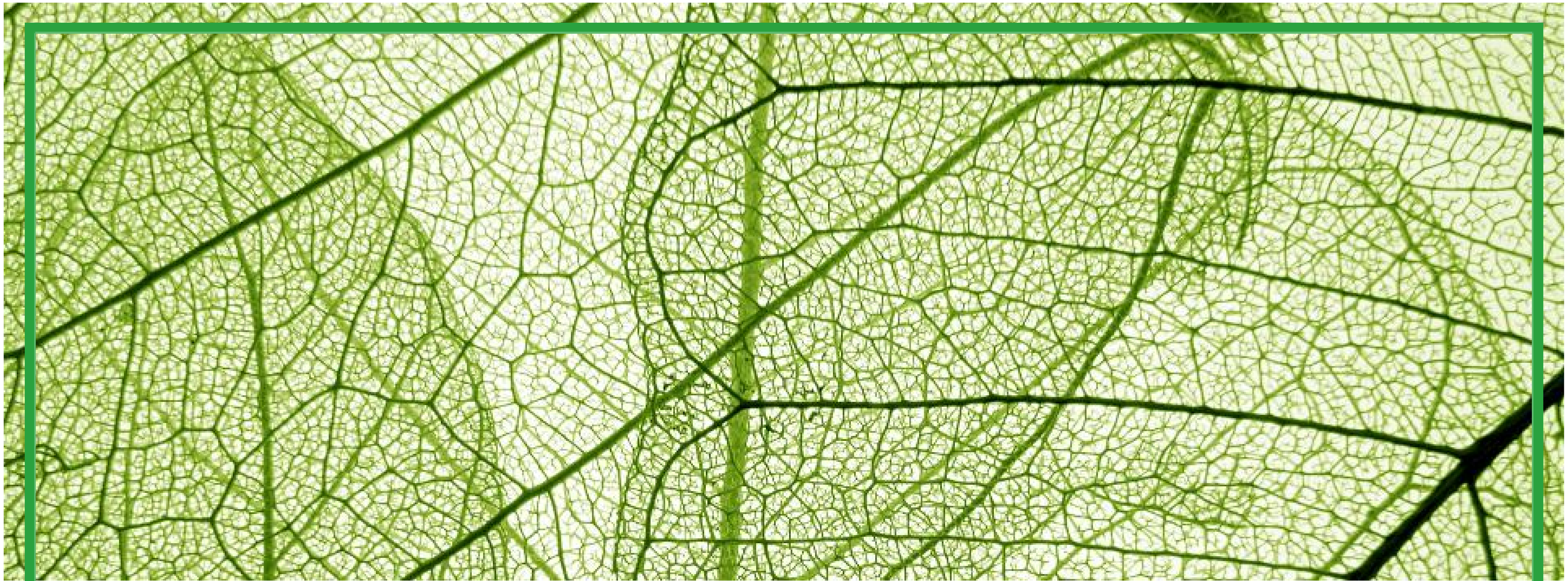

Societal TEA of phytoremediation

A Belgian case study

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Summer course
“New trends in restoration of degraded soils”
13th July 2017

Tom Emile Kuppens
Research Group Environmental Economics

Overview

1. Problem statement
2. (Societal) techno-economic analysis
3. Thermochemical conversion of willow
4. Discounted cash flow model
5. Risk analysis
6. Risk reduction strategies
7. Conclusion and discussion

Problem statement

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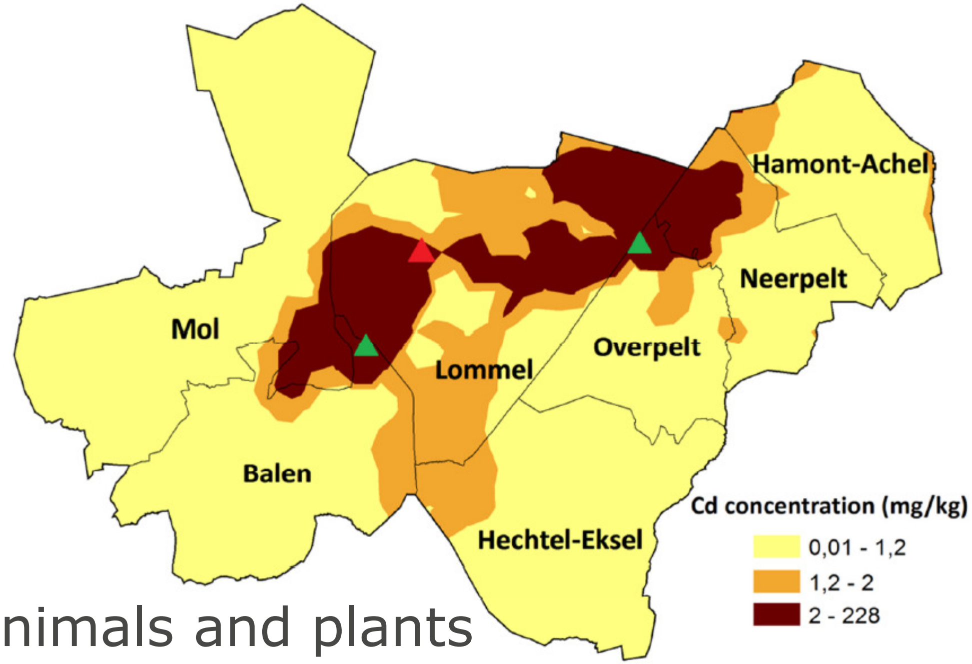
Greetings from Lommel!

Problem statement

- Thermal refinement of zinc (19-20th century)
- Volatilisation of Cd
- Most soils: agriculture



- Risks:
  - Cd uptake by humans, animals and plants
  - exceedance of land remediation standards
  - crop confiscation

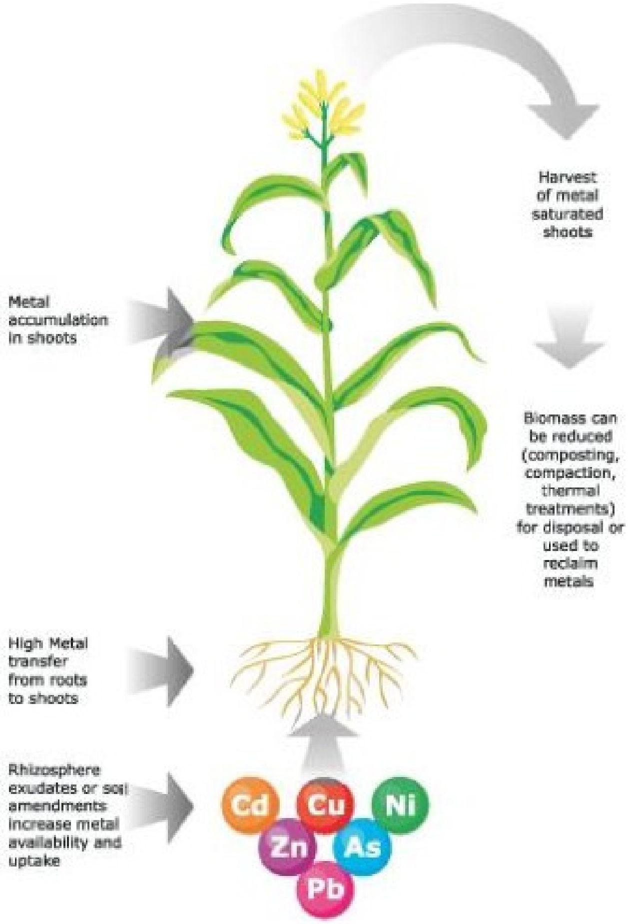
Problem statement

Phytoextraction:

