Fahmi, Bridgwater et al. 2008). Some data points of HHV, LHV and water content μ (in wt%) have been inventoried. Each of these points are then compared with each of the other data points. Each time two data points are compared and the relationship between HHV, LHV and μ has been calculated. Finally, the average relationship has been determined as:

$$LHV = 0{,}968 \times HHV - 4{,}981 \times \mu \qquad (6.1)$$

6.4 Summary of the chemical experiments' results

The chemical experiments are performed in a semi-continuous, home-built, lab scale pyrolysis reactor (Cornelissen, Jans et al. 2009). Each time the dry feedstock with a mass of 100 g (being either 100 g dry willow or a dry willow/biopolymer blend with a w/w ratio of 1:1) has been pyrolysed at 723 K. Heat transfer takes place by an Archimedean screw constantly moving the sand medium. The entire system was continuously flushed with nitrogen gas in order to guarantee an oxygen-deficient environment.

Tables 49-51 describe the results of the chemical lab scale experiments. In table 49 an overview of the pyrolysis yields of condensables (= total amount of bio-oil and crystals), char and non-condensable gases is provided. In table 50 the condensables are subdivided into bio-oil and crystals and shows the water content of each bio-oil obtained from the fast pyrolysis of pure willow or the fast co-pyrolysis of willow and biopolymers. The averaged experimental HHVs of the different bio-oils are summarised in table 51.

In table 49 it is illustrated that fast co-pyrolysis of willow and biopolymers sharply reduces the char yield compared with the willow reference. Except for the blends with corn starch and Eastar, fast co-pyrolysis with bioplastics also increases the amount of condensables produced. In table 50 it is shown that a reduction in the water content is obtained via fast co-pyrolysis of willow with biopolymers. An additional advantage of fast co-pyrolysis is shown in table 51: except for Solanyl, the addition of biopolymers increases the HHV of the bio-oil produced from willow/biopolymer blends in comparison with the bio-oil of pure willow. Fast co-pyrolysis of willow and PHB results, besides in bio-oil, in crystals of crotonic acid which are easily separated.

Tables 49, 50 and 51 are now translated into financial data based on the assumptions described in paragraph 6.3. These assumptions are then used to calculate the maximum price for collecting the biopolymers.

	Pure willow	*Willow - PLA*	*Willow - Corn starch*	*Willow - PHB*	*Willow - Biopearls*	*Willow - Eastar*	*Willow - Solanyl*	*Willow - Potato Starch*
Input (wt%)*								
Willow	100,00	51,80	50,36	50,06	49,90	49,83	52,57	49,97
Biopolymer	0,00	48,20	49,64	49,94	50,10	50,17	47,43	50,03
Moisture	1,88	0,00	0,48	0,17	0,00	0,00	1,05	0,00
Output (wt%)								
Condensables	50,10	51,96	43,72	64,24	52,79	50,01	59,24	51,52
Char	22,39	13,46	14,47	9,50	12,92	13,92	15,24	13,49
Gases (by diff.)	27,50	34,58	41,81	26,26	34,29	36,07	25,52	34,99

table 49: Pyrolysis yields and efficiencies of the condensables, char and gas production for the different biopolymer options

	Pure willow	*Willow - PLA*	*Willow - Corn starch*	*Willow - PHB*	*Willow - Biopearls*	*Willow - Eastar*	*Willow – Solanyl*	*Willow - Potato starch*
Crystals (g)	0,00	0,00	0,00	29,70	0,00	0,00	0,00	0,00
Bio-oil (g)	50,10	51,96	43,72	34,54	52,79	50,01	59,24	51,52
Water content (wt% of bio-oil)	36,65	15,53	26,94	15,97	16,81	18,96	32,82	16,17

table 50: Subdivision of condensables into crystals and bio-oil; obtained out of 100 g input

	Pure willow	*Willow - PLA*	*Willow - Corn starch*	*Willow - PHB*	*Willow - Biopearls*	*Willow - Eastar*	*Willow - Solanyl*	*Willow - Potato Starch*
HHV (MJ kg^{-1})	16,1	18,5	18,5	20,2	19,1	20,8	15,7	19,2

table 51: HHVs of the bio-oils in Mega Joule per kilogram

6.5 Profitability of fast co-pyrolysis of willow and biopolymers

In order to calculate whether fast co-pyrolysis of willow and biopolymers is more profitable than fast pyrolysis of pure willow, the unit cost for collecting, transporting and pre-treating biopolymers is first equated with 57 EUR t_{dm}^{-1}, which is the sum of the willow purchase price (50 EUR t_{dm}^{-1}, cf. supra) and the willow transport cost (7 EUR t_{dm}^{-1}, cf. supra). This is actually a rather 'pessimistic' assumption, as it is expected that waste streams are more likely to have a negative price, i.e. the investor in a fast pyrolysis plant is expected to get paid for processing bioplastic waste. The fast (co-) pyrolysis process with the highest NPV of the cash flows then is economically the most attractive for commercialisation. In table 52 the NPV of the cash flows for fast pyrolysis of pure willow and for fast co-pyrolysis of all the willow/biopolymer blends is shown, under the assumptions described in paragraph 6.4. It is striking that the NPV of fast pyrolysis of pure willow is very negative, especially given the double scale of 5,5 t_{dm} of willow per hour compared to the positive NPV of 3,04 MEUR in table 19 for a fast pyrolysis plant processing 2,78 t_{dm} of willow per hour for the combined production of heat and power. At first sight this seems to contradict the assumed economies of scale. But one should bear in mind the technical differences with regard to table 19. In chapter 4, i.e. the base case assumptions are based on the most prevalent figures in literature, whereas the calculations in table 52 have been based on experimental data published by Cornelissen, Jans et al. (2009). The negative NPV in the current chapter is explained by the difference in oil yield on the one hand (50,10 m% according to the experiments compared to 65 m% according to literature) and the lower heating value of the produced oil on the other hand (14 GJ t^{-1} based on the HHV of 16 GJ t^{-1} in the experiments and 17 GJ t^{-1} according to literature). This actually confirms the finding in table 48 in the previous chapter that the oil yield has an important influence on the net present value of an investment in fast pyrolysis.

The last column of table 52 (where the difference between the NPV of the fast co-pyrolysis of willow and biopolymers and the NPV of the fast pyrolysis of pure willow has been calculated) proves that fast co-pyrolysis of willow with any biopolymer is economically more interesting than fast pyrolysis of pure willow, because the difference in NPV of the cash flows is positive in each row of the table (though in some case it is still negative). Fast co-pyrolysis of willow and PHB is, from an economical point of view, the most promising option, because its NPV is the highest (both for crotonic acid as a source of chemicals as for crotonic acid as a source of energy). Co-pyrolysis of willow with Eastar seems to be the second best option, followed by Biopearls, potato starch, PLA, Solanyl and corn starch. Pyrolysis of pure willow has a negative NPV of cash flows, because the experiments have been performed on willow with a rather low heating value and with a rather low oil yield. This ranking is different from the ranking obtained in Cornelissen et al. (2009) because here the focus is purely on economic aspects. As a consequence the weights of the criteria used in Cornelissen et al. (2009) will change if they would have been expressed in monetary terms. The market price for crotonic acid e.g. is much higher than the market price for electricity so that it is more than twice as important from an economic viewpoint. Also the importance of the energy recuperation criterion will differ, because the costs of the input materials reflect more dimensions than only its energy input: the costs incorporate production costs, transport costs, drying costs, etc. Based on table 52 the common conclusions with Cornelissen et al. (2009) are:

- PHB is always preferred over all the other biopolymer options, even if the crystals formed during fast co-pyrolysis of willow and PHB are not sold as crotonic acid, but when they are burnt for the production of heat and electricity assuming a LHV of 23,1 MJ kg^{-1} (Cornelissen et al., 2009) for crotonic acid. In the remainder of this article the crystals are supposed to yield revenues from sales as crotonic acid, as an economic agent will only consider the option with the highest NPV;
- PLA, Biopearls, potato starch and Eastar lead to comparable results due to the similar order of magnitude for the difference between the NPV of cash flows of fast pyrolysis of pure willow and fast co-pyrolysis of willow with one of these biopolymers;
- PLA, Biopearls, potato starch and Eastar are preferred over Solanyl, corn starch and willow;
- Solanyl is preferred over corn starch and corn starch is preferred over willow (although both blends do not result in a profitable investment yet).

The only difference compared to Cornelissen et al. (2009) is the ranking between PLA, Biopearls, potato starch and Eastar.

1:1 w/w ratio willow/biopolymer blend	**NPV (MEUR)**	**Difference**
Pure willow	-10,610	
Willow/PLA	2,494	13,104
Willow/Corn starch	-5,159	5,452
Willow/PHB *(crotonic acid - chemicals)*	341,764	352,375
Willow/PHB *(crotonic acid - fuel)*	23,408	34,019
Willow/Biopearls	4,571	15,182
Willow/Eastar	5,549	16,159
Willow/Solanyl	-1,708	8,902
Willow/Potato starch	3,633	14,243

table 52: Difference between the NPV of fast co-pyrolysis of willow and biopolymers and the NPV of fast pyrolysis of pure willow, assuming a purchase price of 50 EUR t_{dm}^{-1} for all feedstock

6.6 Importance of the distinct expenditure and revenue items

The next figures show the share of the main revenues and expenses expressed as a percentage of total discounted revenues or expenses (over the 20 year life span of the pyrolysis reactor), assuming a purchase price of 50 EUR t_{dm}^{-1} for all feedstock. In figure 23 the share of the main revenue items in the total discounted revenues for fast co-pyrolysis of the 1:1 willow/PHB blend (crystals as a source of chemicals) is illustrated. In figure 24 the same has been done for the 1:1 willow/Eastar-blend. Except for the willow/PHB-blend, the share of the main revenue items in the total discounted revenues is comparable for all blends and for pure willow.

The share of the main expenditure items in the total discounted expenditure for fast co-pyrolysis of the 1:1 willow/PHB-blend is represented in figure 21. These shares are comparable for all blends when expressed as a percentage of total discounted expenditure, e.g. illustrated by figure 22 for the willow/Eastar-blend. Except for the willow/PHB-blend, the green power certificates (cf. figure 24) make up the most important revenue when bio-oil produced during pyrolysis is converted into heat and power. The main expenditure in all cases is the investment in the pyrolysis reactor. For fast co-pyrolysis of willow and PHB the main revenue stems from the sales of crotonic acid. From a commercial viewpoint the key difference between the different feedstock mixes is that the willow/PHB plant can be considered as a crotonic acid plant that produces electricity and heat as byproducts. Its revenue is dependent on the market value of its principal produce which makes it is far less dependent on government subsidies. Because of the importance of these cash flow items, their impact is analysed during Monte Carlo sensitivity analysis.

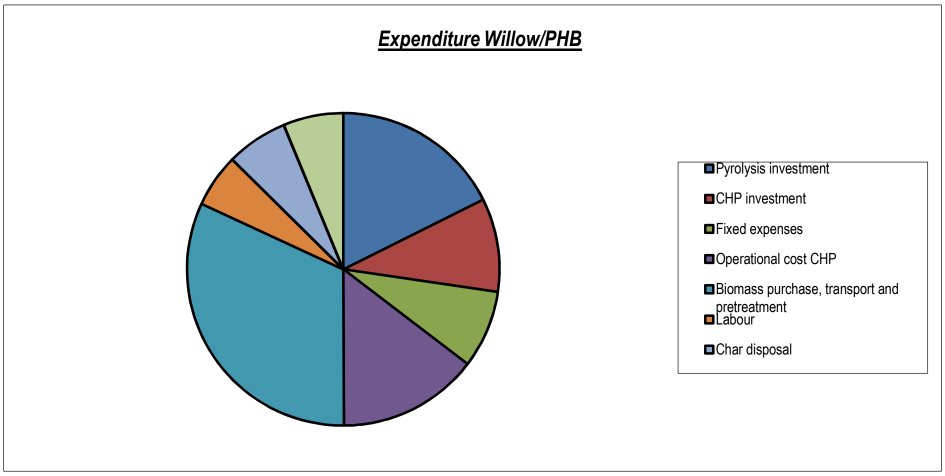

figure 21: Share of expenditure items in total expenditure for fast co-pyrolysis of willow and PHB (discounted over 20 years)

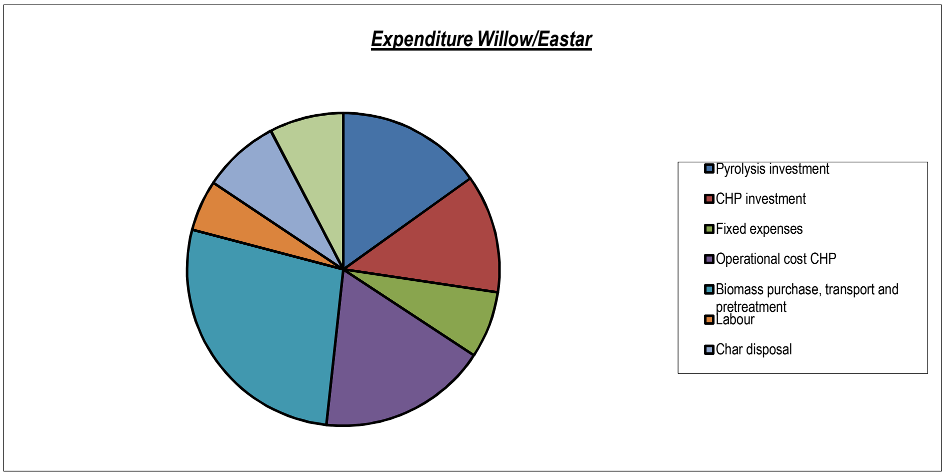

figure 22: Share of expenditure items in total expenditure for fast co-pyrolysis of willow and Eastar (discounted over 20 years)

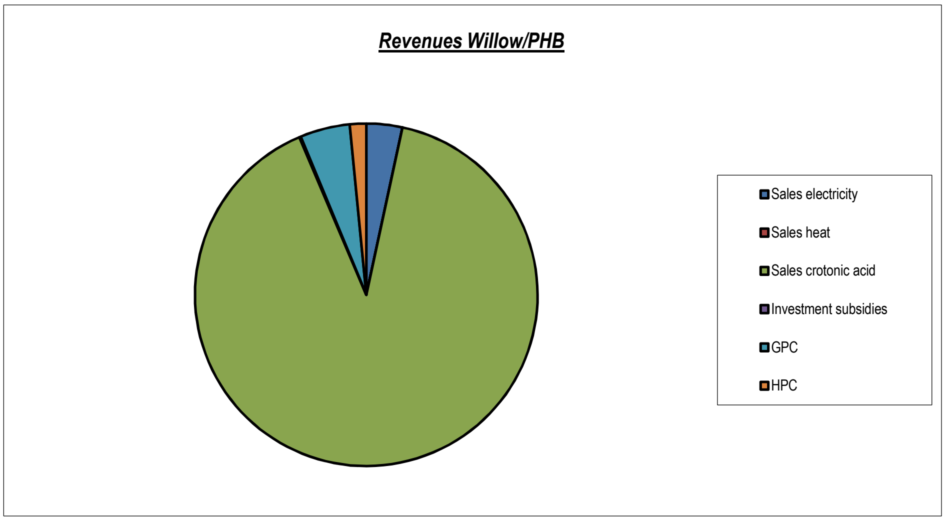

figure 23: Share of revenue items in total revenues for fast co-pyrolysis of willow and PHB (discounted over 20 years)

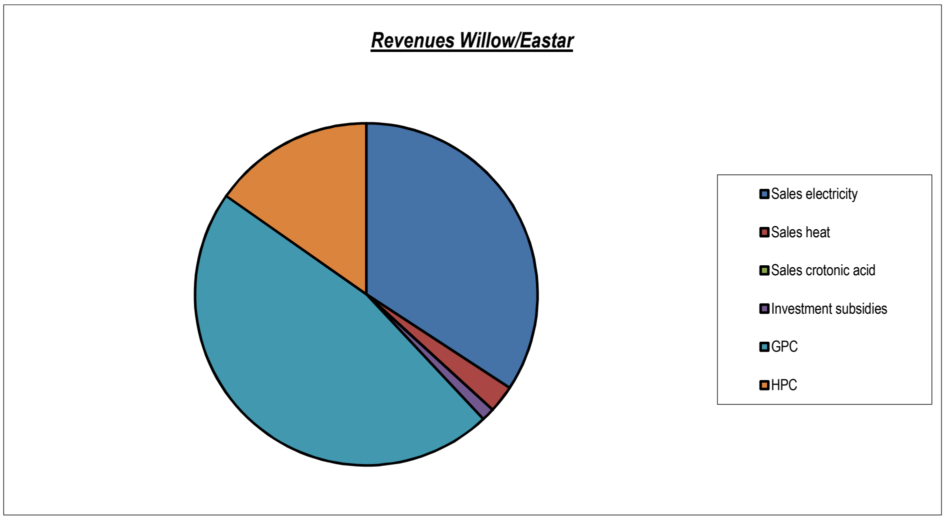

figure 24: Share of revenue items in total revenues for fast co-pyrolysis of willow and Eastar (discounted over 20 years)

6.7 Monte Carlo sensitivity analysis

For each fast (co-)pyrolysis process, five variables for which the numerical values could be uncertain have been identified. The identified variables are either variables of which it is expected that their value might change, or variables that determine the most important revenues and expenditure according to figure 21, figure 22, figure 23 and figure 24. The five identified variables (the investment constant, the investment exponent, the market price of green power certificates, the electricity price, the lower heating value of the pyrolysis oil, and the crotonic acid sales price) are now allowed to change within the ranges that have been identified in chapters 4 and 5 (realistic ranges). Also the LHV of the bio-oil is subject to uncertainty. Each LHV is allowed to change only with 7,5% above or below its initial value, because a higher deviation might make LHV > HHV which is technically impossible. The degree to which the distribution of the NPV outcomes can be explained by the variability of one of the base case variables is shown in table 53.

In table 53 (row1/column1) it is illustrated that for an investment in pure willow pyrolysis, 43,7 % of the distribution of the NPV of the cash flows can be explained by the variability of the value of the green power certificates. The variability of the pyrolysis investment cost contributes in two ways to the distribution of the NPV of the cash flows: 23,0 % (row1/column 4 of table 53) of the NPV variance for pure willow is explained by the variability of the investment constant and 8,6 % is explained by the variability of the investment exponent. The contribution in columns 4 and 5 has a negative sign, because the NPV of the cash flows varies inversely as the investment cost: the NPV decreases as the investment cost increases. The reverse relationship is valid for the LHVs, the price of the green power certificates and the electricity price: 13,5 % can be explained by the variability of the calorific value. If one of those increases, the amount of revenues increase and hence the NPV diminishes.

Except for the willow/PHB-blend, the three most important variables for explaining the NPV's distribution are the lower heating value of the bio-oil produced, the market price for green power certificates and the combined effect of the investment constant and exponent. In the case of willow/PHB, only the sales price of crotonic acid seems to explain the distribution of the NPV.

Blend	LHV bio-oil	Price GPC	Price elect.	Investment constant	Investment exponent	Price crotonic acid
	(1)	(2)	(3)	(4)	(5)	(6)
Pure willow	13,5	43,7	11,2	-23,0	-8,6	0
Willow/PLA	15,5	49,9	12,9	-15,6	-6,1	0
Willow/C. starch	13,7	45,2	11,6	-21,5	-8,1	0
Willow/PHB	0,2	1,1	0,4	-0,3	-0,1	97,8
Willow/Biopearls	15,9	50,8	13,2	-14,4	-5,7	0
Willow/Eastar	18,7	49,7	12,9	-13,3	-5,3	0
Willow/Solanyl	14,7	41,7	12,3	-18,3	-7,0	0
Willow/Pot. starch	15,7	50,5	13,1	-19,9	-5,8	0

table 53: Contribution of the variability of the base case variables to the variability of the NPV of the cash flows

6.8 Maximum price for collecting and transporting biopolymers

Collecting, sorting and transporting a waste stream of biopolymers via regular refuse collection is not yet economical today due to the currently scattered and low supply of biopolymers. An alternative could be to conclude a contract with organisations that are willing to dispose of a relatively large stream of one specific type of biopolymer. Using the net present value model described before, the maximal price for each biopolymer has been determined as a way of thinking to estimate the attractiveness of fast co-pyrolysis with biopolymers. The purchase price for dry willow stays set at 50 EUR t_{dm}^{-1} and its transport price at 7 EUR t_{dm}^{-1}, so that the total willow cost still is 57 EUR t_{dm}^{-1}. The variability for the values of the five variables identified in paragraph 6.7, has been taken into account when estimating the maximal expense for collecting and transporting biopolymers. The maximum biopolymer price is defined as the price that a pyrolysis investor can maximally pay guaranteeing a 95 % chance of a positive NPV (i.e. NPV is at least zero). The prices in table 54 can be considered to be the maximum prices when negotiating with waste producers. Prices have been calculated for the realistic ranges of the values of the five variables identified in paragraph 6.7

In the base case, the maximum cost for collecting and transporting corn starch (see the left side of figure 26) has a negative sign, meaning that co-pyrolysis with corn starch is only cost-effective if the corn starch waste stream leads to an incoming cash flow for the pyrolysis investor, i.e. when the producer of corn starch waste pays a gate fee of 31 EUR t_{dm}^{-1} for pyrolysing corn starch. For the owner of the corn starch waste stream, fast co-pyrolysis is preferred to composting, as the cost of composting is higher (80 EUR t_{dm}^{-1}). The highest price that can be paid in the base case, is the price for PHB waste: 2 757 EUR t_{dm}^{-1}. The market price of pure PHB (i.e. no PHB waste, but the price paid for PHB bought from a biopolymer producer) lies between 6 000 and 10 000 EUR t_{dm}^{-1} (Media Business Press 2004). This means that it is possible to recover at least 25 % of the purchase price. All other biopolymers can be converted at a positive price in the base case. Also for the conversion of Solanyl a gate fee should be paid to the organisation investing in fast co-pyrolysis. The gate fee however is lower than the composting cost, so that fast co-pyrolysis is preferred to composting for all biopolymer waste streams.

6.9 Scenario analysis

6.9.1 Scenario identification

As some assumptions might turn out to have deviant outcomes in practice, the impact of these positive or negative deviations on the maximal biopolymer price is analysed. Five scenarios have been identified:

- *Negative willow price*: the willow purchase price is -20 EUR t_{dm}^{-1} instead of 50 EUR t_{dm}^{-1}, i.e. we receive money in order to convert willow contaminated with heavy metals. This might occur when, from the viewpoint of the investor in the pyrolysis reactor, there is not enough willow available to benefit from positive scale effects. It means that the investor in a pyrolysis reactor is willing to convert willow only if he is paid for doing so (Thewys and Kuppens 2008; Kuppens and Thewys 2010);
- *High investment*: the investment constant and the investment exponent are at their highest level, so that the base case investment for the pyrolysis reactor increases from 10,7 MEUR to 16,1 MEUR;
- *Low investment*: the investment cost for the pyrolysis reactor is lower than in the base case (7,8 MEUR instead of 10,7 MEUR). This might be possible when the investor(s) are able to build the reactor with their own knowledge instead of buying it from a supplier;
- *Lower char cost*: Char has no useful applications and must be landfilled at a cost of 122 EUR t_{dm}^{-1}, because the heavy metals present in the willow are expected to concentrate in the char during fast (co-)pyrolysis. If it is possible to remove the metals out of the char (i.e. phytomining), char can be utilised as a soil amendment, fertiliser, fuel or filtration media (Downie, 2007). If the revenues and expenses brought about by phytomining would lower the char disposal cost beneath 122 EUR t_{dm}^{-1}, then phytomining would be an economical alternative for landfilling. As the exact height of these revenues and expenses is not known yet, maximum biopolymer

prices have been calculated assuming that phytomining might reduce the char disposal cost by half to 61 EUR t_{dm}^{-1};

- *Low green current price*: In the long run, the system of green power certificates might be dismissed and replaced by another system only taking into account the external benefit of reduced CO_2 emissions. If 1 kWh green energy reduces CO_2 emissions with 461 g (Flemish Government, s.d.) and the external cost of 1 t CO_2 emissions is 20 EUR, then 1 MWh of green electricity is worth roughly 10 EUR instead of 100 EUR.

Their impact on the maximal biopolymer price is illustrated from figure 25 until figure 31, assuming the uncertainties about the base case values. The left column in figure 25 until figure 31 shows the prices in the base case scenario. The other columns in figure 25 until figure 31 show the impact on maximum biopolymer prices if one scenario comes true. The bold line in represents the price one has to pay for composting waste of bioplastics: if an organisation wants to dispose of bioplastic waste, it needs to pay 80 EUR t_{dm}^{-1} waste to the composting firm.

Biopolymer	Price of the pure biopolymer (MEUR t_{dm}^{-1})	Maximum price (EUR t_{dm}^{-1})	Fast co-pyrolysis or composting?
PLA	1,5 -5	28	pyrolysis
Corn starch	3	-31	pyrolysis
PHB	6-10	2 757	pyrolysis
Biopearls	1,5-3	45	pyrolysis
Eastar	1,1-1,5	52	pyrolysis
Solanyl	1	-4	pyrolysis
Potato starch	2,25	37	pyrolysis

table 54: Maximum price for collecting, sorting and transporting biopolymers to the pyrolysis reactor guaranteeing a 95% chance that NPV of the pyrolysis cash flows >0 (base case)

6.9.2 Results of the scenario analysis

- *Negative willow price*: All of the maximum prices now become positive, meaning that it is possible for the pyrolysis investor to pay for the collection and transport of the waste stream: e.g. he can pay 98 EUR t_{dm}^{-1} for PLA waste. This is much lower than the market price – range between 1 500 and 5 000 EUR t_{dm}^{-1} (Media Business Press 2004; Stassin 2006; Villers 2006) - for pure PLA directly bought from a PLA producer. One must bear in mind however that PLA waste might have a higher value in practice as uncontaminated PLA waste streams can be depolymerised for material recuperation. Fast co-pyrolysis is now preferred to composting for all biopolymer waste, even for corn starch.
- *High investment*: If we assume that the investment constant and exponent for the pyrolysis reactor are at their highest value (so that the base case total plant cost increases from 10,7 MEUR to 16,1

MEUR), the maximum prices payable by the pyrolysis investor decrease significantly. Co-pyrolysing willow with corn starch, potato starch or Solanyl can only be converted at a fast pyrolysis plant for a gate fee. Co-pyrolysing willow with corn starch has not much potential in this scenario as the owner of corn starch waste will be almost indifferent between paying 80 EUR t_{dm}^{-1} to a composting enterprise for processing its waste or paying 70 EUR t_{dm}^{-1} to a pyrolyser.

- *Low investment*: Next we assume that the investment cost for the pyrolysis reactor is lower than in the base case (7,8 MEUR instead of 10,3 MEUR). This is, together with the negative willow price, one of the most optimistic scenarios as they lead to the highest attainable prices compared to other scenarios.
- *Lower char cost*: The price for PLA for instance can rise from 28 EUR t_{dm}^{-1} in the base case to 98 EUR t_{dm}^{-1} if phytomining (i.e. recuperating metals out of the char) is possible. Also in the lower char cost scenario fast co-pyrolysis with willow is preferred to composting for processing waste of biopolymers.
- *Low green current price*: In the long run, the system of green power certificates might be dismissed and replaced by another system only taking into account the external benefit of reduced CO2 emissions (cf. the discussion about the green power certificates for solar energy). All biopolymer prices, except the PHB price, become negative. Except for PHB, composting the biopolymer waste is now preferred above fast co-pyrolysis. One could argue that if the government abolishes the system of green power certificates, chances for the commercialisation of fast pyrolysis of biomass will be very low. Energy prices however might have risen by that time, so that the loss of green power certificates might be compensated by a higher sales price for energy. Pyrolysing biopolymers then might still be preferred to composting, but then an ad hoc analysis is needed to decide on this.

Comparing the maximum biopolymer prices in the third column of table 54 with the price of the pure biopolymers left to it, it is obvious that pure biopolymers are too expensive raw materials for fast co-pyrolysis with willow. The profitability of fast co-pyrolysis therefore is strongly dependent on the availability of biopolymer waste streams.

In general, biopolymer waste prices are very sensitive to each of the possible occurring scenarios. If the relative increment or decrease in biopolymer price between two scenarios in terms of percentages are compared, only the PHB price seems to be more or less "stable". One reason for this, is that PHB revenues stem for more than 90% from sales of crotonic acid. Only when the crotonic acid price changes, the PHB price will be affected very much: calculations show that the PHB price can decrease to as low as 1 310 EUR kg^{-1} if crotonic acid can only be sold at 2,5 EUR kg^{-1}. This means also that the PHB price will be 1 310 EUR kg^{-1} if only half of the produced crotonic acid can be sold on the market at the base case price of 5 EUR kg^{-1}. If the price for crotonic acid is as high as 10 EUR kg^{-1}, the maximum attainable price for PHB waste increases to 4 750 EUR kg^{-1}. If we get PHB for free, i.e. the maximum price for PHB is 0 EUR kg^{-1}, the price for crotonic acid should be at least 0,30 EUR kg^{-1} for a positive NPV of the cash flows. This means that the PHB price will only be negative (in other words one needs to pay for having PHB waste converted via pyrolysis) if the sales price for crotonic acid falls beneath 6 % of the assumed base case price of 5 EUR kg^{-1}, which is fairly unrealistic as the base case price of 5 EUR kg^{-1} is already a factor 10 lower than the market price of crotonic acid of 50 EUR kg^{-1}.

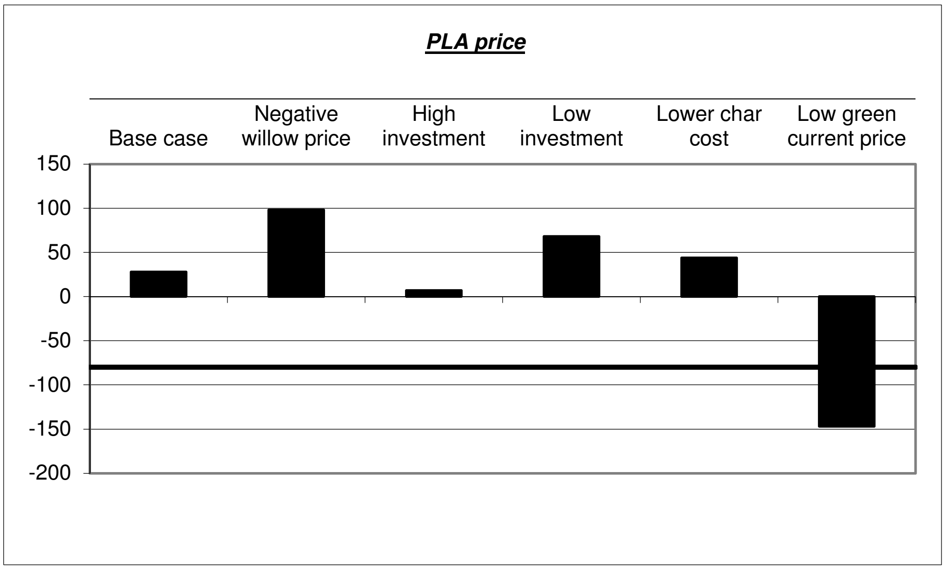

figure 25: Maximum PLA price (EUR t_{dm}^{-1}) at six different scenarios

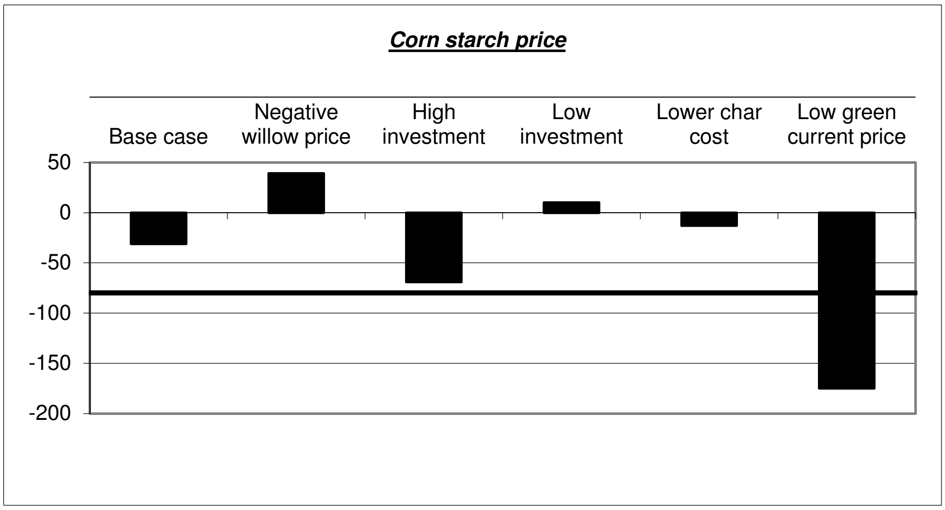

figure 26: Maximum corn starch price (EUR t_{dm}^{-1}) at six different scenarios