= form of phytoremediation using plants that translocate metals to the aboveground parts

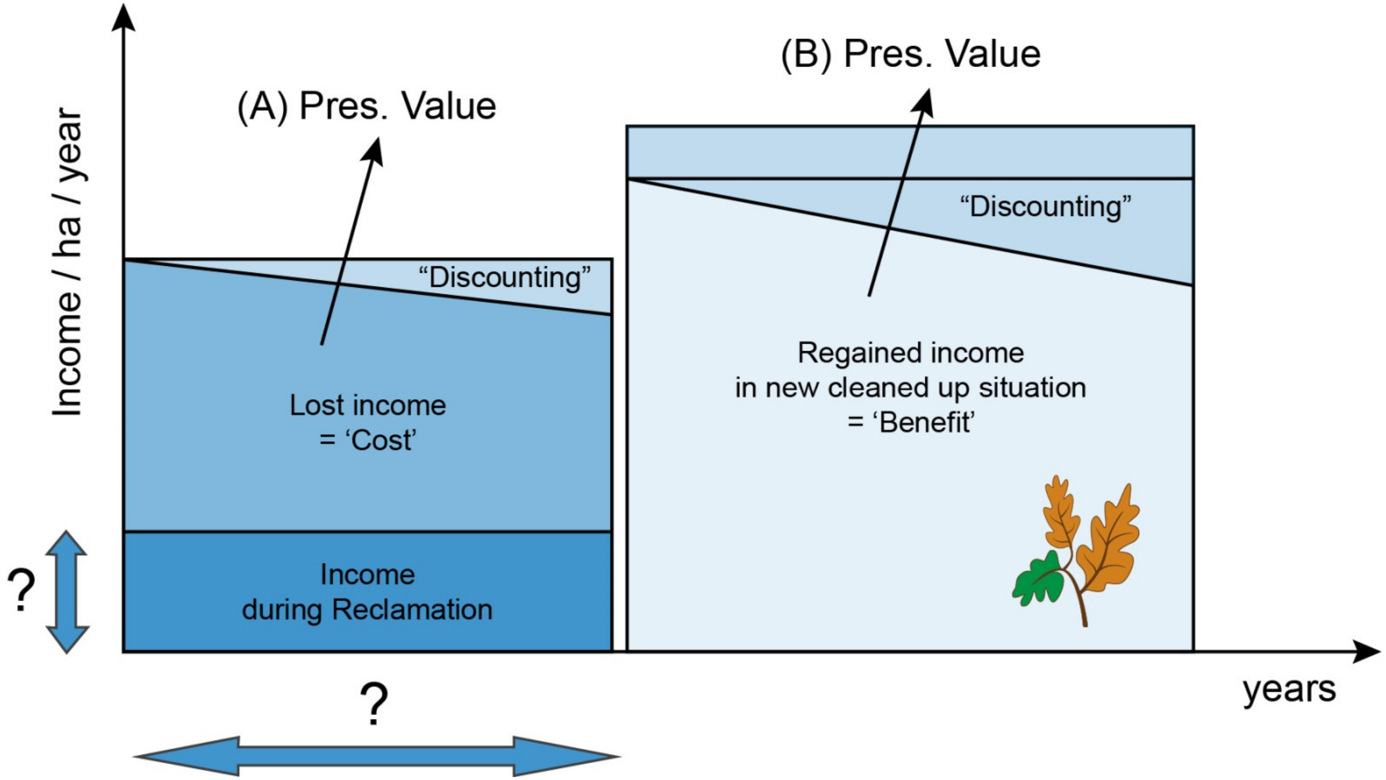
+ cost-effective
+ sustainable

- very long time period
- income effect



Problem statement

Simplified (private) cost-benefit framework



Vassilev, Schwitzguébel, Thewys, Van der Lelie and Vangronsveld (2004)

Problem statement

How to reduce the time period?

Crop choice: willow cultivated in short rotation remediates faster than poplar, maize, rapeseed and sunflower

How to reduce the income effect?

Conversion of willow into valuable products (energy, chemicals, materials)

→ investor's point of view

Research objectives

1. Development of a methodological framework for techno-economic assessments (TEA), including the assessment of economic risk

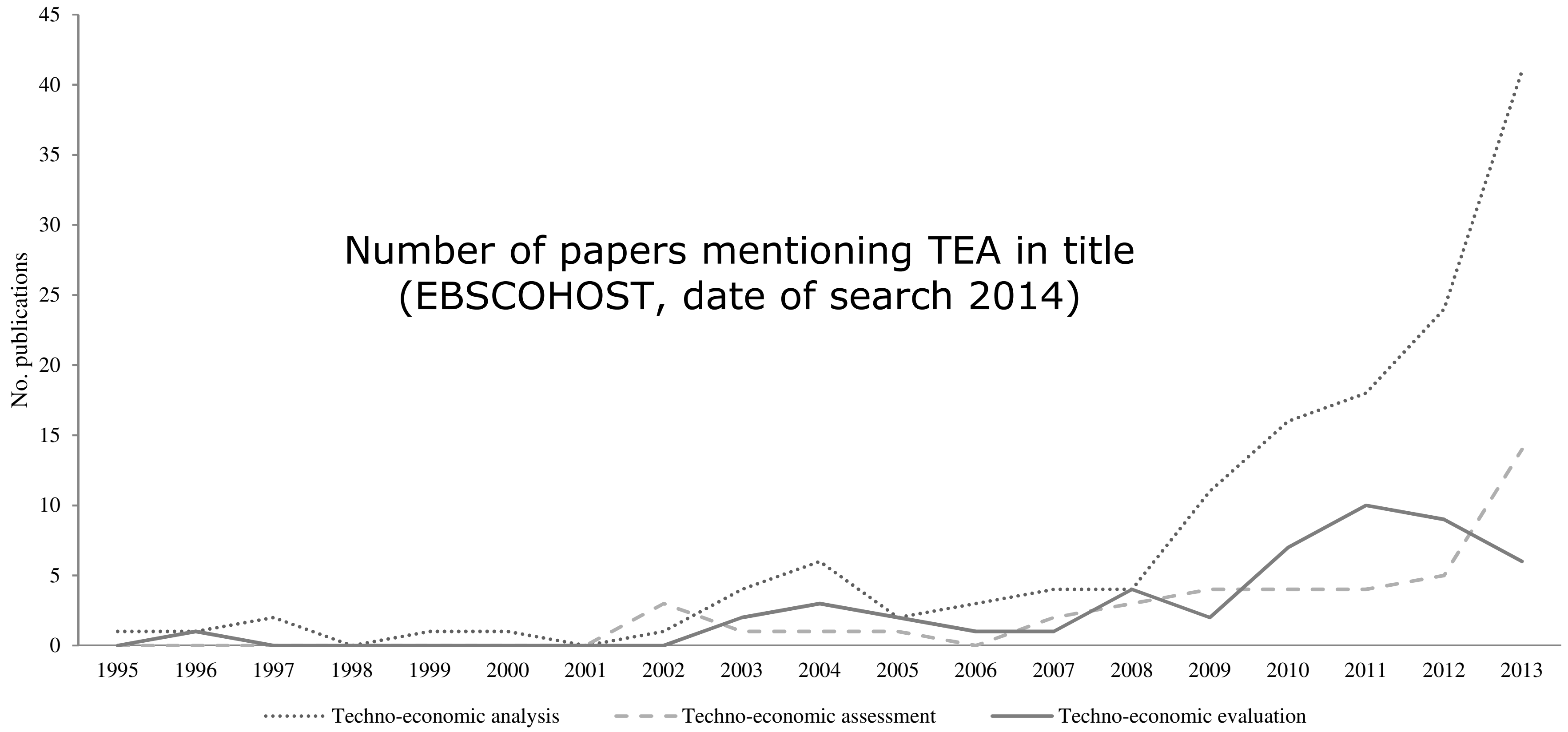
2. Apply TEA to thermochemical conversion technologies (fast pyrolysis, gasification, combustion) for the conversion of phytoextracting crops