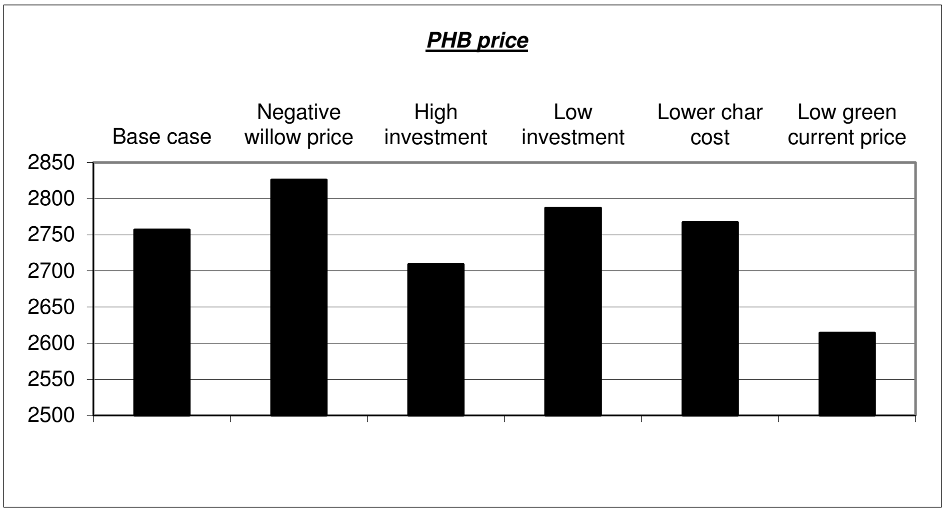

figure 27: Maximum PHB price (EUR t_{dm}^{-1}) at six different scenarios

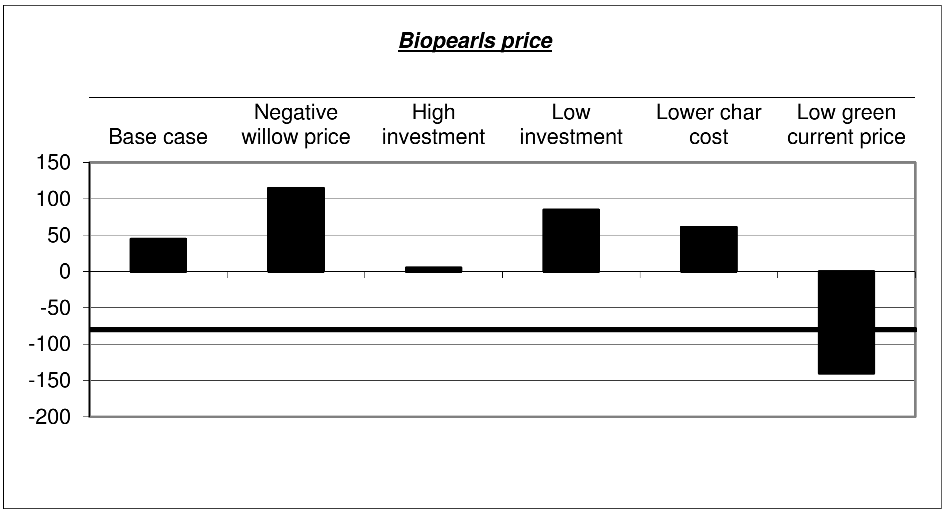

figure 28: Maximum Biopearls price (EUR t_{dm}^{-1}) at six different scenarios

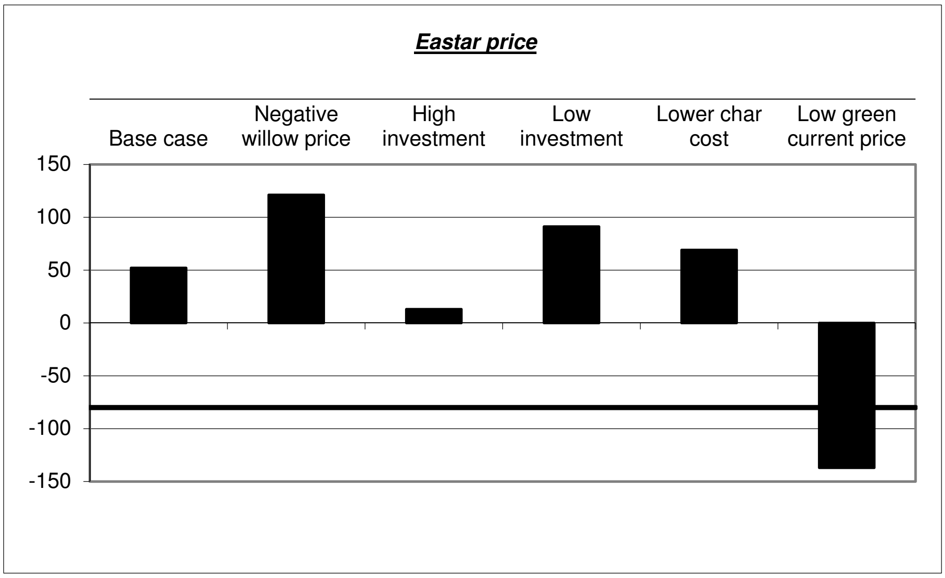

figure 29: Maximum Eastar price (EUR t_{dm}^{-1}) at six different scenarios

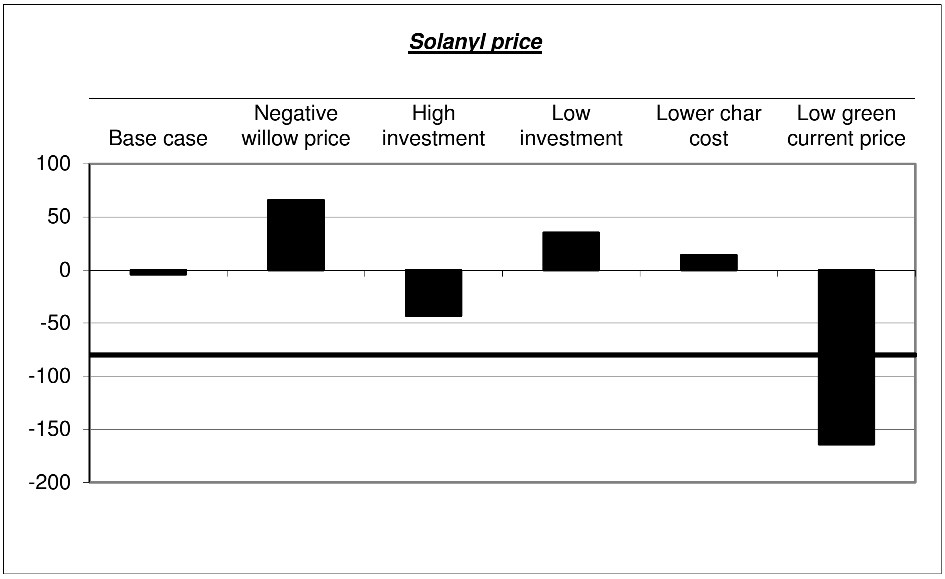

figure 30: Maximum Solanyl price (EUR t_{dm}^{-1}) at six different scenarios

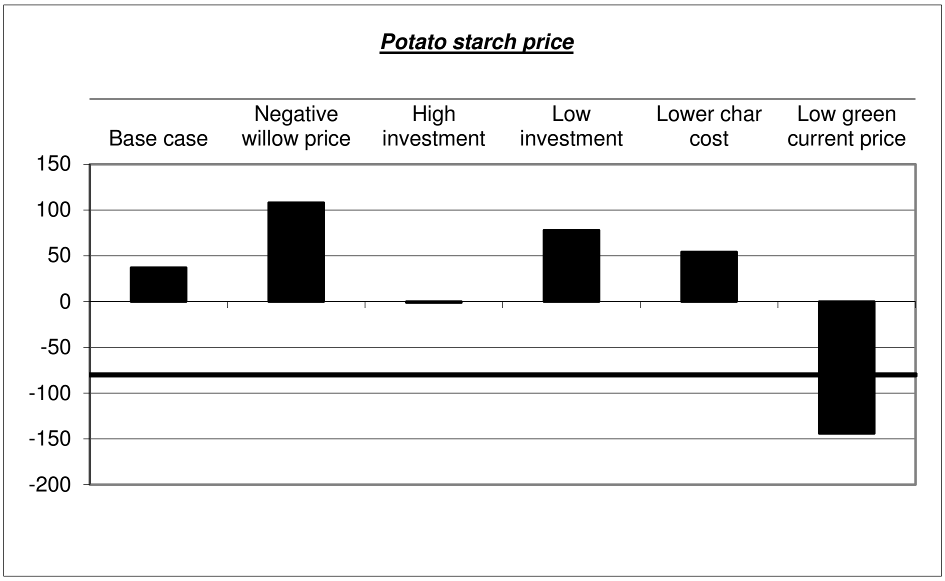

figure 31: Maximum potato starch price (EUR t_{dm}^{-1}) at six different scenarios

6.10 Conclusion

Fast co-pyrolysis leads to better economic results as compared to fast pyrolysis of pure willow: the NPV of cash flows has been increased with at least 5,5 MEUR (for the willow/corn starch blend). Fast co-pyrolysis of willow and PHB even increases the NPV with 352 MEUR due to the high value of crotonic acid. Except for the willow/PHB-blend, the economics however depend largely on the presence of green power certificates which make up the largest part of total revenues for each blend. Because of the currently small supply of biopolymers, however, it is not possible yet to determine the exact costs for collecting and transporting biopolymer waste to the pyrolysis plant. For this reason the maximum cost for the biopolymer feedstock has been calculated for different scenarios taking into account several uncertainties. In the most expected scenario, i.e. the base case, the maximum prices for all biopolymers are positive, except for corn starch and solanyl which means that fast co-pyrolysis of willow with corn starch or solanyl is only profitable if the stream of corn starch waste generates an income for the investor in the pyrolysis reactor. Fast co-pyrolysis can be seen as an alternative technology for processing waste of PLA, PHB, Biopearls, Eastar, solanyl and potato starch, as it is cheaper than composting which costs 80 EUR t_{dm}^{-1}. Only for waste of corn starch, however, composting can be cheaper sometimes. Only when the system of green power certificates would have been phased out without some other compensation, composting will always (except for PHB waste) be preferred above fast co-pyrolysis as the latter would cost between 137 EUR t_{dm}^{-1} for the disposal of Eastar waste and 175 EUR t_{dm}^{-1} for disposal of corn starch waste. Under the condition that biopolymers make their full entry in the plastic industry, fast co-pyrolysis of willow and PHB is the only option to be commercialised in the short term with a value for PHB waste between 2 600 and 2 830 EUR t_{dm}^{-1}.

7 Risk reduction: output optimisation

7.1 Introduction

In the introduction of chapter 6 it has already been announced that risk can be reduced either by changing the inputs to the production process or by selecting process parameters for obtaining a different mix of outputs. Besides, in chapter 6 it has been illustrated that some outputs of the pyrolysis process might have a very large influence on the profitability of the plant, cf. the crotonic acid that is produced during fast co-pyrolysis of willow and PHB. This change in outputs however originated from a change in the inputs of the pyrolysis process and the crotonic acid can be easily separated from the pyrolysis oil.

In this chapter, the focus is on the valorisation of the other important products of pyrolysis. Unless it is possible to combust char at low temperature to prevent metal volatilisation, the pyrolysis gas is required for internal energy provision (see table 8). Therefore the focus in this chapter is on the valorisation of the pyrolysis char. Two innovative potential valorisation options have been identified: biochar as a soil amendment and pyrolysis char as a resource for active coal production. The option of charcoal for energy has been abondoned for aforementioned reasons (metals).

In a next step, after describing the basic technological feasibility, the economic potential has been explored. Once valorisation of the byproduct appears profitable, the potential economic trade-off between char and oil production has been explored by applying and elaborating the model proposed by Yoder, Galinato et al. (2009). In chapter 2 this model has been explained, and a solution to its main drawback, i.e. the use of prices for goods for which no market exists, has been proposed and applied in this chapter.

7.2 Biochar

7.2.1 Terra Preta do Indio

It has been discovered that Amazonian soils contain high amounts of organic carbon that explain sustained fertility in those soils. These soils have a very dark colour and are often called "Amazonian Dark Earth" or "Terra Preta do Indio". It is believed that biochar was intentionally buried as a soil enhancement agent by pre-Columbian inhabitants of the Amazon Basin to increase the productivity of otherwise infertile soils (Lehmann and Joseph 2009).

Biochar is "the carbon-rich product obtained when biomass, such as wood, manure or leaves, is heated in a closed container with little or no available air. In more technical terms, biochar is produced by so-called thermal decomposition of organic material under limited supply of oxygen (O_2), and at relatively low temperatures (<700°C) … The defining property is that the organic portion of biochar has a high C content, which mainly comprises so-called aromatic compounds characterized by rings of six C atoms linked together without O or hydrogen (H), the otherwise more abundant atoms in living organic matter." (Lehmann and Joseph 2009). It is "a carbon-rich material capable of resisting chemical and microbial breakdown, allowing the carbon to be sequestered for periods of time approaching hundreds or thousands of years" produced by pyrolysis of plant material (Brown, Wright et al. 2011). Shackley, Hammond et al. (2011) define biochar as the "porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen-depleted atmosphere that has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement."

As explicitly mentioned in the definitions by Brown, Wright et al. (2011) and Shackley, Hammond et al. (2011), the term "biochar" is specifically used to designate pyrolysis char that is intentionally applied to soils in order to improve soil characteristics and to distinguish it from charcoal that is used as fuel for heat, as a filter, as a reductant in iron-making or as a colouring agent in industry or art (Lehmann and Joseph 2009).

7.2.2 Benefits

Four complementary objectives motivate biochar applications for environmental management which individually or in combination must have either a social or a financial benefit or both (Lehmann and Joseph 2009):

- soil improvement by amelioration of soil structure and fertility (e.g. by better water retention, improving soil pH, reduction of nitrate leaching, better conservation of nutrients such as N, P and K), thereby improving biomass yields and possible savings by reduced fertiliser use;
- waste management as an alternative conversion route for organic waste disposal, which significantly reduces the volume and weight of the waste and decreases methane emissions from landfills (although strict quality control is a prerequisite);
- climate change mitigation as a means of sequestering atmospheric carbon dioxide (CO_2) because biochar decomposes much more slowly (opinions range from centennial to millennial timescales according to Lehmann (2007)) than plant biomass that is formed on an annual basis, so that carbon is diverted from the rapid biological cycle into a much slower biochar cycle while reducing emissions even further than the fossil fuel offset in its use as fuel;
- bioenergy (e.g. syngas, pyrolysis oil or heat) production in addition to biochar production so that besides carbon sequestration, also emissions are reduced.

Using biochar as a soil amendment aids carbon sequestration and might result in increased crop productivity. The impact of the use of biochar as a soil amendment on crop productivity in terms of biomass yield however is not very clear: it depends on the types of biochar used, soil type, climate and type of crop amongst others (Galinato, Yoder et al. 2011). Shackley, Hammond et al. (2011) confirm that many of the potential biochar benefits remain highly uncertain to date, but they state that carbon sequestration is the most certain benefit and that there is reasonably good evidence that biochar increases pH (see also Galinato, Yoder et al. (2011)).

7.2.3 Biochar economics

Methods for sequestering carbon dioxide through afforestation or reforestation have already been accepted as tradable “carbon offsets” or “certified emission reductions” (CERs) under the Clean Development Mechanism of the Kyoto Protocol (Lehmann 2007), although carbon sequestration in agricultural crops and soils are currently not eligible yet (Galinato, Yoder et al. 2011). In any case, the potential of carbon storage in greenhouse gas accounting should be calculated by life cycle carbon assessments and depends on the feedstock for biochar production, the amount of biochar produced (during slow versus fast pyrolysis) and the current conventional (waste) treatment or disposal context (i.e. the reference scenario or system in life cycle analysis) of the biochar feedstock (Ibarrola, Shackley et al. 2012). Ibarrola, Shackley et al. (2012) calculated net carbon abatement for wood waste: wood that can be incinerated has a carbon abatement potential of 0,50 tonnes of CO_2 per tonne of feedstock produced by slow pyrolysis, whereas biochar production from wood that otherwise should be landfilled can save up to 1,25 tonnes of CO_2 equivalents per tonne of feedstock from slow pyrolysis. In the latter reference system of landfilling, fast pyrolysis has a net carbon abatement potential of less than 0,9 tonnes of CO_2-equivalents per tonne of feedstock. Brown, Wright et al. (2011) calculated the amount of CO_2-equivalents that can be sequestered by biochar production from corn stover: they assumed that fast pyrolysis would result in 0,47 tonnes of CO_2-equivalents saved per tonne of corn stover, whereas slow pyrolysis augments CO_2 abatement to 0,99 tonnes CO_2 per tonne of corn stover. So it can be concluded that slow pyrolysis results in the highest carbon offset potential for any feedstock. The remaining question is whether the economics of slow pyrolysis are sufficient in order to make it a viable biochar production route (compared to fast pyrolysis). According to the references cited below it is unfortunately not the case. Fast pyrolysis appears to be the most profitable conversion technology, even for biochar applications.

Lehmann (2007) calculated that biochar sequestration in conjunction with bioenergy from pyrolysis becomes economically attractive, when inexpensive feedstock is continuously available in sufficient quantities, and when the value of avoided carbon dioxide emissions reaches 37 USD t^{-1} (or 29 EUR t^{-1}). Galinato, Yoder et al. (2011) calculated the profit from winter wheat production in Washington State, with and without biochar application. Because the consistent effect of biochar was on soil pH, they considered biochar as a substitute for agricultural lime. They stated that it may not be economically feasible for farmers to use biochar solely for pH adjustment since it would entail a relatively higher cost compared to agricultural lime. Therefore they investigated the economic potential of the additional benefit of carbon sequestration when it would have been possible to trade its carbon offsets. Because prices of traded CO_2 offset are highly volatile (cf. the Chicago Climate Exchange and the European Climate Exchange), they calculated the profits of biochar application both when the offset price equals 1 USD t^{-1} CO_2 and when a high price of 31 USD t^{-1} CO_2. They concluded that biochar application is only profitable at a high carbon offset price of 31 USD t^{-1} CO_2 (or 25 EUR t^{-1}) and at the same time a low biochar price of 87 USD t^{-1} biochar. The latter underpins the finding of Lehmann (2007) because a low biochar price might only be possible for inexpensive feedstocks (e.g. waste streams). Shackley, Hammond et al. (2011) confirms that the most profitable source of biochar is from waste, but they state that such materials will face complex regulatory issues and testing.

Shackley, Hammond et al. (2011) state that the standard approach in evaluating technology costs by empirical relationships between component costs and e.g. power output is difficult in the case of pyrolysis biochar systems, as there is a lack of peer-reviewed data available on the realistic costs of slow pyrolysis (contra fast pyrolysis) at different scales. McCarl, Peacocke et al. (2009) used the same cost structure for slow pyrolysis and they used exactly the same fixed pyrolysis cost for 1 tonne of biomass. For slow pyrolysis, biomass pre-treatment costs were reduced by 50 %, whereas all other operating costs were assumed to remain the same per tonne of feedstock. Galinato, Yoder et al. (2011) found that biochar application for winter wheat production is not profitable at all when the biochar has to be bought by a farmer at a price that equals the break-even price of 350,74 USD t^{-1} biochar (or 278,37 EUR t^{-1}) calculated by Granatstein, Kruger et al. (2009). The latter price has been confirmed by Brown, Wright et al. (2011) who quote a minimum product selling price of 346 USD t^{-1} of biochar (or 275 EUR t^{-1}) for slow pyrolysis. This is quite high when compared to the revenue that can be generated by carbon offsets: one tonne of biochar from corn stover has a carbon offset value of 20 USD t^{-1} of biochar (16 EUR t^{-1}) if the assumed carbon offset value is 17,33 USD t^{-1} CO_2 or 13,88 EUR t^{-1} CO_2 (Brown, Wright et al. 2011). Current prices on the market of European Union Allowances (January 2012) however are only between 6 and 8 EUR t^{-1} CO_2 whereas the values of Certified Emission Reductions is between 4 and 6 EUR t^{-1} CO_2. Even if biochar application would lead to higher crop productivity, McCarl, Peacocke et al. (2009) calculated that the biochar value at the pyrolysis plant (for application as a soil amendment on a maize field) equals 32,94 USD t^{-1} biochar (or 26,37 EUR t^{-1}), i.e. excluding the benefit of greenhouse gas offset. Despite the higher carbon offset potential from slow pyrolysis, McCarl, Peacocke et al. (2009) calculated that both fast and slow pyrolysis are unprofitable (the difference with our calculations is that they do not take into account exploitation subsidies such as green power certificates or combined heat and power certificates), but that the fast plant is less loss making than the slow pyrolysis plant. Brown, Wright et al. (2011) confirms that a pyrolysis facility that operates primarily to generate biochar as a carbon offset (i.e. a slow pyrolysis plant) is unlikely to be profitable, whereas a pyrolysis facility that co-produces biochar for carbon sequestration and bio-oil for transportation fuel (i.e. a fast pyrolysis plant) has relatively attractive economics.

7.2.4 Potential in the Belgian Campine

Heavy metals present in the feedstock are most likely to remain and concentrate in the biochar (Koppolu, Agblevor et al. 2003; Koppolu and Clements 2003; Koppolu, Prasas et al. 2004; Cornelissen 2009; Lievens, Carleer et al. 2009; Stals, Thijssen et al. 2009; Shackley and Sohi 2010). Therefore one should first draw up a metal balance and then check with the relevant norms with respect to the maximum content of heavy metals in soil improver according to VLAREMA, the Flemish Regulations concerning the sustainable management of material cycles and waste.

According to Stals, Thijssen et al. (2009) 723 K (or 450 °C) is a suitable pyrolysis temperature with minimal amounts of Zn and Cd transferred to the obtained pyrolysis oil. They performed leaching tests which suggest that significant fractions (up to 35 %) of the target elements in chars are available for plants and hence they recommend to not freely dispose of the char into the environment. In table 55 the metal content of the willow stems and leaves is represented. The minimum concentrations correspond to the metal uptake reported by Schreurs, Voets et al. (2011) and Vangronsveld, Herzig et al. (2009), whereas the maximum concentrations correspond to the ones reported in the experiments of Stals, Thijssen et al. (2009). In the last two columns we calculated the metal content for a 4:1 weight ratio willow stems:leaves, corresponding to the natural occurring dry weight stem and leaves ratio when willow would be harvested before leave fall in autumn.

Now we know the metal concentrations in the stems and the blends, we can calculate the metal concentrations in the chars both when willow is harvested before and after leave fall in autumn. At 723 K pyrolysis char yields were 21 m%, both for experiments on stems only and for the blend of wood and leaves. A hot-gas filter can be applied in order to prevent entrained flow of heavy metals and to reduce the amount of Zn and Cd in the pyrolysis oils without influencing oil or char yields. The percentage of metals that remain in the char after fast pyrolysis are depicted in figure 32.

Element (mg kg^{-1})	Willow stems		Willow leaves		Willow blend	
	Min	Max	Min	Max	Min	Max
Zn	400,0	822,0	2 800,0	4 636,0	880,0	1 584,8
Cd	24,0	40,9	60,0	80,0	31,2	48,7
Pb	0,89	26,3	13,1	14,4	3,3	23,9

table 55: Heavy metal concentrations in stems and leaves of the willow feedstock, based on Stals, Thijssen et al. (2009)

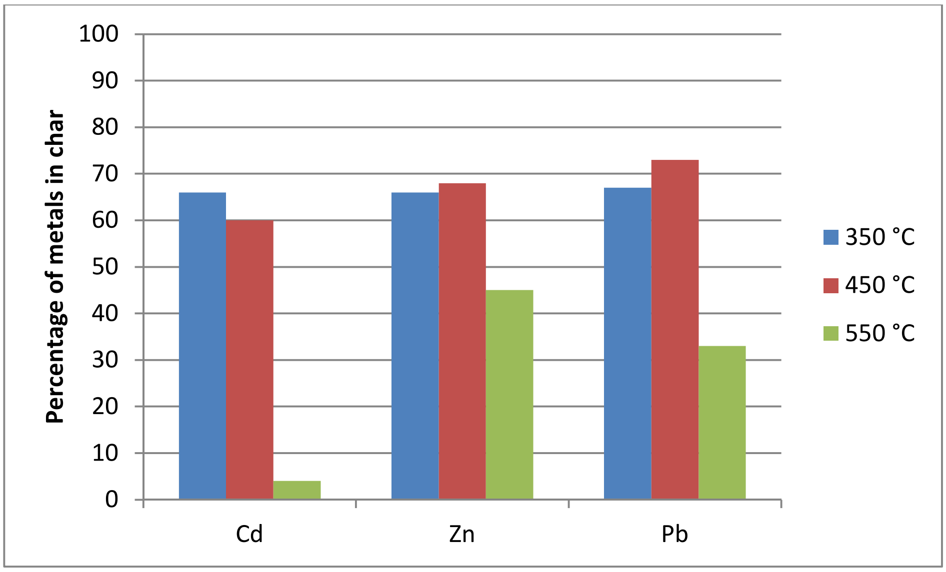

figure 32: Metal recovery in char at various pyrolysis temperatures (experiments without a hot-gas filter) (Stals, Thijssen et al. 2009)

From this figure it is clear that all metals, especially cadmium, are strongly volatilised at 823 K compared to the lower pyrolysis temperatures. A first glance at figure 32 indicates that the percentage of metals that are retained in the char are lower than expected, given the fact that the total zinc concentrations in oil appear less than 1 % of the metals available in the feedstock. Stals, Thijssen et al. (2009) therefore assumed that the sand bed in their experimental reactor retains the remainder of the metals. Applying the char yield of 21 m% and the metal recovery percentages at 723 K of figure 32, results in the metal concentrations in the char calculated below. For instance, the maximum Cd concentration in the pyrolysis char of willow harvested in autumn (after leave fall, thus stems only) equals 93,5 mg Cd per kg of char. This can be calculated by multiplying the maximum Cd concentration in the willow stems (40,9 mg Cd per kg of stems) as reported in table 55 with the percentage of metals retained in the char as indicated by figure 32. At a temperature of 723 K, the red bar indicates that 58 % of the Cd originally present in the stems is retained in the pyrolysis char at 723 K. Thus, from this 40,9 mg Cd only 23,7 mg is retained in the char. Taking into account the volume reduction during pyrolysis, i.e. that one kg of stems yields 0,21 kg char (char yield of 21 m%), the resulting metal concentration in the char equals: 23,7 mg Cd per 0,21 kg char or in other words 116,9 mg Cd per kg char (see table 56).

Element (mg kg^{-1})	Willow stems		Willow blend (4:1)		Norm (VLAREMA)
	Min	Max	Min	Max	
Zn	1 295,2	2 661,7	2 681,9	4 829,9	900
Cd	68,6	116,9	86,2	134,6	6
Pb	3,1	91,4	11,4	82,0	300

table 56: Metal concentrations in the pyrolysis chars

In table 56 it can be seen that the Zn and Cd concentrations exceed the norms for use as a soil improver stated by VLAREMA. The concentrations of Pb are expected to be lower than the norm. Therefore, unless it would be possible to remove the metals from the char, it is concluded that there is no potential for pyrolysis chars from wood in the Belgian Campine to be used as biochar, i.e. as a soil amendment.

7.3 Activated carbon

Economic trade-offs exist between the production of biochar and bio-oil from pyrolysis of biomass (Yoder, Galinato et al. 2011). Bridgwater (Bridgwater, Meier et al. 1999) already illustrated that the yield of the typical fast pyrolysis products is dependent on the process temperature: maximum oil yields are obtained at temperatures between 500 and 520 °C with residence times of less than 2 s, while the char yield decreases with temperature. Several valorisation opportunities exist for these pyrolysis products: the char can be applied as a source of energy, a soil amendment or a resource for active coal production, whereas pyrolysis oil can be used for the production of heat and/or electricity and chemicals. These valorisation routes influence the potential sales prices of the pyrolysis products. As a consequence, careful selection of the process temperature is required to optimise the total incoming revenues and hence the profitability of a fast pyrolysis plant. In this chapter the optimal process temperature for a fast pyrolysis plant has been calculated, by elaborating Yoder's model when biochar is used as a resource for active coal production and the pyrolysis oil is burnt in a combustion engine for the combined production of heat and power (CHP).

Yoder, Galinato et al. (2009) assume that both the pyrolysis char and oil will be used as an energy source, and relate the price to the energy content of the product. Because a real market for pyrolysis oils and chars is absent, prices might deviate in practice. As a solution it is assumed that the pyrolysis products can be converted into products for which markets do exist: here it is assumed that pyrolysis char can be converted into activated carbon (AC), and the oil will be converted into electricity and heat. As a consequence our model uses *net revenues* instead of *prices* for oil and char, which take into both the sales price of AC and oil and the relevant processing costs.

7.3.1 Char and oil yield in function of temperature

The starting point of the optimisation process are the results of Yoder's review and elaboration of equations 2.27 and 2.28. Based on an extensive literature review, Yoder developed the equation of pyrolysis oil and char yield in function of temperature for fast pyrolysis.

For fast pyrolysis of willow, equations 2.27 and 2.28 can be approached with Yoder's regression for fast pyrolysis of forest products (Yoder et al. 2011):

$$q_{char}(T) = 80{,}67 - 0{,}1655T + 9{,}4x10^{-5}T^2 \qquad (7.1)$$

$$q_{oil}(T) = -3{,}42 + 0{,}2205T - 2{,}1x10^{-4}T^2 \qquad (7.2)$$

The regressions are based on a data sample with a minimum temperature of 250 °C and a maximum temperature of 1000 °C. Oil and char yields have been calculated for these ranges in figure 33. As can be seen from figure 33 the temperature that provides maximum bio-oil yield is 525 °C, though it depends on type of biomass and process parameters such as heating rate and residence times. From then on both oil and char yields decrease. The economically relevant temperature range thus must be lower than that which provides maximum oil yield, i.e. the area to the left of 525 °C (Yoder et al. 2009; Yoder et al. 2011). The product transformation curve can also be constructed from the data in figure 33 and it represents the char yield in function of the oil yield graphed in figure 34.

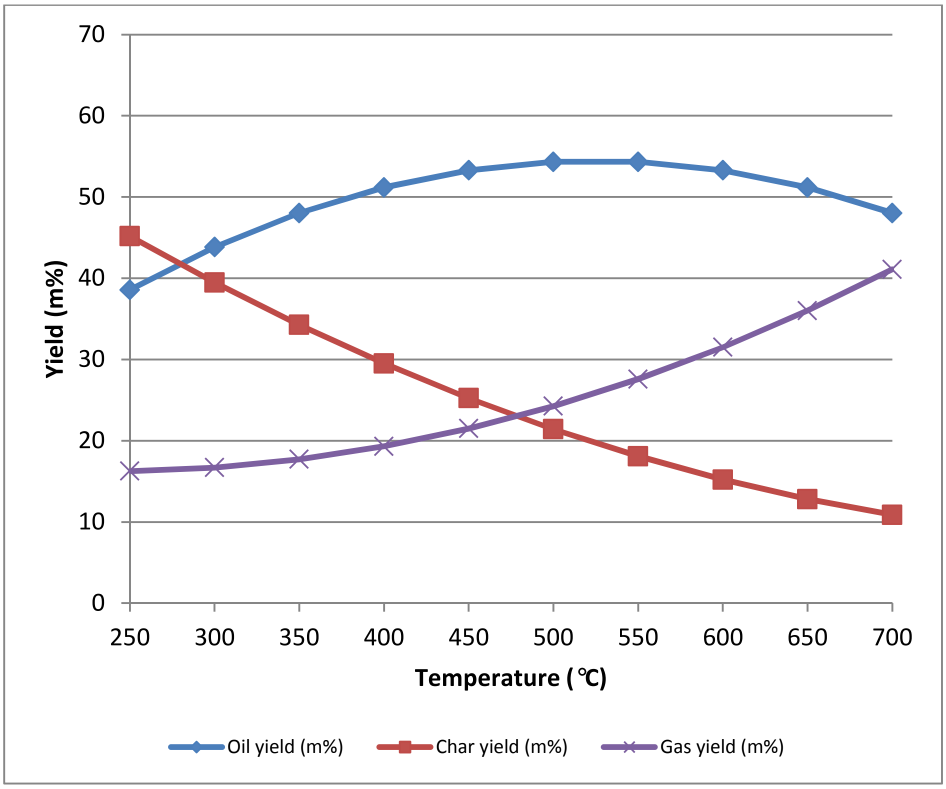

figure 33: Oil, char and gas yield in function of temperature (°C) (based on Yoder, Galinato et al. (2011))

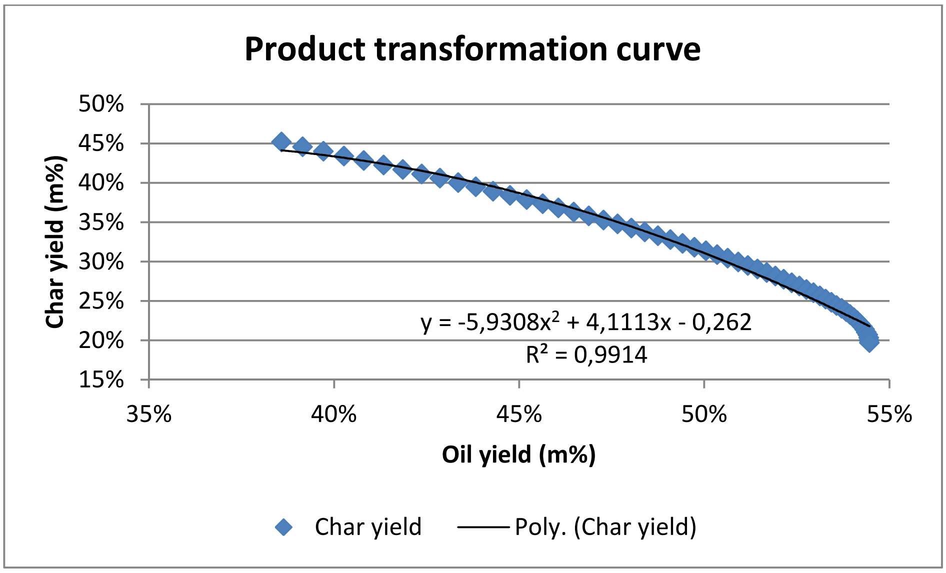

figure 34: Product transformation curve

The first derivative of the char yield to the oil yield in every point of this product transformation curve (PTC) now provides information about the price ratio at which a point of the curve is optimal. For instance, suppose an oil yield of 50 m%, which can be attained at a temperature of 379 °C. The corresponding char yield is 31 m%. In this point of the PTC the first derivative of the product transformation curve equals :

$$-2 \times 5{,}9308 \times 0{,}50 + 4{,}1113 = -1{,}819$$

This should be interpreted as the optimal price ratio of P_{oil}/P_{char} at which the temperature of 379 °C is optimal from a profit maximising point of view, i.e. when the price or net revenue of oil is 1,8 times higher than the char price, the optimal pyrolysis temperature equals 379 °C. In the next table some of the price ratios are represented.

This table indicates that the optimal temperature increases whenever the oil price or oil revenue increases, which makes sense because it is only profitable to produce more oil when oil is more profitable than char.

T (°C)	Oil %	Char %	Poil/Pchar
250	39	45	0,464905
275	41	42	0,791841
300	44	39	1,087639
325	46	37	1,352301
350	48	34	1,585826
375	50	32	1,788215
400	51	30	1,959467
425	52	27	2,099582
450	53	25	2,20856
475	54	23	2,286402
500	54	21	2,333107
525	54	20	2,348676

table 57: Relationship between price ratio and optimal temperature

7.3.2 Calculation of the gross revenue

In order to calculate the optimal temperature T the next step is to express the net revenues in terms of temperature, so that equations 2.29 and 2.30 can be determined. The net revenues are defined as the difference between the sales price of the end product and the cost of processing the intermediary products. For the char, it is the difference between the expected sales price of active coal and the cost of activating the char in a second pyrolysis kiln. For the oil, it is the difference between the expected sales price of the produced electricity, the produced heat, the green power certificates and the combined heat and power certificates, and the cost of combusting the oil in an internal combustion engine.

In our case, the sales prices of the end products are constant: the sales price of electricity does not vary with temperature. But we believe that the processing costs do vary, because of expected economies of scale: e.g. when oil yield increases with temperature, it is expected that the unit cost of processing one litre of oil decreases. First, we calculate the unit sales price. Next we deduct the unit processing cost (which is a function of temperature) based on previous cost-benefit models of fast pyrolysis investments in the Belgian Campine.

In this paragraph the sales price of the end products is converted in terms of the intermediary product. So the sales price per kg active coal or per MWh energy is expressed in the gross value per kg char or oil respectively.

a) *Active carbon*

Activated carbon is expensive. In 2006, the average bulk price from the major producers in the United States was 2,5 USD kg^{-1} (≈ 2,1 kEUR t^{-1} at the exchange rate of 7th March 2006) (Polat, Molva et al. 2006). Girods et al. (2009) mention a commercial activated carbon designed for the adsorption of pesticides and hydrocarbons from water that is sold at 2,0 kEUR t^{-1} (Girods, Dufour et al. 2009). Vanreppelen et al. (2011) found a typical price range for activated carbon between 1,4 and 6 kUSD t^{-1} (≈ 1,0 – 4,5 kEUR t^{-1}) (Vanreppelen, Kuppens et al. 2011). According to InfoMil (non-impregnated) activated carbon can be purchased at a price between 0,8 and 1,7 kEUR t^{-1} (InfoMil). According to Stals (2011), physical (steam) activation of pyrolysis char from contaminated hardwoods results in activated carbons with a “type IV adsorption behavior” which has a performance level comparable to that of a commercial available activated chars. Here it has been assumed that activated carbon from willow can be sold at a rather low price of 2 kEUR t^{-1}.

This sales price per tonne of activated carbon now is converted into a price per tonne of char. The activated carbon yield of the activation step is expected to be 50 % of the original mass of char (Girods, Dufour et al. 2009). This means that 2 tonnes of char are required to produce 1 tonne of activated carbon, or in other words that 2 kEUR per tonne of activated carbon corresponds to a **gross revenue of 1,0 kEUR per tonne of char or 1,0 EUR kg_{char}^{-1}**.

b) *Combined heat and power*

Converting the price of the end products of combined heat and power requires more calculation steps. First and foremost the combined heat and power engine has 4 salable "end products":

- Electricity savings and/or sales;
- Heat savings and/or sales;
- Green power certificates;
- Combined heat and power certificates.

Electricity savings and/or sales

An electricity producer can deliver the produced electricity to the network at a sales price of 70 EUR MWh_e^{-1}. Part of the produced electricity can be used by the investing company so that the company can save in the purchase of electricity. The purchase price of electricity is more or less 150 EUR MWh_e^{-1} (see paragraph 4.3.3). The difference between the purchase price of electricity from the grid and the sales price of produced electricity to the grid stems from the costs of the network administrator for transmission and distribution of electricity over the electricity grid. Assuming that part of the produced electricity can substitute purchased electricity, it is assumed that one MWh of electricity will on average yield 70 EUR MWh_e^{-1}. It is expected that a combined heat and power engine that converts the biomass yield from 2 400 ha of agricultural land, has a maximum electric capacity of 3,9 MW_e[5] taking into account that the expected oil yield is more or less 50 m% of the original biomass with a lower heating value of 17 MJ kg^{-1}. The expected electric efficiency of a CHP engine is 43 %. This means that in order to produce 1 MWh or 3,6 GJ[6] of electricity, an input of oil of 8,4 GJ[7] is required. The average electricity sales/savings prices expressed in terms of MJ inputs equals 8,4 x 10^{-3} EUR MJ_{in}^{-1}.[8]

Green power certificates

The Flemish Regulation Entity for the Electricity and Gas market (VREG) currently still awards green power certificates for every megawatt hour or 1 000 kWh of electricity produced on the basis of solar energy, wind energy, water power, or even organic biomass. Electricity suppliers are bound to deliver each year a certain amount of green power certificates that they have earned themselves or they can buy from other green current producers. The market price for a green power certificate is more or less 100 EUR MWh_e^{-1}. In terms of MJ inputs, the green power certificates yield 11,9 x 10^{-3} EUR MJ_{in}^{-1}.

Heat savings and/or sales

Heat from combined heat and power has an economic value of 20 EUR MWh_{th}^{-1} (Coenen, Schlatmann et al. 2008). The thermal efficiency of the CHP

[5] 3,9 MW_e = 43 % x [(2 400 ha x 8 t_{dm} ha^{-1} x 50 m% x 17 000 MJ t^{-1})/(5 000 h x 3 600 s h^{-1})]
[6] 1 MWh = 1 MW x 1 h = 1 MJ s^{-1} x 3 600 s = 3 600 MJ = 3,6 GJ
[7] 3,6 GJ = 8,4 GJ x 43 %
[8] 8,4 GJ = 8,4 x 10³ MJ and 70 EUR MWh_e^{-1} = 70 EUR x (8,4 x 10³ MJ)$^{-1}$ = 8,4 x 10^{-3} EUR MJ^{-1}

is expected to be 37 %, so that 1 MWh of thermal energy corresponds to an input of oil of 9,7 GJ[9] and 20 EUR MWh_{th}^{-1} corresponds to 2,1 x 10^{-3} MJ_{in}^{-1}[10].

Combined heat and power certificates

The recalculation of the sales price of 35 EUR per MWh of primary energy savings (i.e. 35 EUR MWh_{PES}^{-1}) of the combined heat and power certificates is somehow more difficult. First of all, the certificates are granted on a monthly basis. A heat and power plant receives 1 certificate for every MWh of primary energy saving that month. The monthly primary energy saving equals the electricity production in that month multiplied by the combined heat and power savings factor (see equation 7.3) (COGEN Vlaanderen 2006):

$$PES = E.\left(\frac{1}{\eta_e} + \frac{\alpha_{th}}{\alpha_e.\eta_{th}} - \frac{1}{\alpha_e}\right) \tag{7.3}$$

With: η_e = Flemish electric reference efficiency, i.e. 42,7 %
η_{th} = Flemish thermal reference efficiency, i.e. 90 %
α_e = electric efficiency of the CHP engine, i.e. 43 %
α_{th} = thermal efficiency of the CHP engine, i.e. 37 %

so that the combined heat and power savings factor equals 97,2 %. This implies that every MJ of primary energy savings corresponds to 1,02 MJ[11] of electricity. The sales price of 35 EUR MWh_{PES}^{-1} thus corresponds to a sales price of 9,7 x 10^{-3} EUR MJ_{PES}^{-1}[12] or 9,5 x 10^{-3} EUR MJ_e^{-1}[13]. As stated above an input of oil of 8,4 GJ is required.in order to produce 1 MWh or 3,6 GJ of electricity, so that 1 MJ_e corresponds to an oil input of 2,3 MJ_{in}. The sales

[9] 1 MWh = 3,6 GJ and 9,7 GJ x 37 % = 3,6 GJ
[10] 9,7 GJ = 9,7 x 10³ MJ and 20 EUR MWh^{-1} = 20 EUR x (9,7 x 10³ MJ_{in}^{-1}) = 2,1 x 10^{-3} MJ_{in}^{-1}
[11] 1 MJ_{PES} = 1,02 MJ_e x 97,2 %
[12] 9,7 x 10^{-3} EUR MJ_{PES}^{-1} = 35 EUR MWh_{PES}^{-1} / (3600 MJ_{PES} MWh_{PES}^{-1})
[13] 9,5 x 10^{-3} EUR MJ_e^{-1} = 9,7 x 10^{-3} EUR MJ_{PES}^{-1} / (1,02 MJ_e MJ_{PES}^{-1})

price of one combined heat and power certificate in terms of oil input thus equals 4,1 x 10^{-3} EUR MJ_{in}^{-1}[14].