3. Develop a meta-model and formulate risk reduction strategies in order to enhance the techno-economic performance of the best available conversion technology

Societal TEA

Techno-Economic Analysis (TEA)

= relatively new methodology (no standards available)



Techno-Economic Analysis (TEA)

DEFINITION

"Evaluation of the **technical performance** and the **economic feasibility** of a new (*clean*) technology that aims to *improve* the **social or environmental impact** of a technology currently in practice"

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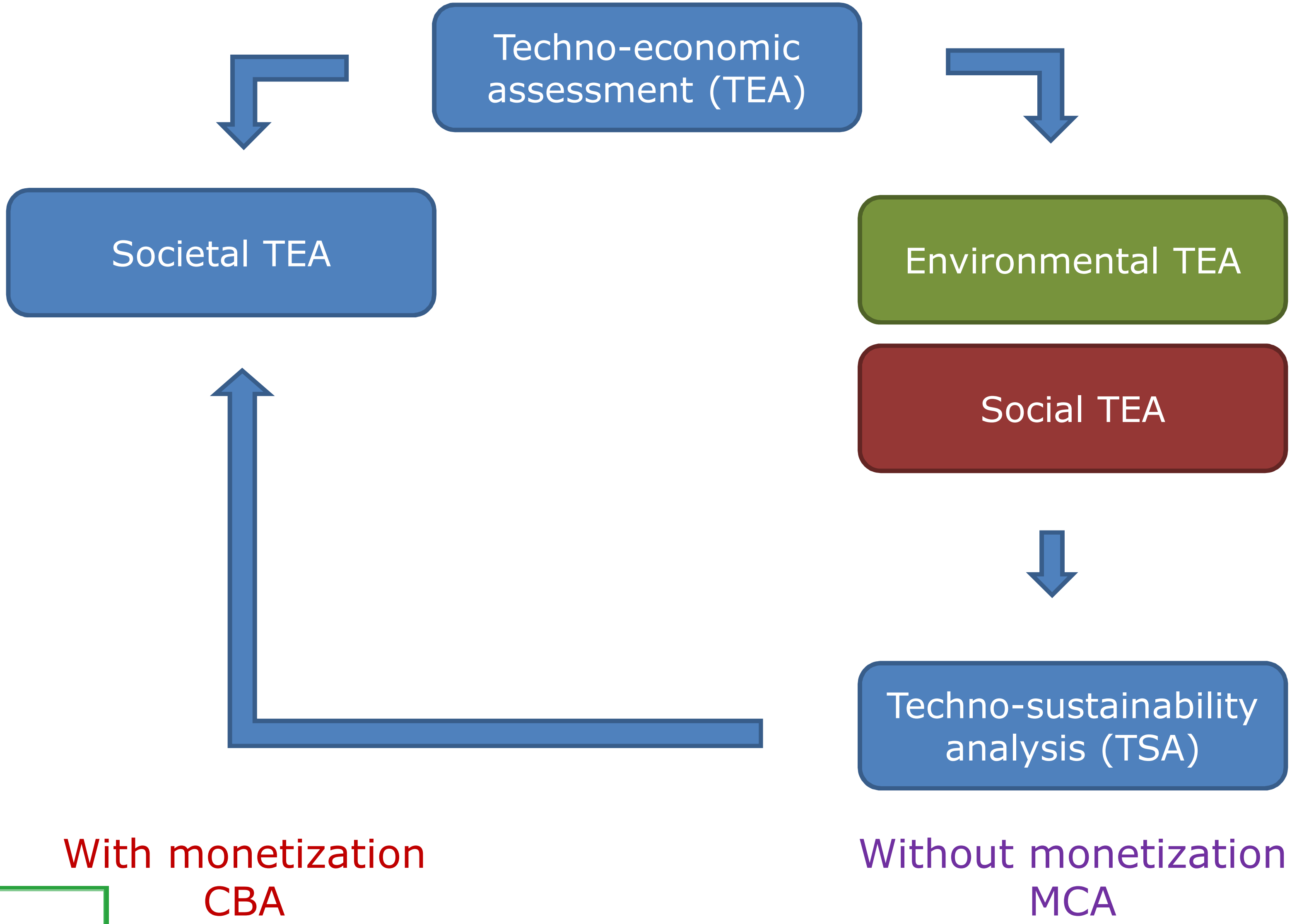
Techno-Economic Analysis (TEA) - Goals

Quantify technology performance and financial viability for a **given technology case** (including quantification of the main performance and viability drivers)