Gross revenue

Now that all revenues have been expressed in terms of oil inputs, they can be summed up. A summary of the above calculations and the summation can be found in table 58:

Revenue item	Original value	In terms of oil input
Electricity sales/savings	70 EUR MWh_e^{-1}	8,4 x 10^{-3} EUR MJ_{in}^{-1}
Green power certificates	100 EUR MWh_e^{-1}	11,9 x 10^{-3} EUR MJ_{in}^{-1}
Heat sales/savings	20 EUR MWh_{th}^{-1}	2,1 x 10^{-3} EUR MJ_{in}^{-1}
Combined heat and power certificates	30 EUR MWh_{PES}^{-1}	4,1 x 10^{-3} EUR MJ_{in}^{-1}
Gross revenue		***26,4 x 10^{-3} EUR MJ_{in}^{-1}***

table 58: Calculation of the gross revenue of pyrolysis oil

In order to be comparable with the gross revenue of the char, the gross revenue in terms of energy input of oil needs to be converted in terms of oil weight. It has been stated above that pyrolysis oil has a lower heating value of 17 MJ kg^{-1}. **The gross revenue of pyrolysis oil in terms of mass therefore equals 0,45 EUR kg_{oil}^{-1}**[15].

[14] 35 EUR MWh_{PES} = 9,7 x 10^{-3} EUR MJ_e^{-1} / (2,3 MJ_{in} MJ_e^{-1}) = 4,1 x 10^{-3} EUR MJ_{in}^{-1}
[15] 0,45 EUR kg_{oil}^{-1} = (26,4 x 10^{-3} MJ_{in}^{-1}) x 17 MJ kg_{oil}^{-1}

7.3.3 Calculation of the net revenue of the intermediary products in function of temperature

As temperature influences product yields, it also influences the total costs of the subsequent processing steps: the costs of the activation step depend on the processed quantity of char and the costs of the combined production of heat and power depend on the quantity of processed oil. The calculation of the costs for the activation step and subsequent fume gas treatment has been explained below. The additional costs of combined heat and power production are explained in chapter 4.

a) *Costs of the activation step*

It has been assumed that, after pyrolysis, the pyrolysis chars are activated in an activation furnace at 800 °C in the presence steam as activation agent. Steam is generated in a steam boiler and condenser using the hot flue gases from the pyrolysis and activation step. After cooling, the activated carbon is transported to a storage silo before screening and packaging. The remaining gases are cooled to recover water from the steam generator. After cooling they are discarded. An extra gas cleaning unit is required in order to avoid the emission of the heavy metals that have been accumulated in the pyrolysis char during the pyrolysis step and which volatilise at the high activation temperatures.

The capital cost of the activation step has been calculated by first calculating major equipment cost. The extra major equipment items that are required during activation are:

- activation furnace;
- steam boiler and condenser;
- silo for storage before packaging;
- screening and packaging.

The equipment cost has been based on the literature sources and adapted to current estimates by means of the CEPCI and to actual scales in the Belgian Campine by means of the six-tenth rule.

The equipment cost of the **activation reactor** resembles the equipment cost of a pyrolysis reactor (Vanreppelen, Kuppens et al. 2011) and can be calculated using equation 4.16 which is the result of the meta-analysis on the total capital investment of a fast pyrolysis plant, by replacing the hourly input flow of dried and grinded willow with the hourly output flow of pyrolysis char from the pyrolysis step, because the latter is the actual feedstock for the activation reactor. Because equation 4.16 represents the total capital investment and thus comprises more than equipment costs alone, we estimate the equipment cost of an activation kiln by dividing the total plant cost by the percentage that is often applied in the method of percentage of delivered equipment costs. Bridgwater, Toft et al. (2002) stated that the total plant cost of a pyrolysis reactor is 169 % of the direct plant cost. The direct plant cost in turn is the product of the estimated equipment cost and the direct cost factors. The percentages of these direct cost factors that Bridgwater, Toft et al. (2002) used are not defined, but the factor can be found in Peters, Timmerhaus et al. (2004): 39 % for erection, 31 % for piping, 26 % for instruments, 10 % for electrical systems, 55 % for civil works and 29 % for structures and buildings. Hence, it is assumed that the direct plant cost equals 290 % of the equipment cost (i.e. 100 % or the equipment cost of the reactor itself plus 190 % to cover the other direct costs). Applying Bridgwater's assumption the total capital investment equals 169 % of the direct plant cost, thus in other words equals a total capital investment that corresponds to 490,1 % of the purchased equipment. The equipment cost of the activation reactor thus can be approximated by:

$$Equipment\ cost\ = \frac{TPC_{Kup12}}{490{,}1\%} = \frac{3\,486\,567 \times \left(\eta_{char}^{py} \times \Phi_{py}^{h}\right)^{0{,}6914}}{490{,}1\%} \qquad (7.4)$$

The cost of the **steam boiler and condenser** has been based on Choy, Barford et al. (2005). They calculated a unit cost for a steam boiler of 103 338 USD (in 2002 values) for a boiler that processes 3 781 kg of water per hour. Together with the cost of the condenser of 9 500 USD, the total cost of the steam boiler and condenser equals 112 840 USD in 2002. This has been updated to 2011 values by first multiplying with the ratio of the CEPCI in 2011 to the CEPCI of 2002 (which equals 582,8/395,6 or 1,473) and then applying the EUR/USD exchange rate which equalled on average 1 USD = 0,74458 EUR in 2011. Next the cost has been resized by calculating the steam requirements following Ko, Mui et al. (2004) who estimate a steam requirement of 134 000 tonne per year for a plant processing 30 tonnes of feedstock per day with 24 hours per workday and 330 working days per year. In other words, Ko et al. (2004) require 13,5 tonne water per tonne of feedstock. When one knows the hourly char feedstock to the activation reactor, one can estimate the hourly need of steam to rescale the equipment cost of the steam boiler and condenser with the six-tenths rule.

The cost of a **silo** for storage of the activated carbon before screening and packaging equals 380 000 EUR (2009 value) for a silo that can store 500 m^3 of activated carbon for a pyrolysis plant processing 0,5 tonne of char per hour (Vanreppelen, Kuppens et al. 2011).

The cost of **screening and packaging** 139,9 kg activated carbon per hour equals 50 000 USD (2005 values) (Lima, McAloon et al. 2008).

b) *Cost of fume gas treatment*

During the activation step, heavy metals come into the flue gases either by volatilisation or bound to fine particles of char that come free during activation. When metal fumes are emitted, electrostatic precipitators and wet scrubbers are suggested to control emissions (Bond, Straub et al. 1972; Liu and Lipták 1996). Heavy metals in flue gases can also be captured by activated charcoal (Gostomczyk and Lech-Brzyk 2010), which of course is no option when the released heavy metals stem from active carbon production.

Before estimating the cost of the fume gas treatment, we first calculate the maximum potential metal pollution in the fume gases and compare it to emission norms so that the required degree of purification (or efficiency) of the fume gas treatment can be determined. As stated before, activation of one tonne of pyrolysis char, yields 50 m% of active carbon (Girods, Dufour et al. 2009). The other half thus is released in the form of gases. Under the assumption that the mass density of the fume gases equals more or less 1,30 kg Nm^{-3} (based on discussions with Vanreppelen, Yperman and Carleer), every tonne of char results in 384,62 Nm^3 of gases. Most probably willow will be harvested in autumn after leave fall and it is expected that the Cd concentration in willow that has been cultivated for phytoextraction within a time frame of more or less 40 years, will equal the minimal Cd concentration of table 56 or 68,6 mg Cd kg^{-1} char or 68,6 g Cd t^{-1} of char. In the worst case all metals volatilise in the fume gases so that 54,9 g of cadmium ends up in 384,62 Nm^3 of gases from activation, so that the Cd concentration in the product gases of char activation equals more or less 142,74 mg Cd Nm^{-3} which is quite high compared to emission limits stated in VLAREM II: we compare with emission limits for incineration installations of untreated wood which are 0,1 mg Cd Nm^{-3} for installations with an electric capacity between 5 and 50 MW_e. The fume gas treatment thus should have a Cd removal efficiency of at least 99,299 %. For other heavy metals like Cu, Pb and Zn the sum of their concentrations might not exceed 1,5 mg Nm^{-3}. The total concentration of Zn and Cu equals 1 298,1 mg kg^{-1} char, which results in a metal concentration of 3 375,0 mg Nm^{-3} in the fume gases or a **minimal efficiency** of the fume gas treatment of **99,970 %**.

Hardly any information is available in the literature with regard to the investment costs of individual plant components and entire flue gas cleaning systems (Achternbosch and Richers 2002) who performed an elaborate study on the capital cost of fume gas treatment systems. Next we select the best fume gas treatment proposed in Achternbosch and Richers (2002). The efficiency of 99,970 % can only be obtained with four proposed flue gas cleaning systems that are a combination of ESP (electrostatic precipitator) and wet scrubbers (which was also proposed by Bond, Straub et al. (1972) and Liu and Lipták (1996)). The systems had a capital cost of 29 to 30 million DM (Deutsche Marke) for two incineration lines or more or less 15 million DM for a flue gas cleaning system for one incineration plant, which were the most expensive fume gas treatment systems proposed in their study. This fume gas treatment processes 2 350 Nm^3 of gases per ton of input (which is 100 000 tonnes per year). This information has been used and adapted by means of the six-tenths rule, the CEPCI (for year adjustment) and the DM EUR exchange rate.

c) Operational costs

The annual maintenance cost is accounted for 3%, the annual overhead and insurance cost for 2% of the total fixed capital investment. The labour costs are calculated according to Bridgwater et al. (2002) by adjusting for the hourly input of char:

$$L_{py} = 3{,}12 \times \left(\eta_{char}^{py} \times \Phi_{py}^{h}\right)^{0{,}475} \qquad (7.5)$$

No delivered feed cost has been calculated for the char, because it is the output of the pyrolysis of willow that has been used as an input for the activation step. To provide an oxygen free environment, nitrogen gas is applied to act as a purging gas. In this study a rate of 8 kg nitrogen gas t^{-1} feed input with a cost of 2,5 EUR kg^{-1} is applied (Ko, Mui et al. 2004). Bridgwater et al. (2002) used 18,5 m^3 water t^{-1} input material for cooling the produced pyrolysis liquid and Ko et al. (2004) used 13,5 m^3 water per tonne input material to generate steam for the activation and cooling water for the produced pyrolysis liquid. The quantity of cooling water (from surface water 20 °C) needed to cool the produced AC from 800 °C to 20 °C is 13 t h^{-1}.

Here, the water requirements are assumed to be 13,5 m^3 water per tonne input material with a cost of 0,77 EUR m^{-3}.

Another utility required in the process is energy which can be split in two parts, power and heat requirements. A 1,25 t h^{-1} processing plant producing AC uses 200 kW electricity (Ko, Mui et al. 2004). So it is assumed that for a 1 t h^{-1} facility the electricity consumption is 160 kW. In this estimation the cost of electricity is set at 70 EUR MWh^{-1} as it is assumed that electricity from the CHP engine will be used so that electricity sales decrease.

The heat of pyrolysis for municipal solid waste is calculated by Baggio, Baratieri et al. (2008) as 1,8 MJ kg^{-1}. For biomass a range of 2 MJ kg^{-1} to 3,47 MJ kg^{-1} can be found in literature (Diebold and Bridgwater 1999; Polagye, Hodgson et al. 2007). In our case a value of 2,5 MJ kg^{-1} for the activation step is taken. In the activation step steam is also needed. Heating water from 20 °C to 800 °C requires 5,5 MJ kg^{-1}. In most pyrolysis reactors (for the production of pyrolytic oil) the required heat is provided by the combustion of the gas and/or the char. In this application only AC and gases (as by-product) are produced. The gases will be thermally destroyed and provide the required heat (Vanreppelen, Kuppens et al. 2011).

d) <u>Net average revenues</u>

In table 59 one can follow the calculation of the net average revenue per kilogram of oil and char. In the first three rows one can see the relationship between process temperature, oil yield and char yield which can also be found in figure 33. From the first column it is clear that an oil yield of 39 m% can be reached at a process temperature of 250 °C. At this temperature, the char yield equals 45 m% and so on. It is also clear that as temperature increases, that the oil yield also increases from 39 m% to 54 m% (row 2) and that the char yield decreases from 45 m% to 22 m% (row 3).

		Unit	(1)	(2)	(3)	(4)	(5)	(6)
(1)	**Temperature**	**°C**	250	300	350	400	450	500
(2)	**Oil Yield**	**%**	39%	43%	48%	51%	53%	54%
(3)	**Char yield**	**%**	45%	40%	35%	30%	26%	22%
(4)	**Total act. cost**	**MEUR/yr**	3,11	2,85	2,62	2,44	2,31	2,24
(5)	**Total CHP cost**	**MEUR/yr**	0,91	1,03	1,11	1,18	1,23	1,25
(6)	**Total char product.**	**kt/yr**	8,67	7,58	6,58	5,67	4,84	4,11
(7)	**Total oil product.**	**kt/yr**	7,41	8,42	9,22	9,83	10,23	10,43
(8)	**Unit cost char**	**EUR/kg**	0,358	0,379	0,402	0,433	0,478	0,545
(9)	**Unit cost oil**	**EUR/kg**	0,115	0,114	0,113	0,112	0,112	0,111
(10)	**Gross rev. char**	**EUR/kg**	1,000	1,000	1,000	1,000	1,000	1,000
(11)	**Gross rev. oil**	**EUR/kg**	0,449	0,449	0,449	0,449	0,449	0,449
(12)	**Net revenue char**	**EUR/kg**	0,642	0,621	0,598	0,567	0,522	0,445
(13)	**Net revenue oil**	**EUR/kg**	0,326	0,329	0,329	0,330	0,330	0,330
(14)	**Price ratio**		0,508	0,529	0,551	0,582	0,632	0,725
(15)	**1st ord. derivative**		-0,043	-0,053	-0,059	-0,061	-0,061	-0,060

table 59: Calculation of the net revenue of oil and char

In the 5th row it is illustrated that the total processing cost of the combined heat and power engine increases with increasing oil yield and temperature, while the total cost of the activation step decreases with decreasing char yield in row 4. In row 6 the total char production in one year has been calculated by multiplying the weight percentage char yield with the yearly amount of willow that can be harvested from the Belgian and Dutch Campine. Here it has been assumed that not only the 2 400 ha in the Belgian Campine will be phytoextracted, so that 19,2 x 10^3 tonne dry matter of willow harvested after phytoextraction and 8,67 x 10^3 tonne of char is produced at a temperature of 250 °C (i.e. at a char yield of 45 m%) (see column 1 row 6). The total oil production in row 7 can be calculated by multiplying the weight percentage oil yields of row 2 with total annual willow production of 19,2 x 10^3 t_{dm} yr^{-1}: for instance 39 m% of 19,2 x 10^3 equals a total oil production of 7,41 x 10^3 t (see column 1 row 7). Next, the total cost of the subsequent processing step has been expressed on a per unit basis: in row 8 one finds the unit activation cost of the char by dividing the total cost of the activation step in row 4 by the total char production of row 6. In row 9 one finds the unit processing cost of oil by dividing the total cost of the CHP engine in row 5 by the total oil production of row 7. Finally the unit costs have been subtracted from the gross revenue calculated in paragraph 7.3.2. The resulting net revenue of char, which is the difference between the gross revenue of the char in row 10 and the unit cost of the char in row 8, can be found in row 12; whereas the net revenue of oil, i.e. the difference between the gross revenue of oil in row 11 and the unit cost of processing the oil in row 9, can be found in row 13.

Next, the function of the net revenue of char and oil in dependence of process temperature has been determined. In row 13 we can see that the net revenue of oil is more or less constant, but if we look into more detail we see that the net revenue of oil increases with increasing temperature from 0,326 EUR kg^{-1} oil at 250 °C until 0,330 EUR kg^{-1} oil at 500 °C. This indicates that the net revenue of oil can be a function of temperature of the first or second order. The best fit for both net revenue of oil and char is presented in figure 35. This figure also represents the concrete values of the parameters of equations 2.29 and 2.30, so that they become:

$$nr_{char}(T) = \delta_0 + \delta_1 T + \delta_2 T^2 \quad (7.6)$$

$$nr_{oil}(T) = \gamma_0 + \gamma_1 T + \gamma_2 T^2 \quad (7.7)$$

with: δ_0 = 0,4767; δ_1 = 0,0013; δ_2 = -3 x 10^{-6}
γ_0 = 0,3185; γ_1 = 5 x 10^{-5}; γ_2 = -5 x 10^{-8}

In other words:

$$nr_{char}(T) = 0{,}4767 + 0{,}0013T - 3 \times 10^{-6}\, T^2 \quad (7.8)$$

$$nr_{oil}(T) = 0{,}3185 + 5 \times 10^{-5} T - 5 \times 10^{-8} T^2 \quad (7.9)$$

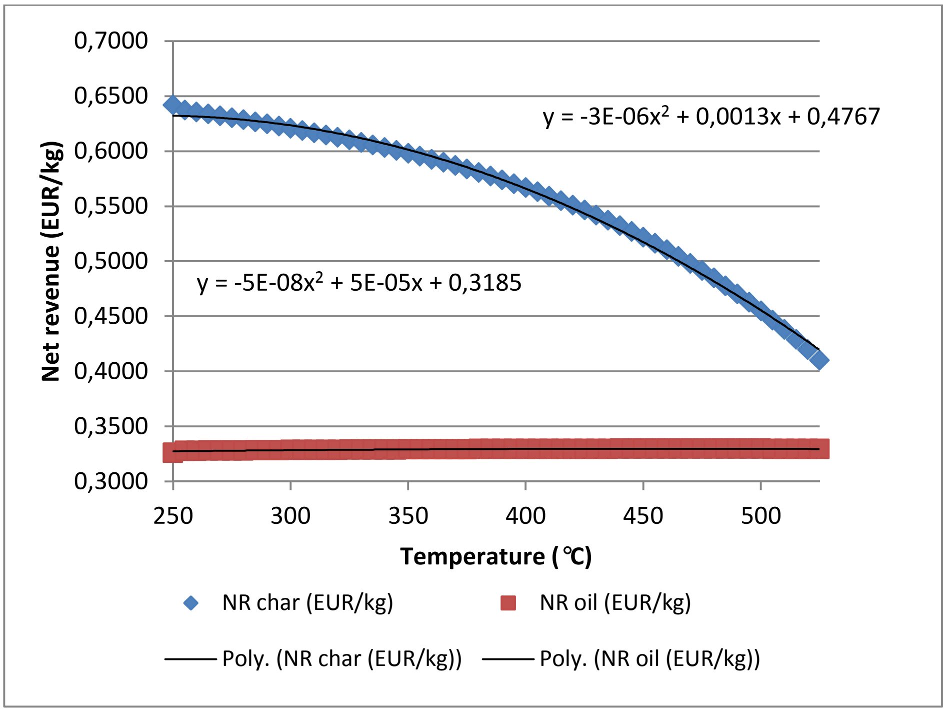

figure 35: Net revenue of oil and char in function of temperature

As can be derived from row 13 in table 59 and in figure 35, the net revenue of one kilogramme of oil is more or less constant: it is between 0,326 and 0,330 EUR kg^{-1}, whereas the net revenue of the char price decreases from 0,642 EUR kg^{-1} to 0,445 EUR kg^{-1} which indicates that economies of scale are more important to char activation compared to energy production from pyrolysis oil.