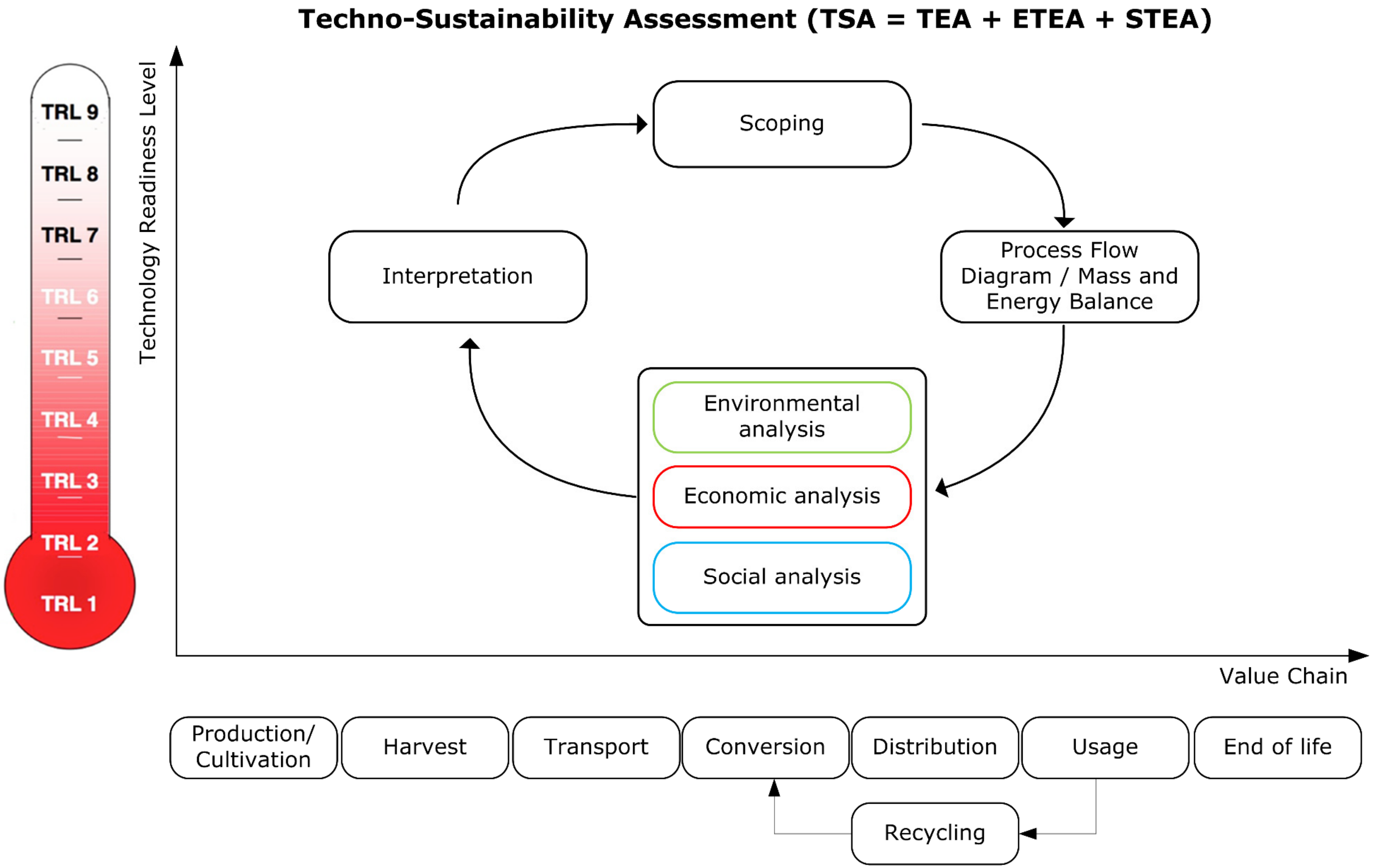
Quantify **required technology performance** in order to meet economic target (including quantification of the main performance drivers)

Determine and **prioritize R&D** for the main drivers that will **improve** the **commercial viability** of the technology

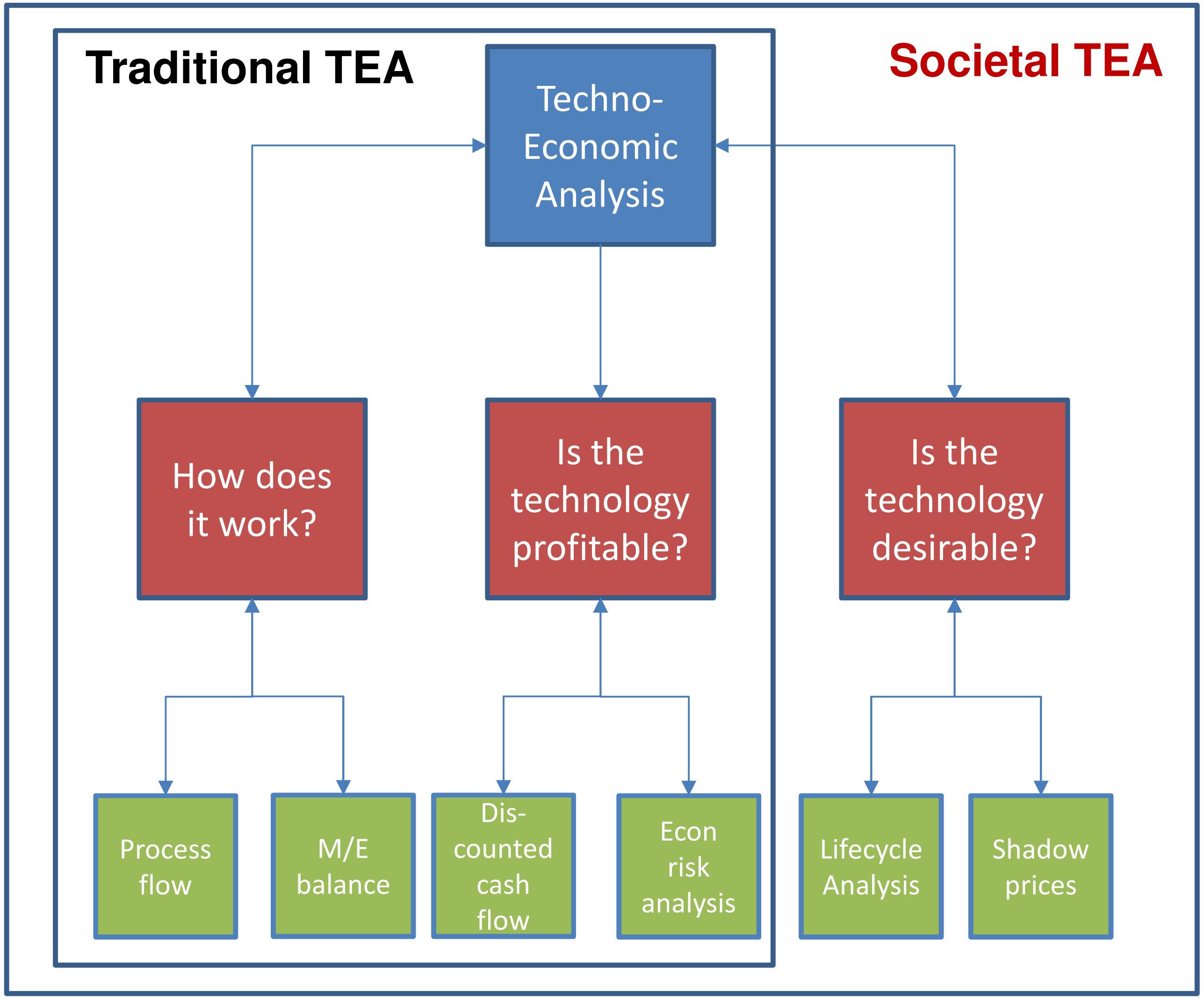
Options for integrating sustainability with TEA



Techno-economic assessment (TEA)