7.3.4 Optimal temperature

The optimal temperature is the temperature at which **total** revenue is maximated, i.e. the product of the *net* revenue per unit (represented in figure 35) and the number of units (or quantity, represented in figure 33) produced. All parameters of equations 2.27 until 2.30 are known so that the optimal temperature T can be determined for the fast pyrolysis process under investigation, by calculating the first order and second order derivatives of equation 2.31, i.e. by calculating the values of A, B, C and D in equation 2.40 until 2.43. First, the parameters of equations 2.27 until 2.30 are summarized in table 60.

Equation	Constant	T	T²
q_{char} (2.27)	80,67 (α_0)	-0,1655 (α_1)	9,4x10^{-5} (α_2)
q_{oil} (2.28)	-3,42 (β_0)	0,2205 (β_1)	-2,1x10^{-4} (β_2)
nr_{char} (2.29)	0,4767 (δ_0)	0,0013 (δ_1)	-3 x 10^{-6} (δ_2)
nr_{oil} (2.30)	0,3185 (γ_0)	0,00005 (γ_1)	-5 x 10^{-8} (γ_2)

table 60: Parameters net revenue and production functions of oil and char in function of temperature

Equation 2.39 can be rearranged in the form AT³ + BT² + CT + D = 0 with:

$$A = 4(\alpha_2\delta_2 + \beta_2\gamma_2) = -1{,}086 \times 10^{-9}$$

$$B = 3(\alpha_1\delta_2 + \alpha_2\delta_1 + \beta_1\gamma_2 + \beta_2\gamma_1) = 1{,}792 \times 10^{-6}$$

$$C = 2(\alpha_0\delta_2 + \alpha_1\delta_1 + \alpha_2\delta_0 + \beta_0\gamma_2 + \beta_1\gamma_1 + \beta_2\gamma_0) = -9{,}361 \times 10^{-4}$$

$$D = \alpha_0\delta_1 + \alpha_1\delta_0 + \beta_0\gamma_1 + \beta_1\gamma_0 = 9{,}604 \times 10^{-2}$$

Solving an equation of the third order can be done by means of the method of Cardano (Stikker 2004). The method of Cardano itself will not be proved here, but the calculation steps according to Stikker (2004) are followed which comprise the following steps:

1. First of all, one needs to calculate p and q:

$$p = \frac{C - \frac{B^2}{3A}}{A} = \tag{7.10}$$

$$q = \frac{\frac{2B^3}{27A^2} - \frac{CB}{3A} + D}{A} = \tag{7.11}$$

2. Next, one needs to calculate g so that:

$$g^2 + qg - \frac{p^3}{27} = 0 \tag{7.12}$$

3. The next step is to calculate u:

$$u = \sqrt[3]{g} \tag{7.13}$$

4. Calculate v:

$$v = \frac{p}{3u} \tag{7.14}$$

5. Calculate y:

$$y = u - v \tag{7.15}$$

6. Calculate the solution x:

$$x = y - \frac{b}{3a} \tag{7.6}$$

This results in one real solution for x, i.e. x = 139 °C which falls outside the economically relevant temperature interval of]250; 524,92[. Therefore we have to check the function by means of the second order derivative with the functional form of $3AT^2 + 2BT + C$ should be solved for temperature:

$$3AT^2 + 2BT + C = 0 \tag{7.17}$$

with: $3A = -3{,}3 \times 10^{-9}$

$2B = 3{,}6 \times 10^{-6}$

$C = -9{,}4 \times 10^{-4}$

The discriminant equals: $(2B)^2 - 4(3A)C = 6{,}39 \times 10^{-13}$, so that there are two temperatures T that solve for equation 7.17:

$$T_1 = \frac{-(2B) + \sqrt{6{,}39x10^{-13}}}{2(3A)} = 672\ °C \tag{7.18}$$

$$T_2 = \frac{-(2B) - \sqrt{6{,}39x10^{-13}}}{2(3A)} = 427\ °C \tag{7.19}$$

These temperatures now can be used to evaluate the course of the first derivative:

Temperature		**427 °C**		**672 °C**	
2nd order derivative	negative	0	positive	0	negative
1st order derivative	decreasing		increasing		decreasing

table 61: Second order derivative analysis (base case)

Now we know that the first order derivative is strictly decreasing before 427 °C, increasing between 427 °C and 672 °C and decreasing again after 672 °C. We are only interested in the relevant economic temperature range of fast pyrolysis, which has been defined before as the temperatures between 250 °C and 524,92 °C. Therefore it suffices to calculate the value of the first order derivative at the end points of the temperature interval. This has been done in row 14 of table 59. From this table it can be learnt that the first order derivative is always negative in the temperature interval, which means that the original revenue function is strictly decreasing in the temperature interval]250; 524,92[so that the maximal revenue must be at 250 °C. It has also been illustrated that the first order derivative is indeed decreasing until 427 °C (i.e. more negative) and increasing from 427 °C.

7.3.5 Intuitive interpretation of the results

The calculation of the optimal temperature by optimisation of an equation of the third degree confirms what – in this case (not always) – could have been intuitively deduced from figures 33 and 35. From figure 33 one can see that the quantity of char and oil is more or less equal between 250 and 300 °C, whereas the net revenue of the char (assuming the use as a resource for activated carbon production) is twice the net revenue of the pyrolysis oil (compare 0,642 EUR kg^{-1} char to 0,326 EUR kg^{-1} oil). At the other side of the economic temperature range, i.e. 525 °C the quantity of oil is 2,5 times the quantity of char, i.e. the quantity of oil has increased with 20 % from 39 m% to 54 m%, whereas the char quantity has been reduced with more than half from 45 m% to 20 m%. Because the net revenue of oil is more or less constant, one can clearly see that revenues from combined heat and power production have increased with 20 % (because of the rise in quantity produced), whereas the revenues from AC production have been reduced to less than one third of the revenue at 250 °C (both the quantity and the net revenue have decreased). The increase in revenues from oil production thus clearly do not outweigh the loss in revenues from AC production.

Besides, the revenues from oil production are actually overestimated. It has been assumed that the cost of the fast pyrolysis process is constant. This is true for the capital cost (as the plant initially still processes the same amount of biomass), but not for the operational costs. Especially the energy costs differ, because of the difference in temperature. The calculation of the gross revenue of oil production started from the assumption that the pyrolysis gases provide sufficient energy for the fast pyrolysis process. Though in reality this gross revenue is lower because part of the heat produced by the CHP should be used for providing energy to the fast pyrolysis plant. This would strengthen the case for actived carbon production even more.

From table 59 one can also conclude that AC production is more beneficial than disposal of the char, so that the net present value of the total process (from willow pyrolysis to AC production) is augmented. The disposal cost of char is 122 EUR t_{dm}^{-1} or 0,122 EUR kg^{-1}. The production cost of AC from char is much higher: between 0,358 EUR kg^{-1} and 0,545 EUR kg^{-1} (see row 8 of table 59), though it is largely compensated by the high revenue from the sales of AC: the sales price of AC compensates the production cost and even results in a positive net revenue so that AC production is clearly preferred above char disposal. Actually, when the AC price is at least 0,423 EUR kg^{-1} (in kg of char or 0,846 EUR kg^{-1} AC) one can say that an investor is indifferent (under 100 % certainty) between AC production and char disposal. Besides the NPV of the total plant (pyrolysis + CHP + AC production) is increased to 64 MEUR in the base case (450 °C) which illustrates the augmented profitability of AC production compared to pyrolysis of contaminated willow with disposal of the char (see results in chapters 5, 6 and 7). Pyrolysis at 250 °C increases the expected plant's profitability even further to 94 MEUR which confirms the aforementioned finding of the optimal temperature of 250 °C.

7.4 Scenario analysis for activated carbon production

Recapitulating table 57 where the relation between the oil/char price ratio and optimal process temperature was represented, we identify some scenarios that might be beneficial for oil production in a way that the oil/char price ratio might be increased. For instance, the production of oil is promoted when the net revenues from oil are 2,3 times higher than the char price. As can be derived from row 13 in table 59, the net revenue of one kilogramme of oil is more or less constant: it is between 0,326 and 0,330 EUR kg^{-1}. This can be attained by either an increase of the net revenue of oil or a decrease in the net revenue of char or, which can be realised by a higher scale of operation or lowering the AC sales price.

7.4.1 Scale of operation

One option might be to increase the scale of operation, including the biomass potential from the Dutch part of the Campine region. From table 4 it is clear that the available farmland would increase from 2 400 ha to more or less 6 400 ha. The results of the above calculations are summarised in what follows and the optimal temperature has been determined.

As can be seen in table 62 a higher scale reduces the unit cost of char activation and combined heat and power production (see rows 8 and 9 of table 62 compared to table 59), so that net revenues increase. This decrease in unit cost/increase in net revenues is more substantial for the unit cost of char activation than for combined heat and power production from oil, so that the distance between the net revenue curves of char and oil increase (see the distance between the blue and the red line in figure 36) and the price ratio decreases. Intuitively one can thus expect that also at large scales activated carbon production is preferred above oil production.

		Unit	(1)	(2)	(3)
(1)	**Temperature**	**°C**	300	400	500
(2)	**Oil Yield**	**%**	44%	51%	54%
(3)	**Char yield**	**%**	39%	30%	21%
(4)	**Total activation cost**	**kEUR/yr**	5,49	4,64	4,22
(5)	**Total CHP cost**	**kEUR/yr**	2,51	2,90	3,06
(6)	**Total char production**	**kt/yr**	20,21	15,11	10,97
(7)	**Total oil production**	**kt/yr**	22,44	26,20	27,82
(8)	**Unit cost char**	**EUR/kg**	0,274	0,309	0,386
(9)	**Unit cost oil**	**EUR/kg**	0,111	0,110	0,110
(10)	**Gross revenue char**	**EUR/kg**	1,000	1,000	1,000
(11)	**Gross revenue oil**	**EUR/kg**	0,439	0,439	0,439
(12)	**Net revenue char**	**EUR/kg**	0,726	0,691	0,614
(13)	**Net revenue oil**	**EUR/kg**	0,338	0,339	0,339
(14)	**Price ratio**		0,466	0,491	0,552
(15)	**First order derivative**		-0,05	-0,06	-0,06

table 62: Calculation of the net revenue of oil and char (total Campine case)

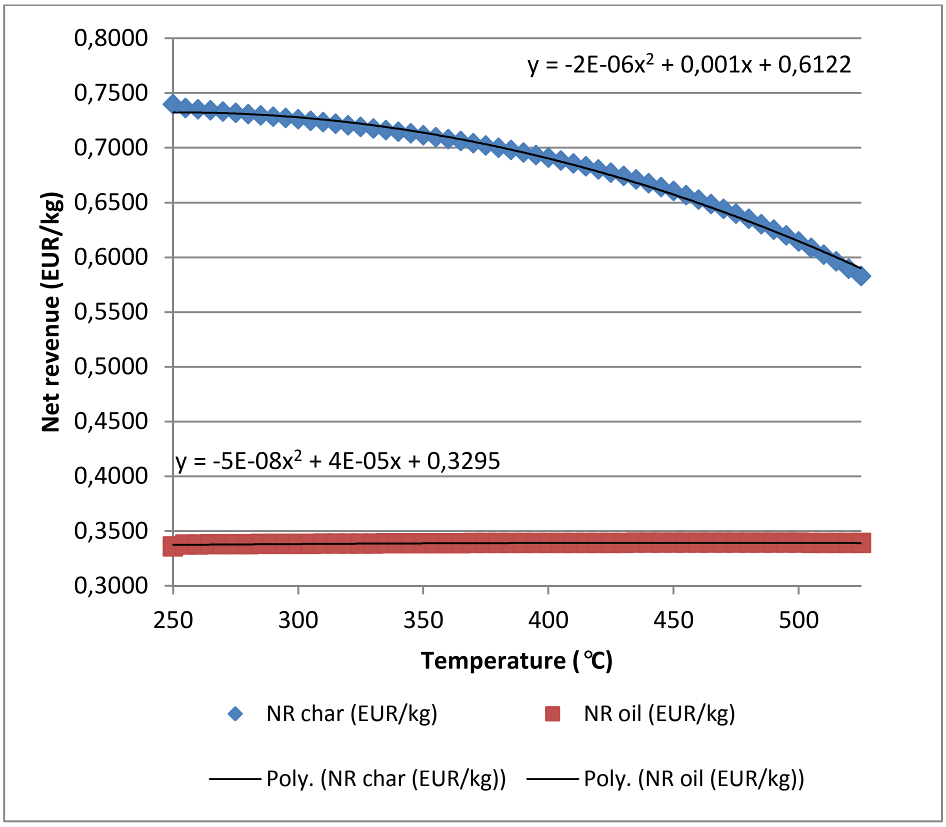

figure 36: Net revenue of oil and char in function of temperature (total Campine case)

The results of the net revenue functions have been summarized below.

Equation	Constant	T	T²
q_{char} (2.27)	80,67 (α_0)	-0,1655 (α_1)	$9,4 x 10^{-5}$ (α_2)
q_{oil} (2.28)	-3,42 (β_0)	0,2205 (β_1)	$-2,1 x 10^{-4}$ (β_2)
nr_{char} (2.29)	0,6122 (δ_0)	0,001 (δ_1)	-2×10^{-6} (δ_2)
nr_{oil} (2.30)	0,3295 (γ_0)	0,0004 (γ_1)	-5×10^{-8} (γ_2)

table 63: Parameters net revenue and production functions of oil and char in function of temperature (total Campine case)

Repeating the method of Cardano results in one real solution for x, i.e. x = 94 °C which falls outside the economically relevant temperature interval of]250; 524,92[. Therefore we have to check the function by means of the second order derivative with the functional form of 3AT² + 2BT + C, so that the optimal temperature again equals 250 °C (or char production is preferred).

Temperature		441 °C		701 °C	
2nd order derivative	negative	0	positive	0	negative
1st order derivative	decreasing		increasing		decreasing

table 64: Second order derivative analysis (total Campine case)

Increasing the scale of operation thus might be an advantage in terms of economies of scale, but this is true both for activated carbon production as for energy production from oil. Economies of scale however are more distinct for active carbon production, so that even cost advantages for oil production are not persistent enough to tilt the balance in favour of oil production.

7.4.2 Lower sales price activated carbon

One example is the decrease of the AC sales price, ceteris paribus, so that the oil/char price ratio increases from 0,725 (see row 14 of column 6 in table 59) to 2,333 (see price ratio at 500 °C in table 57) at a temperature of 500 °C. When all other variables are being held constant, this implies that the net revenue of the char, which is currently 0,445 EUR kg^{-1} should decrease to 0,141 EUR kg^{-1}[(16)]. Given the unit cost of the char of 0,545 EUR kg^{-1} at 500 °C, this requires that the gross revenue can be 0,686 EUR kg^{-1} at maximum or a sales price for activated carbon of 1,372 EUR kg^{-1}. To illustrate this, we repeat the above calculations for an AC price of 1,2 EUR kg^{-1} or a gross revenue from char production of 0,6 EUR kg^{-1} in table 65, figure 37.

		Unit	(1)	(2)	(3)
(1)	**Temperature**	**°C**	300	400	500
(2)	**Oil Yield**	**%**	44%	51%	54%
(3)	**Char yield**	**%**	39%	30%	21%
(4)	**Total activation cost**	**kEUR/yr**	2,85	2,44	2,24
(5)	**Total CHP cost**	**kEUR/yr**	1,03	1,18	1,25
(6)	**Total char production**	**kt/yr**	7,58	5,67	4,11
(7)	**Total oil production**	**kt/yr**	8,42	9,83	10,43
(8)	**Unit cost char**	**EUR/kg**	0,379	0,433	0,545
(9)	**Unit cost oil**	**EUR/kg**	0,121	0,120	0,120
(10)	**Gross revenue char**	**EUR/kg**	0,600	0,600	0,600
(11)	**Gross revenue oil**	**EUR/kg**	0,449	0,449	0,449
(12)	**Net revenue char**	**EUR/kg**	0,221	0,167	0,055
(13)	**Net revenue oil**	**EUR/kg**	0,329	0,330	0,330
(14)	**Price ratio**		1,486	1,976	6,012
(15)	**First order derivative**		6,02	17,75	52,24

table 65: Calculation of the net revenue of oil and char (low AC sales price case)

16 $\frac{nr_{oil}}{nr_{char}} = \frac{0,330}{0,141} = 2,333$

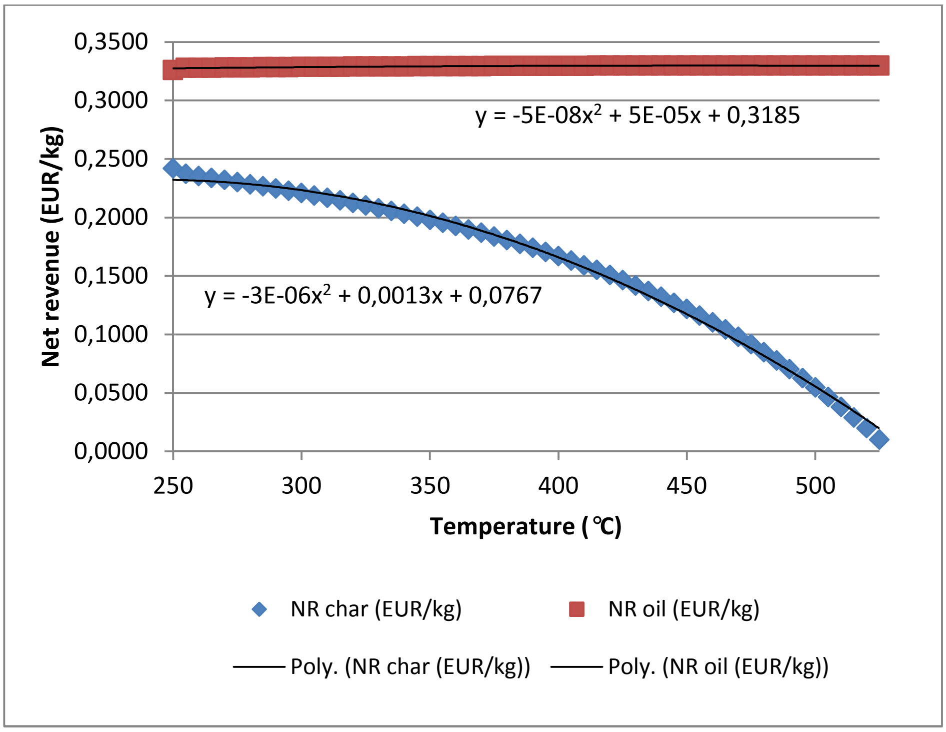

figure 37: Net revenue of oil and char in function of temperature (low AC sales price case)

Equation	Constant	T	T²
q_{char} **(2.27)**	80,67 (α_0)	-0,1655 (α_1)	$9{,}4\text{x}10^{-5}$ (α_2)
q_{oil} **(2.28)**	-3,42 (β_0)	0,2205 (β_1)	$-2{,}1\text{x}10^{-4}$ (β_2)
nr_{char} **(2.29)**	0,0767 (δ_0)	0,0013 (δ_1)	$-3 \text{ x } 10^{-6}$ (δ_2)
nr_{oil} **(2.30)**	0,3185 (γ_0)	0,00005 (γ_1)	$-5 \text{ x } 10^{-8}$ (γ_2)

table 66: Parameters net revenue and production functions of oil and char in function of temperature (low AC sales case)

Applying the above figures from table 66, which only differs from table 60 with respect to the value of δ_0) now clearly is advantageous for oil production, which can also be derived from the value of the first order derivative in row 15 of table 65: as long as the first order derivative is greater than zero in the economically relevant temperature interval, the profits are increasing. Hence the most optimal temperature now is at the other range of the economically relevant temperature range or at 525 °C.