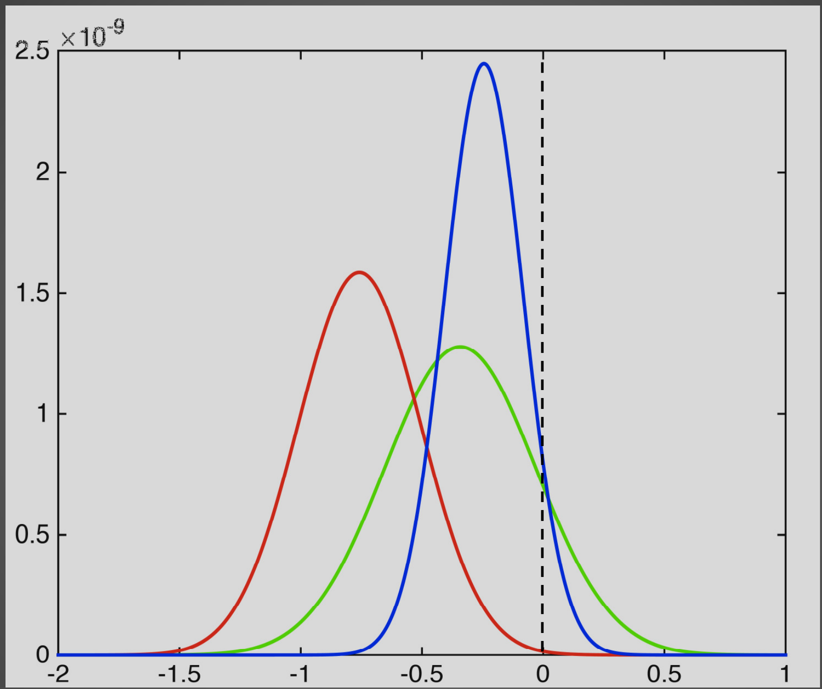


Techno-Economic Analysis (TEA)



Techno-Economic Analysis (TEA)

Investor perspective:

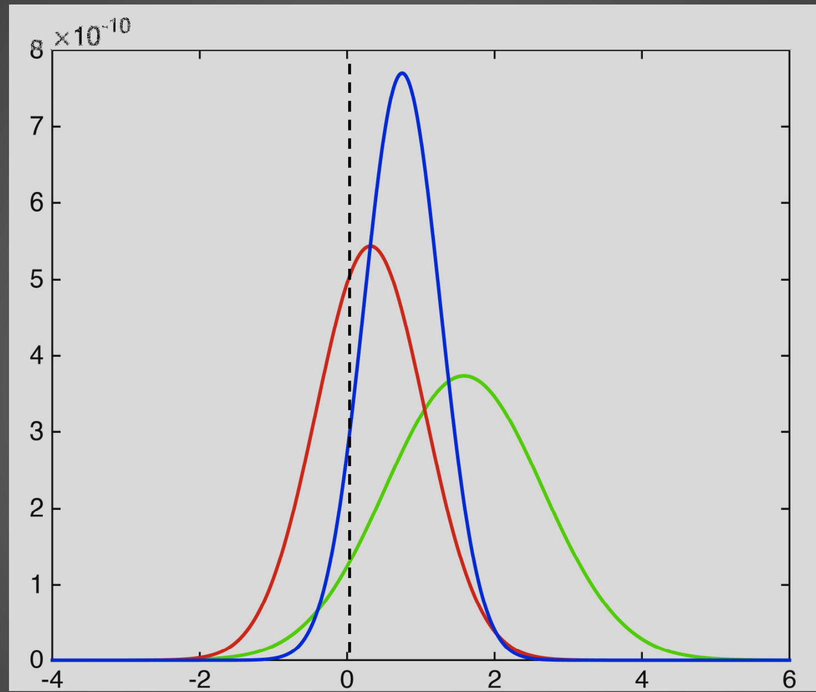


Net present value ($B)*

Probability of NPV>0:

14%, 0.1%, 7%

"Societal" perspective:



Net present value ($B)

Probability of NPV>0:

93%, 67%, 92.5%

FT MD
Plasma FT MD
ATJ MD

Assumptions used for societal case

- Costs of carbon based on US EPA social costs of carbon
- Societal costs of capital of 3.2%
- Taxes and subsidies excluded as they constitute transfers

Pitfalls in TEA

Wrong	Right
Monodisciplinarity	Multidisciplinarity
Ex post economic analysis	Integrated techno-economic analysis
Static TEA	Dynamic TEA
Uncertainties not considered	Inclusion of uncertainties
Local sensitivity analysis	Global sensitivity analysis
R&D driven by ‘gut feeling’	R&D driven by ‘risk assessment’

Techno-economic assessment

1. Preliminary process design
2. Material and energy balance
3. Estimate capital cost (meta-analysis)
4. Discounted cash flow analysis (private CBA)
5. Economic risk analysis
6. Formulate risk reduction strategies
7. Refine process design

Thermochemical conversion

Adding value to short rotation willow

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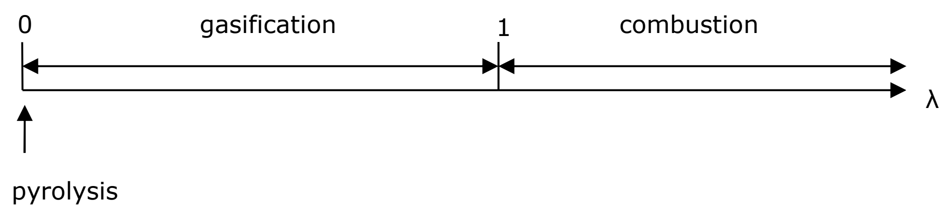
Thermochemical conversion

- Willow = lignin, cellulosis, hemicellulosis

  cannot be decomposed by microorganisms
  → thermochemical conversion

- Thermochemical conversion
  → uses heat (and catalysts) to transform plants into energy, fuels or chemicals
- Main technologies:
  - combustion
  - gasification
  - (fast) pyrolysis



Thermochemical conversion

- **Combustion**
  - most widely applied conversion method
  - CO_2, H_2O, heat → steam → electricity
  - high T → costly gas treatment (?)
  - low electric efficiency: 18 – 30 %
- **Gasification**
  - partial oxidation
  - high T → costly gas treatment (?)
  - production of combustible gas energy carrier
  - followed by gas engine < 4 MW_e
  - followed by gas turbine combined cycle > 6 MW_e
  - high electric efficiency: up to 50 %

Thermochemical conversion

- **Fast pyrolysis**
  - rapid heating of the biomass
  - low residence time for biomass and vapours
  - rapid cooling of the pyrolysis vapours
    → pyrolysis oil and non-condensable gases
  - production of oil (60-70 m%), gas and char
  - relatively low process temperature: 450 °C
    → metals remain in char
        → disposal cost
        → not suitable for internal energy
  - oil can be burnt in boilers and engines

Thermochemical conversion

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 assumptions			
Electric efficiency	21 %	34 %	24 %
P_{ne} (MW_e)	2,6 MW_e	4,5 MW_e	5,3 MW_e
Operating hours	8 000 h	8 000 h	reactor 7 000 h engine 5 000 h
Electricity produced	20,7 GWh_e yr^{-1}	35,5 GWh_e yr^{-1}	25,5 GWh_e yr^{-1}

Gasification performs better energetically, but what about economics?

Discounted cash flow model

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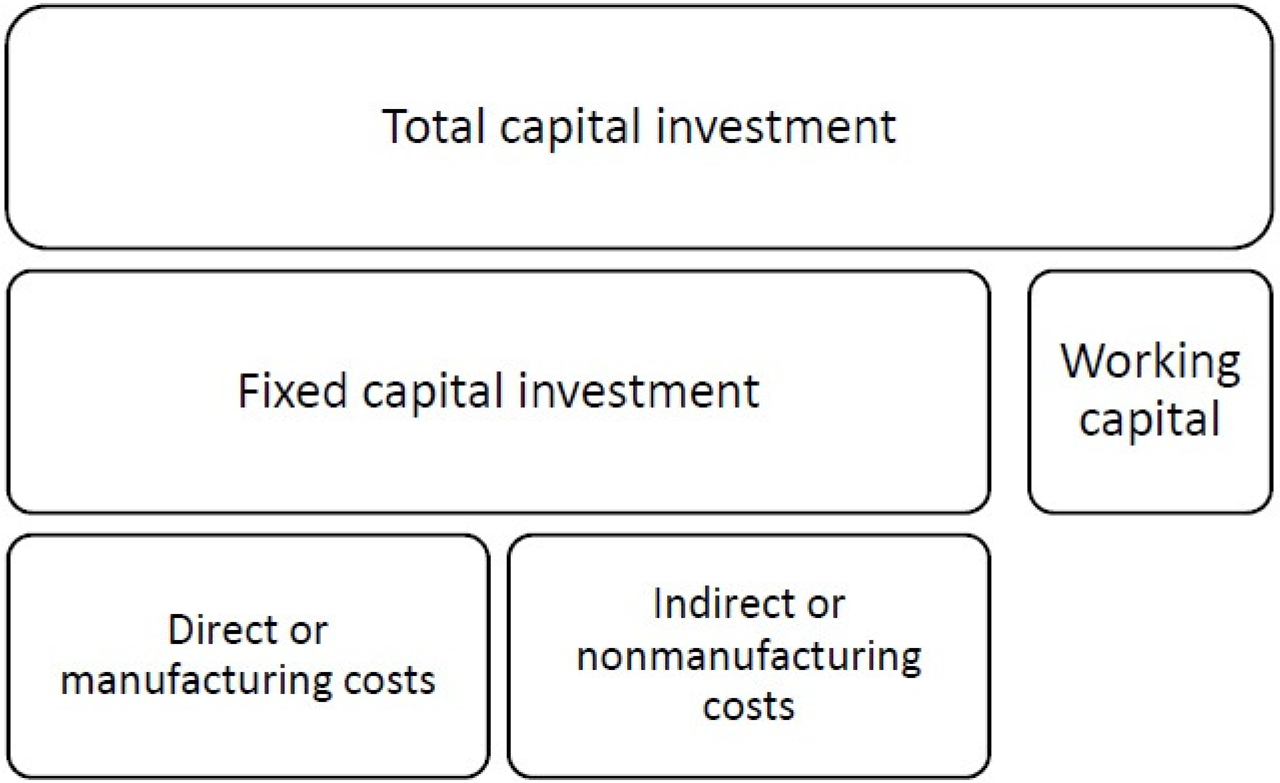
Discounted cash flow model – capital cost estimation



Discounted cash flow model – capital cost estimation

- Class 5 – Order of magnitude [-20-50%;+30+100%]
  very limited information, previous cost data
- Class 4 – Study estimate [-10-30%;+20+30%]
  knowledge of the major equipment needed
- Class 3 – Preliminary estimate [-10-20%;+10+30%]
  prepared for budget authorisation (most process data are defined and preliminary engineering)
- Class 2 – Definitive estimate [-5-15%; +5+20%]
  almost complete data but before completion of engineering drawing and specifications
- Class 1 – Detailed estimate [-3-10%;+3+15%]
  drawings and specifications complete

Discounted cash flow model – capital cost estimation

- Ask offers from potential suppliers

  - if they don't want to cooperate
    → tell them which value you have in mind
    → they will react!

  - if they are not available
    (not marketed yet)
    → perform a meta-analysis
    → use simulation software
    (Aspen)

Discounted cash flow model – capital cost estimation

- Detailed item estimates
  → requires list of specific equipment, materials, ...
  → difficult in early stages of process or product development

- Percentage of delivered equipment cost
  → Lang factors

- Capacity factored estimates
  → Six tenth rule

- Parametric cost estimation
  → meta-analysis: $C = aQ^x+bT^y+cL^z$
  (with Q = quantity, T = technology, L = location)

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Capital cost estimation – Lang factors

- **Percentage of delivered equipment cost**
  see also Peter, Timmerhaus, West (2004) Plant Design and Economics for Chemical Engineers, McGrawHill

Table 6.1. Typical factors for estimation of project fixed capital cost

Item	Process type		
	Fluids	Fluids–solids	Solids
1. Major equipment, total purchase cost	PCE	PCE	PCE
f_1 Equipment erection	0.4	0.45	0.50
f_2 Piping	0.70	0.45	0.20
f_3 Instrumentation	0.20	0.15	0.10
f_4 Electrical	0.10	0.10	0.10
f_5 Buildings, process	0.15	0.10	0.05
*f_6 Utilities	0.50	0.45	0.25
*f_7 Storages	0.15	0.20	0.25
*f_8 Site development	0.05	0.05	0.05
*f_9 Ancillary buildings	0.15	0.20	0.30
2. Total physical plant cost (PPC) $PPC = PCE(1 + f_1 + \cdots + f_9)$ $= PCE \times$	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital $= PPC(1 + f_{10} + f_{11} + f_{12})$ $= PPC \times$	1.45	1.40	1.35

*Omitted for minor extensions or additions to existing sites.

- **Equipment costs:** see Dutch Association of Cost Engineers

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Capital cost estimation - Capacity

- **Six tenth rule**

$$C_B = C_A \left(\frac{S_B}{S_A}\right)^N$$

Where C_B = approximate cost of equipment with size S_B

C_A = approximate cost of equipment with size S_A

N component: can vary between 0.3 and 0.8 (often **0.6**)

Example: Cost of a plant half the size of a plant costing € 92 000?

$$€92{,}000\left(\frac{50}{100}\right)^{0.6} = €60{,}697$$

Double sized plant is not twice as expensive

→ **economies of scale**

Capital cost estimation - Time

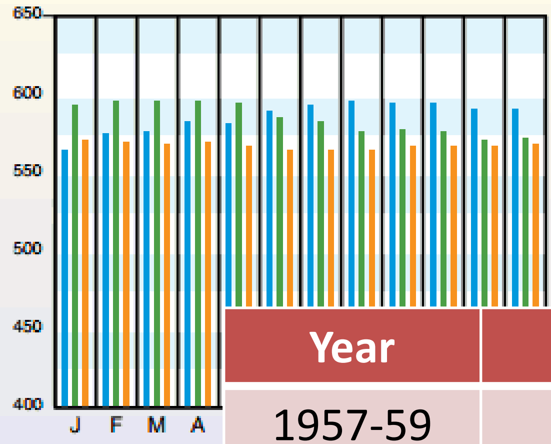
- **CEPCI (Chemical Engineering Plant Cost Index)**
  - Introduced in 1963 and published in every issue of CE.
  - 1957-1959 = 100
  - Construction costs for *chemical plants*