The sales price of activated carbon is crucial in determining whether oil or char production should be promoted. Our calculations above imply that oil production is preferred whenever the AC sales price is below 1,372 EUR kg^{-1}. Char production or a process temperature of 250 °C on the other hand is optimal when the oil/char price ratio diminishes to 0,465 (see table 57). Taking into account the unit cost of char activation of 0,358 EUR kg^{-1} and the net revenue of energy production from pyrolysis oil of 0,326 EUR kg^{-1} at this temperature, this implies that the AC sales price equals more or less 2,1 EUR kg^{-1} which is consistent with earlier findings. As a conclusion one can state that whenever AC can be sold at prices of 2,0 EUR or higher the optimal temperature equals 250 °C and whenever the AC sales price is lower than 1,4 EUR kg^{-1}, the optimal process temperature should be in favour of oil production (or 500 °C).

7.5 Conclusion and discussion

Risk can be reduced either by changing the inputs to the production process or by selecting process parameters for obtaining a different mix of outputs. Changing process parameters such as temperature or residence times influence the produced quantities of oil and char. Once it is possible to valorise the char byproduct of fast pyrolysis, an economic trade-off exists between the pyrolysis product. Two innovative potential valorisation options have been identified for the char output: biochar as a soil amendment and pyrolysis char as a resource for active coal production. Using biochar as a soil amendment is not possible unless the heavy metals can be removed, because the metal concentrations exceed VLAREMA norms. Therefore the economic calculations were focused on active coal production in the remainder of the chapter.

The calculation of the economic trade-off has been based on the model proposed by Yoder, Galinato et al. (2009). This model initially calculated economic trade-off by using prices for products for which no markets exist yet. It is therefore proposed to adjust the model, by processing the pyrolysis products to final products for which markets do exist (electricity and active coal). Instead of using prices for oil and char, it is then suggested to use net revenues instead (i.e. the difference between the sales price of the final product minus the cost of processing oil and char to their final product).

The economics of the pyrolysis plant however depend on the process temperature. The latter determines the energy required for heating. Besides, the quality of the char and the oil might change. Activation of char produced at 250 °C or 500 °C might result in a different quality and quantity of char, however, as we do not dispose of any relevant experiments, it is suggested that the results obtained in this chapter should first be validated by experimental research.

Production of activated carbon is more profitable than disposal of the char, despite of the higher production costs compared to the disposal costs. Thanks to the expected market value of the activated carbon, the processing costs of activation are expected to be more than compensated. Revenues from AC production even outweigh revenues from combined heat and power production so that its process economics are increased by shifting process parameters towards char production. As long as activated carbon can be sold at prices above 2 kEUR t_{dm}^{-1} the optimal process temperature corresponds to 250 °C. The process temperature in favour of oil production (500 °C) is only optimal when the price of activated carbon falls beneath 1,4 kEUR t_{dm}^{-1}.

The data in this chapter though should be considered with care: they are best considered as a preliminary feasibility study of active coal production and result in a strong recommendation to focus research on possibilities for char valorisation. Some technical uncertainties though still need to be validated by experimental research in a next step. For instance, what about the quality of char and oil when the feedstock is pyrolysed at different temperatures? Probably product quality differs along with different process parameters, so in order to be able to really estimate the economic trade-off, the technological assumptions should be validated by experimental research. Besides, it has been assumed that the gas is required for internal energy procurement because of the heavy metals in the char. If uncontaminated biomass is used, it might be interesting to investigate the trade-off between the three pyrolysis products: gas, char and oil.

8 Conclusion and discussion

8.1 Introduction

During the last quarter of the nineteenth century and the beginning of the twentieth century, the northern part of the Campine region ('*Kempen*' in Dutch) became the centre of the Belgian non-ferrous industry. The pyrometallurgical production of zinc and cadmium caused emission of large quantities of heavy metals in the air due to high process temperatures. As a consequence the historical metal enrichment of the soils covers a surface of more than 700 km² in the trans-border region of the Dutch and Belgian Campine, of which 280 km² in the Belgian municipalities of Balen, Mol, Hamont-Achel, Lommel, Neerpelt, Overpelt and Hechtel-Eksel. In the Dutch part of the Campine, especially the municipalities of Bergeijk, Valkenswaard, Cranendonk, Weert and Nederweert have been polluted with metals as a consequence of the emission by the zinc factory of Budel-Dorplein and the factories in Belgium (Oomen, Janssen et al. 2007). The cadmium concentration of the sandy soils in this region is larger than 1 mg kg^{-1} which is high compared to the natural prevalence of cadmium in the soils at concentrations between 0,1 and 0,8 mg kg^{-1}. In this area two highly contaminated subareas can be discerned close to the zinc factories of Balen, Lommel and Overpelt with a cadmium concentration in the soil of even more than 3 mg kg^{-1} (Staessen, Roels et al. 1995).

The pollution can have severe health and economic risks for inhabitants and farmers in the region. Besides, because of the sandy, acidic structure of the soils, the heavy metals are relatively good available for plants and food and fodder crops cultivated on farmland and in small gardens. Hence, these crops might exceed European safety standards for food and lead to inhibition of sales, resulting in potential economic losses for the farmers.

In order to clean up these farmlands, phytoremediation is better suited than traditional excavation techniques from a cost effectiveness point of view. The main barrier for the development of commercially viable phytoremediation is the long time period for effective soil remediation, which can be countered by using the biomass for profit making. Potential phytoremediating crops have a double advantage of both taking up heavy metals from the soil and being a potential source of renewable energy. From the crops that have been grown in a field experiment, willow in short rotation shows a much shorter clean-up time compared to maize, sunflower, rapeseed and poplar. Therefore this dissertation focuses on the techno-economic assessment of potential conversion technologies for willow.

Because no standards or guidelines exist on how to perform a techno-economic assessment, chapter 2 start with a definition of techno-economic assessments and the identification of the main research goals. Some preliminary framework for a techno-economic assessment has been proposed, with a focus on the (private) economic aspects.

In chapter 3, the fast pyrolysis, combustion and gasification of willow have been proposed as possible conversion technologies for willow (due to the lignin content of the wood) and a brief answer has been provided on the first question to be answered in a techno-economic assessment "How does the technology work?". In chapter 4 discounted cash flow models have been developed in order to investigate the profitability of the distinguished conversion technologies. One of the most important drawbacks of fast pyrolysis, is the uncertainty with respect to its capital investment because the technology is not largely available on a commercial scale yet. Therefore the first part of chapter 4 deals with a meta-analysis of the total capital investment of a fast pyrolysis plant. After developing economic models for private cost-benefit analysis, fast pyrolysis for the production of combined heat and power appeared to be best performing conversion technology with respect to economic valorisation for willow given the scales of operation in the Belgian Campine. However a private investor will probably not be very eager to use contaminated wood due to the extra costs incurred by the presence of heavy metals. In order to stimulate the use of contaminated wood (compared to "clean" wood) a government incentive of 30 EUR t_{dm}^{-1} has been proposed to cover these extra costs. Besides, some directional values have been proposed for the calculation of the unprofitable top and banding factors within the new system of green power certificates with respect to fast pyrolysis (the observatory of the Flemish Energy Agency announced the determination of these unprofitable top and banding factors, which will be published the earliest in April 2013).

Next, chapter 5 focuses on the economic risk, by first calculating maximum prices that an investor in a fast pyrolysis, gasification or combustion plant can pay for the willow, taking into account uncertainties, or in other words provided that the chance of a positive net present value is at least 95 %. Before determining strategies for risk reduction, the second part of chapter 5 maps the economic risk of fast pyrolysis aimed at the combined production of heat and power (because this has been identified as the conversion route with the highest economic potential). Some examples of very risky variables are the value of the green power certificates, the operational scale and the oil yield.

The chapters 6 and 7 then have been dedicated to risk reduction strategies. First it has been investigated whether an increase in scale by fast co-pyrolysis of willow with biopolymers would result a more profitable investment. It illustrates the potential value of waste streams in enhancing the economics of a fast pyrolysis plant: next to the advantages of scale, some other advantages showed up (alternative processing technology, possible presence of chemicals, synergistic effects on oil yield and quality). Though more profitable than pyrolysis of pure willow, also the profitability of a fast co-pyrolysis plant largely depends on the value of the green power certificates. Finally in chapter 7 we identified the risk reduction potential of the valorisation of the other important output of the fast pyrolysis process: the economic trade-off between char as a resource for activated carbon and pyrolysis oil for the combined production of heat and electricity has been mapped. The case studies in chapter 6 and 7 can be interpreted as a strong recommendation towards a shift in research focus from applications primarily for energy purposes towards applications of pyrolysis as a resource for materials (see the examples of crotonic acid and activated carbon).

8.2 Research questions

The main research question has been formulated as:

What is the techno-economic potential of fast pyrolysis for the economic valorisation of short rotation willow cultivated for phytoextraction?

In order to clarify the answer the main research question has been subdivided into subquestions. In what follows, these subquestions will be answered.

What is an appropriate methodological framework for techno-economic assessments?

Techno-economic assessment is a widely used concept for evaluating the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps decision makers in directing research and development or investments. Unfortunately no standards have been found on the way how to perform a techno-economic evaluation. Therefore this dissertation aims to contribute to the development of a methodological framework for techno-economic assessments. It can be stated that a techno-economic assessment (given its goals) ideally answers three important questions, which requires by definition a multidisciplinary approach:

- How does the technology work?
- Is the technology profitable?
- Is the technology desirable?

An answer to the first question can be provided by reviewing the state-of-the-art of a new technology, while indicating the technology's advantages and limitations. Next, a discounted cash flow model can be built based on (preliminary or detailed) process designs and mass and energy balances. From a private investor's point of view, the net present value measures best the plant's profitability. During the development of such a model though the decision maker is confronted with several uncertainties. An in depth analysis of economic risk has been proposed. Monte Carlo simulations have been suggested as an alternative to one-factor-at-a-time sensitivity analysis and scenario analysis, because it has the advantage of simultaneously simulating several "states of the world" taking into account the probability of occurence of each of these states. The information generated in the Monte Carlo simulations can then be used to determine the probability of a positive net present value, the main factors influencing the net present value (i.e. the sensitivity of the net present value to changes of the values of the model's variables). Most often no information about these probabilities is available and they are based on guesses from the expert performing the Monte Carlo simulations. Therefore Plackett-Burman designs (technique from the field of experimental design) have been suggested as an alternative means on providing answers to the question "which factors can make the project go wrong?". The factors should then be controlled by refinement of the technology so that risks can be reduced. Several options exist for reducing risk, though the focus is on controlling operational risk by changing the inputs and outputs of a fast pyrolysis plant. The final question that a techno-economic assessment should address is whether the technology indeed solves the social or environmental issues that it has been designed for. If it does, one can conclude that the technology is desirable from a social point of view. This question was beyond the scope of this dissertation but possible methods are LCA, LCC and extended cost-benefit analysis.

What are the technological advantages of fast pyrolysis for valorising short rotation coppice compared to other thermochemical conversion technologies?

As willow mainly consists of lignin, cellulosis, and hemi-cellulosis, it cannot be converted by digestion or fermentation because the microorganisms responsible for the conversion in these processes are not capable of decomposing lignin. Therefore, willow needs to be transformed into energy by thermal conversion. Three thermal conversion techniques can be distinguished depending on the amount of oxygen (O_2) added to the process: combustion, gasification, and pyrolysis. Within the context of phytoextraction, pyrolysis might be preferred to convert biomass into energy because of the lower process temperature that prevents heavy metals from volatilisation. Research shows that the metals remain in the residual char that results from the pyrolysis process. Both combustion and gasification typically happen at higher temperatures than pyrolysis at which heavy metals (especially Cd, which is the most problematic in the area studied) appear to volatilise more easily.

During fast pyrolysis, biomass is rapidly heated to moderate temperatures (400 until 500 °C) with a vapour residence time of only a few seconds. The hot gases then need to be cooled quickly. Part of the gases are then condensed into a dark brown fluid, the pyrolysis oil. Bubbling fluid beds have been identified as the most common reactor type for fast pyrolysis. Fast pyrolysis typically results in the production of 60-70 m% pyrolysis oil, 15-25 m% pyrolysis and 10-20 m% char. The oil can be combusted in boilers, gas engines and diesel engines for static applications, though pyrolysis oil contains impurities and is corrosive so that minor to moderate modifications to engines are required. In this dissertation the use of pyrolysis oil for power production and combined heat and power production has been investigated. It has been calculated that, under base case assumptions and due to the metals present in the char, all pyrolysis gases are required for internal energy provision. If insufficient, the remaining required energy will be provided by combustion of the pyrolysis oil. Because the presence of a sufficiently large heat demand is required for combined heat and power production, fast pyrolysis has been compared with combustion and gasification for power production only. Combustion and gasification typically require higher process temperatures, which might require costly fume gas treatment. There is a discussion whether the usual gas treatments are sufficient for metal cleaning or not. In order not to overestimate the profitability of a fast pyrolysis plant, it has been compared to combustion and gasification without extra gas treatment for creating a "worst case scenario" for fast pyrolysis. For combustion it is assumed that fluid bed designs are preferred, followed by a steam turbine. Also for gasification only fluid bed designs are considered in applications that generate over 1 MW_e. Atmospheric gasification followed by a gas engine is preferred for smaller scale applications, whereas pressurised gasification with a gas turbine combined cycle has been suggested larger scales. Apparently, capital costs for atmospheric gasification with gas engines are the lowest up to capacities of 4 MW_e, whereas pressurised gasification with a gas turbine combined cycle is cheaper for capacities higher than 6 MW_e. According to efficiency calculations, gasification results in the largest production of power, followed by fast pyrolysis and combustion.

What is the economic potential of fast pyrolysis for valorising short rotation coppice compared to other thermochemical conversion technologies?

As pyrolysis is a new technology there are not a lot of cost data available. Therefore section 4.2 reviews existing estimates for the capital cost of a pyrolysis plant and integrates them by performing a **meta-analysis**. First, the general methods for capital investment estimation are explained. Next, existing estimates for the capital costs of pyrolysis plants have been inventoried. The found capital costs can be either point estimates for a specific case or parametric equations that are a function of the plant's scale which already aggregate existing data on capital cost estimates. The equations are applied to the relevant scales of the Campine case and joined to the point estimates in one dataset that is the subject of a final analysis. Next to capital cost equations, a lot of point estimates have been found in several sources. The cost estimates have been selected based on the fluid bed technology as this is the most cited technology that is believed the first to become commercially available. A final investment equation however should capture information both from the other investment equations and the point estimates. Therefore we calculated the expected investment for all scales of operation in the Belgian Campine and expect that the base case will be between the minimum and maximum investment estimate, with equation 4.14 and 4.15 representing the maximum and the minimum estimate respectively. Finally, the average capital cost has been plotted in function of the hourly feedstock flow with a trendline that is represented in equation 4.16 which is repeated here[17]. We remark that this average corresponds the best to the estimates calculated with the equation of Rogers and Brammer (2012a).

$$\mathrm{TPC}_{\mathrm{Py}}^{\mathrm{Kup12c}} = 3\;486\;567\;\times\;\left(\Phi_{\mathrm{py}}^{\mathrm{h}}\right)^{0{,}6914}$$

It became clear that fast pyrolysis of willow for the combined production of heat and electricity was the only profitable conversion route. Because it is not sure whether the heat can be sold to industrial consumers in the surroundings of the potential fast pyrolysis plant, we checked whether electricity production alone would be profitable. Because fast pyrolysis for electricity production only, is not profitable under the base case assumptions in the Belgian Campine, it has been investigated whether combustion or gasification of the willow would yield better results. Unfortunately, none of these resulted in a positive net present value: electricity production only

[17] As stated before, the superscript added to TPC in this equation refers to the author (Kuppens) and the year of origin (2012) of this equation. The letter c refers to the fact that this is the third equation that has been developed in this dissertation, and it gathers the information contained in the equations with superscript 'Kup12a' and 'Kup12b'

thus is not sufficient for valorising the biomass in the Campine as even the best conversion technology (pyrolysis) is loss making.

From an economic point of view, pyrolysis is the best conversion technique for power production from willow cultivated for phytoextraction in the Belgian Campine. Part of the explanation is the lower investment cost associated with fast pyrolysis. Gasification is clearly the most expensive technology, especially because of the high capital investment. Biomass costs comprise purchase costs, transport costs and pre-treatment costs. They are the same for combustion and gasification, but they are higher for fast pyrolysis because the latter conversion technology has more stringent pre-treatment requirements: smaller particles and a very dry feedstock. Gasification, however, also has the highest revenues, thanks to the beneficial process efficiency. Unfortunately, none of the conversion technologies has sufficient revenues to cover total costs.

Therefore the NPV for fast pyrolysis oil as a subsitute for heavy oil in boilers has also been calculated, because it has the advantage that it can be applied without (or with minor) modifications to the boiler. However when no subsidies from green power production or combined heat and power production are available, also this application is not profitable.

Finally some suggestions for government incentives have been made. First of all, investors will not be eager to use willow contaminated with heavy metals due to the possible extra costs, especially for fast pyrolysis. Therefore it is suggested that government should provide an incentive if it wishes to phytoextract with willow. This incentive should at least cover the disposal cost of char and the extra energy costs incurred because the contaminated char cannot be used for internal energy requirements. It has been calculated that the extra costs (or the incentive) amount to rounded 30 EUR t_{dm}^{-1} willow. Besides, the Flemish Government announced a change in the system of the green power certificates. The impact of the new incentive scheme could not have been calculated yet, but given the large share in the revenue structure of a biomass plant, a significant impact might be expected. The new system is based on calculations of discounted cash flows and results in an unprofitable top and banding factors for several "representative" categories. It is expected that the observatory installed by the Flemish Energy Agency will publish the unprofitable top and banding factors for special technologies the earliest in April 2013, though it is not sure whether pyrolysis will be considered by the observatory. Therefore the unprofitable top and banding factor has been simulated using the discounted cash flow model developed for fast pyrolysis: when electricity can be put on the network at 60 EUR MWh_e^{-1} the unprofitable top for green power equals 107 EUR MWh_e^{-1} which corresponds to a banding factor of 1,10. If the electricity price rises to 100 EUR MWh_e^{-1} the unprofitable top for green power produced by fast pyrolysis oils equals 69 EUR MWh_e^{-1}.

What is a possible price range for willow cultivated in the Belgian Campine as an energy crop?