DOWNLOAD THE *CEPCI* TWO WEEKS SOONER AT *WWW.CHE.COM/PCI*

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Dec.'13 Prelim.	Nov.'13 Final	Dec.'12 Final
CE Index	567.6	566.6	571.9
Equipment	687.9	686.6	693.6
Heat exchangers & tanks	621.6	620.6	634.7
Process machinery	656.0	653.2	657.6
Pipes, valves & fittings	875.7	873.9	895.8
Process instruments	412.6	411.4	415.7
Pumps & compressors	925.8	924.3	899.6
Electrical equipment	513.8	514.1	511.4
Structural supports & misc	746.9	746.3	734.5
Construction labor	318.8	317.8	321.3
Buildings	532.9	532.8	526.8
Engineering & supervision	322.5	323.4	326.9

Annual Index:
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8
2011 = 585.7
2012 = 584.6



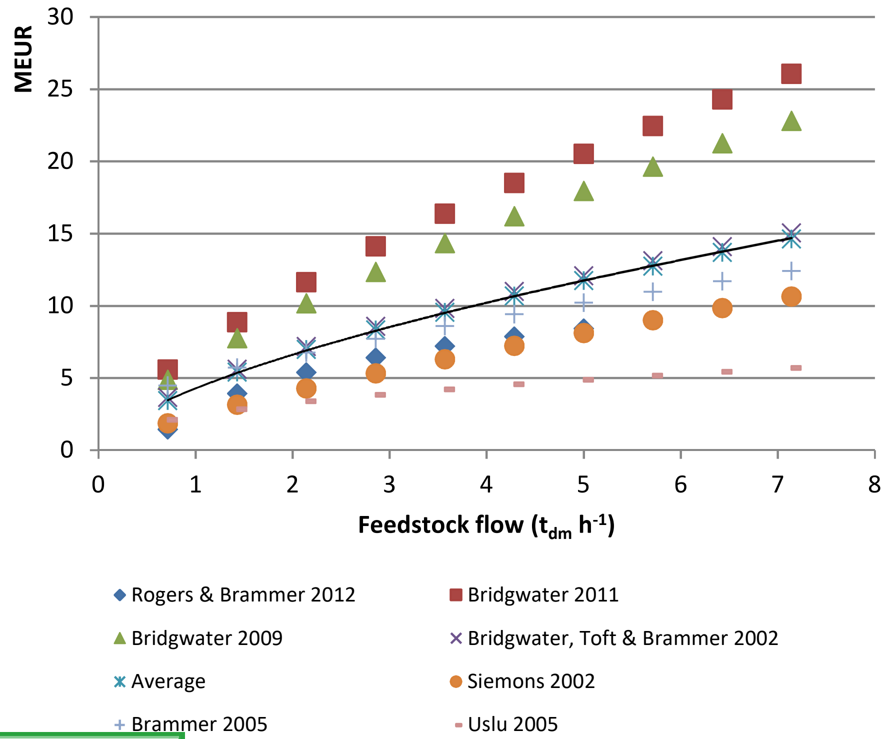
Year	CEPCI
1957-59	100
2000	394.1
2010	550.8
2011	585.7
2012	584.6

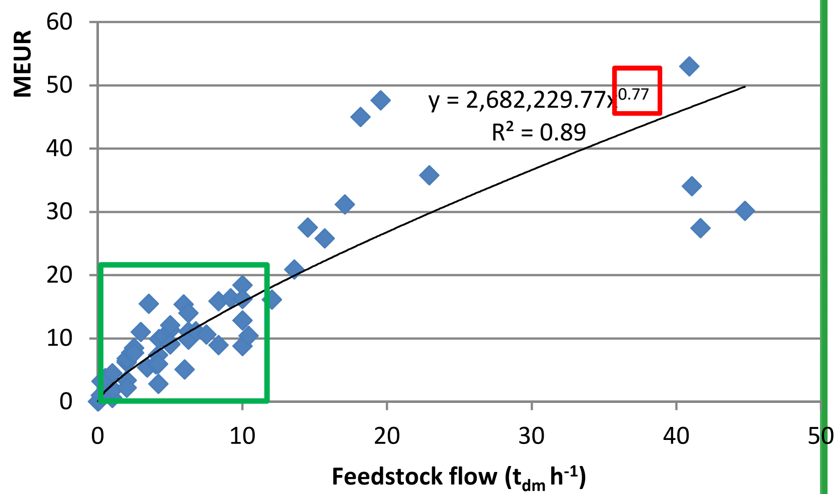
Example: Cost of a pump in 2012 prices given a cost of € 10 000 in 2010?

$$€10{,}000 \left(\frac{584.6}{550.8}\right) = €10{,}614$$

Discounted cash flow model

- Meta-analysis of the capital investment
- Literature: equations + point estimates
- Great uncertainty of capital cost





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Discounted cashflow model

- Economic calculations are directly coupled with technical calculations!
  → Change in technical parameter is translated into economic impact.

- Standard calculations:
  - PBP (and DPBP)
  - NPV
  - IRR

Discounted cashflow model

- Net cash flow in year t before taxes = $R_t - C_t$

With R_t = incoming cashflow in year t
C_t = outgoing cashflow in year t
n = useful life of the investment

Year	0	1	2	…	n
Cost		-10	-10	…	-10
Revenue		15	15	…	15
CF		+5	+5	…	+5

If positive → can start to pay investment back

Discounted cashflow model

- Difference between cash and non-cash transactions
  - When you buy an asset (machine) with a useful life of n years:
    - you often fully pay it on the purchase date (i.e. in year 0);
    - but in a profit and loss account you spread its cost over its lifetime (= depreciation).
    http://www.investopedia.com/video/play/depreciation/
  - Depreciation is a non-cash transaction, which has an influence on the cash transactions of your company by its tax statement
    → depreciation is a deductable cost
    → it lowers the net income or profit and saves paid taxes
    → the amount of taxes you pay is a cash transaction
  - Net cash flow in year t after taxes = $CF_t = (1-\tau).(R_t - C_t) + \tau.D_t$

Discounted cashflow model

- Does not take into account the time value of money!

  €1 now > €1 later

- Discounting
  → r = discount rate = weighted average cost of capital = WACC

- $\text{WACC} = \left(\frac{E}{E+D}\right) \times r_E + \left(\frac{D}{E+D}\right) \times r_D \times (1-\tau)$

  A company wants to finance an investment partly (60%) with a loan at a nominal interest rate of 3% and partly (40%) with equity ("own capital") for which the providers demand a return of at least 15%. (The national tax rate is 33%.)

Discounted cashflow model

- $$\mathrm{WACC} = \left(\frac{E}{E+D}\right) \times r_E + \left(\frac{D}{E+D}\right) \times r_D \times (1-\tau)$$

  A company wants to finance an investment partly (60%) with a loan at a nominal interest rate of 3% and partly (40%) with equity ("own capital") for which the providers demand a return of at least 15%. (The national tax rate is 33%.)