Chapter 5 started with an exploration of the possible price range for willow cultivated in the Belgian Campine for phytoextraction purposes. The exploration started with estimating the cost of growing and harvesting the willow year after year. A discounted cash flow model has been built and by means of the levelised cost method the cultivation cost of willow is expected to be rounded 50 EUR t_{dm}^{-1}. This cost might be considered as the absolute minimum price for willow that a farmer wants to receive for growing willow. The maximum willow price then is defined as the highest price that an investor can pay for purchasing willow assuming a 95 % of a positive net present value. The maximum prices that can be attained by the combustion plant are the lowest and the prices corresponding to the fast pyrolysis plant are the highest. Fast pyrolysis clearly is the most economical technology for all potential scales of operation in the Campine. However, one should note that gasification becomes competitive with pyrolysis at higher scales. At small scales, all prices are negative, which implies that the investor is only willing to convert the wood if a gate fee is paid by the farmer to the bioenergy plant. The difference between the price that can be paid and the cultivation and harvest cost of willow (c_{willow}) of 50 EUR t_{dm}^{-1} has been calculated. Only at the higher scales a price of 50 EUR t_{dm}^{-1} will be reached, or when fast pyrolysis is followed by combined heat and power production.

What is the economic risk of fast pyrolysis?

In the first part of chapter 5, it has been proved that fast pyrolysis is not only the least loss making conversion technology compared to combustion and gasification, but that its standard deviation is also the lowest when real uncertainties are taken into account (even though that the maximum possible NPV is the highest for gasification). Therefore, in the next part of chapter 5, the focus was on the exploration of the economic risk of fast pyrolysis combined with CHP, which is profitable on the condition that there is a neighbouring heat consumer at the pyrolysis plant.

The base case economic model indicated that the NPV of an investment in fast pyrolysis for the combined production of heat and power is positive, which means that the revenues are high enough to recuperate the production cost of electricity. The base case values however are highly uncertain. First, these uncertainties have been studied by Monte Carlo simulations. Under current knowledge there is a 87 % chance of a positive NPV. The problem with Monte Carlo simulations is that the assumed probability distributions are often unknown and hence represent the best guess of the expert. Therefore it has been argued that the results of Monte Carlo simulations might have a level of uncertainty, because the assumed distributions might be different from reality.

The Plackett-Burman design and its Box-Wilson foldover are suggested as an alternative for estimating risk. The problem with the Plackett-Burman design is that they are more difficult to interpret: as the variables either take a value of +1 or -1, the estimator of the main effect is not comparable to the estimator found during Monte Carlo simulations. The standardised coefficients however have more or less the same magnitude, although the order of importance differs. Another problem is that the Plackett-Burman technique only focuses on the extreme values of the ranges found in literature. This information is relevant for decision makers, but the combination of extreme values in the runs of the Plackett-Burman designs are very unlikely to occur in reality, whereas these extreme situations are possibly underrepresented during Monte-Carlo simulations. It is suggested that both Monte Carlo and Plackett-Burman simulations provide complementary information for decision makers. The focus for the Plackett-Burman design should not be on the meta-model, but on the possible outcomes of the NPV: they indicate the maximal losses an investor can run. It is believed that for the main effects the meta-model of the Monte Carlo simulations is better suited. In our opinion, design of experiments is mainly helpful to gain a first understanding of the problem and does not fully grasp economic risk as these techniques are only concerned with the worst case values of the input variables of the economic model.

How can the economic risk of fast pyrolysis be reduced by changing the inputs (i.e. feedstock) of the pyrolysis plant?

At the end of chapter 5 it became clear that the NPV of a fast pyrolysis plant for the combined production of heat and electricity is highly dependent on the scale of the plant, the oil yield and the value of the green power certificates. Therefore it is important to reduce the dependency on these uncertain variables and to identify some potential risk reduction strategies. The scale can be increased by searching for other feedstocks that can complement the stream of willow that will be available in the Belgian Campine. Especially waste streams might be interesting as they have the potential to provide a gate fee to the investor. As a case study fast co-pyrolysis of willow with biopolymers has been investigated, because the co-pyrolysis synergistically improves the characteristics of the pyrolysis process and the pyrolysis oils. Fast co-pyrolysis leads to better economic results as compared to fast pyrolysis of pure willow: the NPV of cash flows has been increased with at least 5,5 MEUR (for the willow/corn starch blend). Fast co-pyrolysis of willow and PHB even increases the NPV with 352 MEUR due to the high value of crotonic acid. Except for the willow/PHB-blend, the economics however depend largely on the presence of green power certificates which almost make up half of total revenues for each blend. Because of the currently small supply of biopolymers, however, it is not possible yet to determine the exact costs for collecting and transporting biopolymer waste to the pyrolysis plant. For this reason the maximum cost for the biopolymer feedstock has been calculated for different scenarios taking into account several uncertainties. In the most expected scenario, i.e. the base case, the maximum prices for all biopolymers are positive, except for corn starch and Solanyl which means that fast co-pyrolysis of willow with corn starch or Solanyl is only profitable if the stream of corn starch waste generates an income for the investor in the pyrolysis reactor. Fast co-pyrolysis can be seen as an alternative technology for processing waste of PLA, PHB, Biopearls, Eastar, Solanyl and potato starch, as it is cheaper than composting which costs 80 EUR t_{dm}^{-1}. Only for waste of corn starch, composting can be cheaper sometimes. When the system of green power certificates would have been phased out (i.e. when the technology does not receive green power certificates at all) without some other compensation, composting will always (except for PHB waste) be preferred above fast co-pyrolysis as the latter would cost between 137 EUR t_{dm}^{-1} for the disposal of Eastar waste and 175 EUR t_{dm}^{-1} for disposal of corn starch waste. Under the condition that biopolymers make their full entry in the plastic industry, fast co-pyrolysis of willow and PHB is the only option to be commercialised in the short term with a value for PHB waste between 2 614 and 2 826 EUR t_{dm}^{-1} thanks to the potential sales of crotonic acid.

How can the economic risk of fast pyrolysis be reduced by changing the outputs (i.e. the proportion of the pyrolysis products) of the pyrolysis plant?

Another opportunity to reduce economic risk (e.g. the dependence on the value of the green power certificates) is to search for alternative outputs. Therefore in chapter 7 the valorisation potential of the pyrolysis char has been investigated. Two innovative potential valorisation options have been identified: biochar as a soil amendment and pyrolysis char as a resource for active coal production. Next, it has been illustrated that economic trade-offs exist between the production of biochar and bio-oil from pyrolysis of biomass. Bridgwater already illustrated that the yield of the typical fast pyrolysis products is dependent on the process temperature: maximum oil yields are obtained at temperatures between 500 and 520 °C with residence times of less than 2 s, while the char yield decreases with temperature. Zn and Cd concentrations in the biochar however exceed the norms for use as a soil improver stated by VLAREMA (= Flemish Regulation on the sustainable management of material cycles and waste). The concentrations of Pb are expected to be lower than the norm. Therefore, unless it would be possible to remove the metals from the char, it is concluded that there is no potential for pyrolysis chars from wood in the Belgian Campine to be used as biochar, i.e. as a soil amendment. Therefore the focus is on the activation of the char for producing activated carbon.

Because the valorisation routes influence the potential sales prices of the pyrolysis products, careful selection of the process temperature is required to optimise the total incoming revenues and hence the profitability of a fast pyrolysis plant. The optimal process temperature for a fast pyrolysis plant has been calculated, by elaborating Yoder's model when biochar is used as a resource for active coal production and the pyrolysis oil is burnt in a combustion engine for the combined production of heat and power (CHP).

Applying Yoder's model, the first order derivative with respect to temperature is always negative in the temperature interval, which means that the original revenue function is strictly decreasing in the temperature interval]250; 524,92[so that the maximal revenue must be at 250 °C under the base case assumptions.

Recapitulating table 57 where the relation between the oil/char price ratio and optimal process temperature was represented, we identified some scenarios that might be beneficial for oil production in a way that the oil/char price ratio might be increased. For instance, the production of oil is promoted when the net revenues from oil are 2,3 times higher than the char price. This can be attained by either an increase of the net revenue of oil or a decrease in the net revenue of char or, which can be realised by a higher scale of operation or lowering the AC sales price.

The scale of operation can be increased by including the biomass potential from the Dutch part of the Campine region. Repeating the method of Cardano results once more in an optimal temperature again of 250 °C (or char production is preferred). Increasing the scale of operation thus might be an advantage in terms of economies of scale, but this is true both for activated carbon production as for energy production from oil. Economies of scale however are more distinct for active carbon production, so that even cost advantages for oil production are not persistent enough to tilt the balance in favour of oil production.

A lower AC price clearly might be advantageous for oil production, which can also be derived from the value of the first order derivative in row 15 of table 65: as long as the first order derivative is greater than zero in the economically relevant temperature interval, the profits are increasing. Hence the most optimal temperature for profit maximization now is at the other range of the economically relevant temperature range or at 525 °C, so that oil production is aimed at.

The sales price of activated carbon is crucial in determining whether oil or char production should be promoted. Our calculations above imply that oil production is preferred whenever the AC sales price is below 1,4 EUR kg^{-1}.

As a conclusion one can state that whenever AC can be sold at prices of 2,0 EUR of higher the optimal temperature equals 250 °C and whenever the AC sales price is lower than 1,4 EUR kg^{-1}, the optimal process temperature should be in favour of oil production (being 500 °C).

8.3 Further research

8.3.1 Feedback to phytoremediation research

This dissertation focused on the techno-economic assessment of fast pyrolysis, which is a suitable conversion technology for lignocellulosic phytoremediating crops. One of the objectives was to explore the price that can be achieved for willow contaminated with heavy metals, by calculating the cost of growing and harvesting the willow on the one hand, and by calculating the maximum price that an investor in fast pyrolysis might be willing to pay for using contaminated willow as a feedstock. This exploration led to the conclusion that thermochemical conversion (combustion, gasification or fast pyrolysis) of willow for electricity production only, is not able to recuperate the costs borne by a farmer for cultivating the willow. Of the three conversion technologies considered and for the expected scale of operation, fast pyrolysis appeared to be the least loss making conversion technology. Fast pyrolysis for the combined production of heat and power however is expected to be a suitable conversion route for contaminated willow, as it has the potential to bring about a willow price that is higher than the unit cost of willow cultivation.

This information can now be used in the larger framework of a general cost benefit analysis of phytoremediation that has been introduced in chapter 2. For instance, former research into the costs and benefits of phytoremediation by Witters (2011) did not take into account fast pyrolysis as a potential valorisation route for contaminated willow. The net present value of the agricultural gross income for short rotation coppice of willow during the phytoremediation period calculated by Witters, Van Slycken et al. (2009) can now be updated, though it is expected that considering fast pyrolysis for CHP will not yield different conclusions with regard to crop choice in a phytoremediation model that takes into account multiple criteria such as remediation duration and carbon sequestration potential. Compared to other phytoremediating crops such as energy maize and rapeseed, short rotation coppice performs relatively well in terms of net avoidance of CO_2 emissions and it results in the shortest phytoremediation duration. The disadvantages of short rotation coppicing of willow are its low acceptance by farmers (it is rather unknown and its cultivation requires different practice), and especially its very low agricultural gross income. Nonetheless, short rotation coppice of willow appeared to be the preferred phytoremediating crop for small to average distances to target, i.e. the difference between the cadmium concentration in the soil and the targeted final concentration (Witters 2011).

Complementary to the research in this dissertation and the dissertation of Witters (2011), we recommend an analysis of the external costs and benefits of willow cultivation, both from the viewpoint of phytoextraction and from the viewpoint of renewable energy production. For instance, the importance of the application of phytoremediation can be emphasized by calculating the benefits of the reduced health effects. The short remediation duration of phytoextraction with willow then might gain importance. Another potential benefit from phytoextraction is the possible increase in the value of farmland for the generations of farmers that succeed phytoremediating farmers. The hedonic pricing approach can be used to see if farmers are aware of the pollution or to value the external costs caused by the presence of cadmium, zinc, lead, etc. According to the first indications however, metal concentrations do not significantly worsen the value of agricultural soils. From the viewpoint of renewable energy production, life cycle analysis can contribute to mapping the external costs and benefits of energy production from phytoextracting willow. Incorporating these external effects will ameliorate the decision power of existing tools for selecting the best phytoextracting crop. Besides, information about the overall external costs and benefits can aid government institutions in deciding on the usefulness and the size of economic incentives to promote phytoextraction with willow.

8.3.2 Other applications for pyrolysis oil and char

The current state of the art of fast pyrolysis points out that the technology is on the verge of becoming commercially available, although there are only few plants that operate at an industrial scale yet. The most short term applications of the oil and the char have been studied in this dissertation, i.e. activation of the char and combustion of the oil in a CHP engine. One of the drawbacks of the char, was its heavy metal concentration so that it could not be applied as a biochar, and that costly fume gas treatment was required in the activated carbon application. Future research can take up techniques for removing the metals from the biochar (e.g. by acidic washing), in a way that the metals can be valorised (i.e. phytomining) and the char can be applied as a soil amendment. However, we do believe that biochar application might probably not significantly enhance soil productivity in Flanders (cf. research at Ghent University). The oil on the other hand, can be hydrogenated in order to upgrade the oil to transport fuels or other fuels with a higher calorific value comparable to fossil fuels (some even speak of qualities comparable to kerosene). It can also be used as a resource for chemicals (e.g. levoglucosan). The main problem with the chemical extraction and upgrading steps is that cost information is unknown or not available. Most of the information still is in the research phase at laboratory scales. Economic research however can contribute to the identification of potentially interesting chemicals and upgrading steps. An exploratory investigation pointed out that there is a lot of potential for applications as resources for chemicals: expected revenues are between 180 and 12 000 EUR per tonne of oil compared to the values based on substitutes for fossil fuels between 170 and 300 EUR per tonne (Christis 2012).

8.3.3 Scale-up

Another important issue for the commercialisation of pyrolysis is to get it from the laboratory to commercial/industrial scale. Therefore it is important to establish demonstration plants that can test the best performing pyrolysis concepts and ameliorate them to make them ready for commercial exploitation. Scaling up comprehends building larger facilities that can convert flexible streams of feedstock, so that other opportunities can be explored. For instance, fast pyrolysis can contribute to the processing of manure, verge cuttings, forest thinning, industrial organic waste, etc. In this way fast pyrolysis can play an important role in the development of integrating energy conversion parks (e.g. development of energy conversion parks in the south of the Netherlands and in Flanders, and potential pyrolysis plants in Hengelo, Groningen, Lommel and Genk) that integrate the processing of waste and locally available biomass residues with the energy needs on an industrial or residential site. Such a bio-energy conversion park is a "multi-dimensional, synergetic concept, converting multiple biomass streams into useful energy and other bio-based products, through an integrated combination of conversion processes and technologies (such as combustion, gasification, digestion, pyrolysis, …)" (Guisson, Van Dael et al. 2012). However, this requires a pyrolysis plant that is able to process multiple feedstocks which increases the complexity of the plant as other feedstocks yield different qualities and quantities of pyrolysis products. For instance, pyrolysis liquids from grasses seem to be of lower quality than those from woods: they oils from grasses have higher alkali content and higher viscosities whereas the wood oils have higher water content and are more acidic (Moses and Bernstein 1994).

8.3.4 Alteration of the certificates system

At the end of May 2012, the Flemish Government announced the alteration of the current support systems for green power and CHP. In the current system one green power certificate is awarded per MWh of green electricity and every certificate gets the same amount of support. In the new system each technology will be awarded the exact amount of support it needs to render it profitable by adjusting the number of green power certificates awarded per technology (e.g. solar, wind, biomass, …). Another change is that the amount of money support per certificate will be adjusted continuously depending on the actual market conditions at the moment of provision of support. The money amount will thus be adjusted in function of the cost of the technology, the market price for electricity and so on. Besides, the duration of the support will be limited to the depreciation period of the technology (i.e. 10 to 15 years depending on the technology), where currently certificates are awarded as long as the technology is in use. These outlines are currently being translated to specific measures, but it is clear that it will impact the profitability of a fast pyrolysis plant for energy production. The exact impact cannot be investigated yet, but it will probably urge for a greater emphasis on research into the economic potential of fast pyrolysis for materials or chemicals (e.g. crotonic acid or activated carbon) production from biomass.

List of publications

Articles published in peer reviewed journals

- Voets, T., **Kuppens, T.**, Cornelissen, T. and Thewys T. (2011). "Economics of electricity and heat production by gasification or fast pyrolysis of short rotation coppice in Flanders (Belgium)." Biomass and Bioenergy 35(5): 1912-1924.
- Vanreppelen, K., **Kuppens, T.**, Thewys, T., Carleer, R., Yperman, J. and Schreurs, S. (2011) "Activated carbon from co-pyrolysis of particle board and melamine (urea) formaldehyde resin: a techno-economic evaluation." Chemical Engineering Journal 172(2-3): 835-846.
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Articles under review in peer reviewed journals

- **Kuppens, T.**, Vanreppelen, K., Wami, W., Yperman, J., Carleer, R., Schreurs, S. and Thewys, T. (2012) "Economic risk analysis of fast pyrolysis for the valorization of phytoextracting crops". Risk Analysis xx(xx):xxxx-xxxx.

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- **Kuppens, T.** and Thewys, T. (2012) "Meta-analysis of capital costs of investments in fast pyrolysis plants for the conversion of biomass." (Journal to be selected)
- **Kuppens, T.**, Vanreppelen, K., Schreurs, S., Yperman, J., Carleer, R. and Thewys, T. (2012) "Economic trade-off between char for active coals and oil for energy from fast pyrolysis of willow cultivated for phytoremediation." (Journal to be selected)

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- **Kuppens, T.** and Thewys, T. (2010). "Pyrolyse als valorisatie-techniek voor korteomloophout uit fytoremediatie." MilieuTechnologie 17(1): 1-4
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- **Kuppens, T.**, Voets, T., Vanreppelen, K., Cornelissen, T., Schreurs, S., Carleer, R., Yperman, J. and Thewys, T. (2012) "Techno-economic assessment of fast pyrolysis for the valorisation of short rotation coppice cultivated for phytoremediation in the Campine." 9th International Phytotechnology Society conference, Diepenbeek (Belgium), 11-14th September 2012 (abstract and oral presentation)
- **Kuppens, T.** and Thewys, T. (2012) "Techno-economic assessment of fast pyrolysis." Belgian Biomass Workshop in the frame of BERA/EERA (Belgian Energy Research Alliance/European Energy

Research Alliance), 27-28th August 2012 (abstract and oral presentation)

- **Kuppens, T.** (2012) "Biochar en economie" Panelgesprek: Is biochar klaar voor de praktijk? Studienamiddag Biochar: bodemverbeternd middel van de toekomst?, Merelbeke (Belgium), 12th June 2012 (panel discussion)
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Legislation

Decree of 13th July 2012 concerning the alteration of the Energy Decree of 8th May 2009 with regard to environment friendly energy production (i.e. art. 7.1.1 and next of the Energy Decree), published in the Belgisch Staatsblad 20th July 2012.

Law on the Income Tax. Law of 10th April 2012. Consolidated version of 20th September 2012.

Materials Decree. Decree of 23rd December 2011 issued by the Flemish Parliament concerning the sustainable management of material cycles and waste (effective from 1st June 2012).

Soil Decree. Decree of 27th October 2006 issued by the Flemish Parliament concerning the remediation and the conservation of soils. Consolidated version of 28th February 2011.

VLAREBO. Decision of 14th December 2007 of the Flemish Government containing the determination of the Flemish regulation concerning the remediation and the conservation of soils. Consolidated version of 1st June 2012

VLAREMA. Decision of 17th February 2012 of the Flemish Government concerning the sustainable management of material cycles and waste (effective from 1st June 2012).