- $\mathrm{WACC} = 0{,}4 \times 0{,}15 + 0{,}6 \times 0{,}03 \times (1 - 0{,}33) = 0{,}07386$
  → the appropriate discount rate is 7,386%

- What if the investment would be fully financed by the loan?

Discounted cashflow model

- $\text{WACC} = \left(\frac{E}{E+D}\right) \times r_E + \left(\frac{D}{E+D}\right) \times r_D \times (1 - \tau)$

  A company wants to finance an investment partly (60%) with a loan at a nominal interest rate of 3% and partly (40%) with equity ("own capital") for which the providers demand a return of at least 15%. (The national tax rate is 33%.)

- $\text{WACC} = 0{,}4 \times 0{,}15 + 0{,}6 \times 0{,}03 \times (1 - 0{,}33) = 0{,}07386$
  → the appropriate discount rate is 7,386%

- What if the investment would be fully financed by the loan?
  → the appropriate discount rate is 2,31%

Discounted cashflow model

- Net Present value (NPV) = $\sum_{n=1}^{T} \frac{CF_n}{(1+r)^n} - I_0$

  With T = project lifetime

  CF_n = cash flow in year n (revenues – costs)

  I_0 = investment in year 0

  r = discount rate

- When the NPV > 0, the investment project is acceptable.

Discounted cashflow model

- What should we do with interest payments?

  - They are cash transactions
  - However, we do not incorporate them in the cash flow table
  - This leads to the most straightforward interpretation of the NPV
    - ✓ If NPV = 0, then we are able to repay exactly the interests (but we earn no extras)
    - ✓ If NPV > 0, then this value is the actual value of the money we will earn above interest payments

Discounted cashflow model

- A company invests in new equipment with a purchase value of 1 MEUR. The useful life of the equipment is 5 years.
  The investments generates a yearly revenue of 0,5 MEUR.

- What is its NPV, given a discount rate of 3%?

Discounted cashflow model

- A company invests in new equipment with a purchase value of 1 MEUR. The useful life of the equipment is 5 years.
  The investments generates a yearly revenue of 0,5 MEUR.

- What is its NPV, given a discount rate of 3%?

-

0	1	2	3	4	5	(years)
-1	+0,5	+0,5	+0,5	+0,5	+0,5	(MEUR)

Discounted cashflow model

- A company invests in new equipment with a purchase value of 1 MEUR. The useful life of the equipment is 5 years.
  The investments generates a yearly revenue of 0,5 MEUR.

- What is its NPV, given a discount rate of 3%?

- 0 1 2 3 4 5 (years)

  -1 +0,5 +0,5 +0,5 +0,5 +0,5 (MEUR)

- $NPV = -1 + \frac{0,5}{(1+0,03)^1} + \frac{0,5}{(1+0,03)^2} + \frac{0,5}{(1+0,03)^3} + \frac{0,5}{(1+0,03)^4} + \frac{0,5}{(1+0,03)^5} = 1,3$

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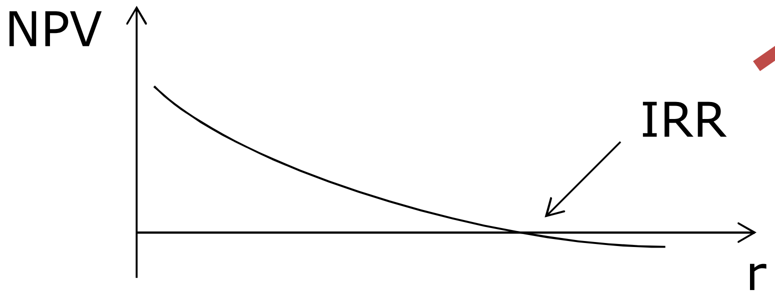
Discounted cashflow model

- Internal rate of return (IRR)

It is possible that the IRR does NOT exist!



Discounted cashflow model

- IRR or NPV?

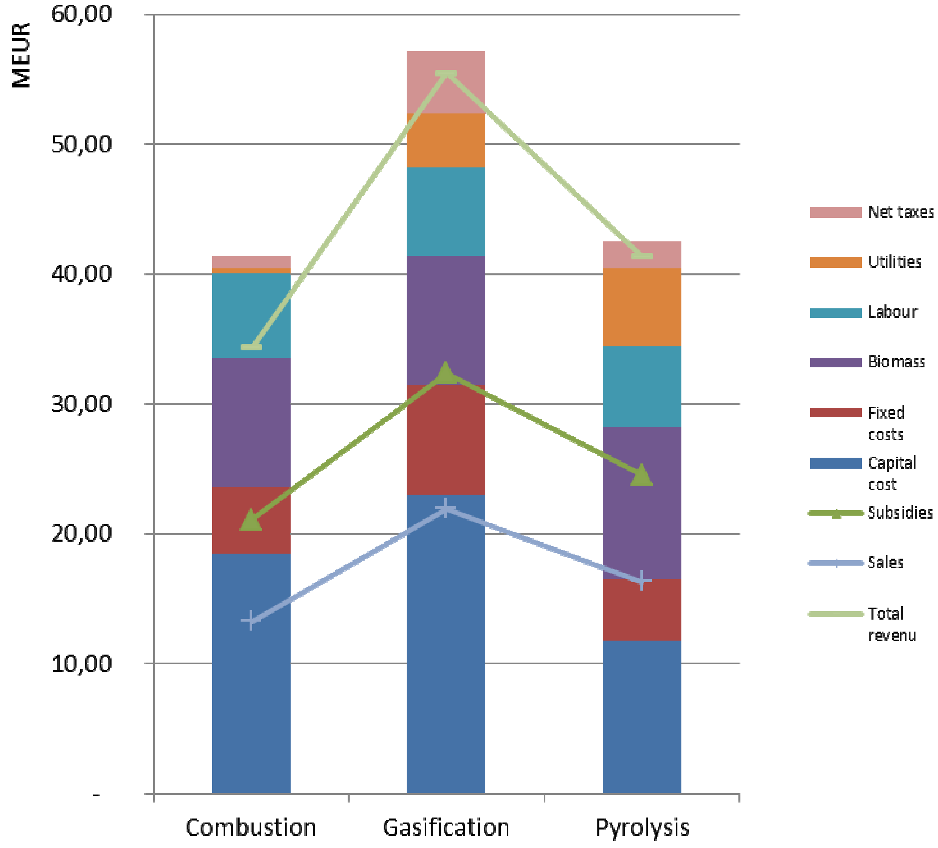
- Businesses often use IRR, but this might in some cases be misleading!

- IRR gives the “feeling” of representing your return on investment
(these two concepts however have a different meaning)

- IRR is dimensionless:
consider an IRR of 50% on an investment of 1 EUR vs. 5% on 1 MEUR
→ therefore it is better to consider the NPV

Discounted cash flow model – Applied to Belgian case

- Electricity production only is not profitable (but CHP is)
- Gasification: most costly
- Fast pyrolysis: least loss making
- 60 % of the revenues stem from subsidies



Risk analysis

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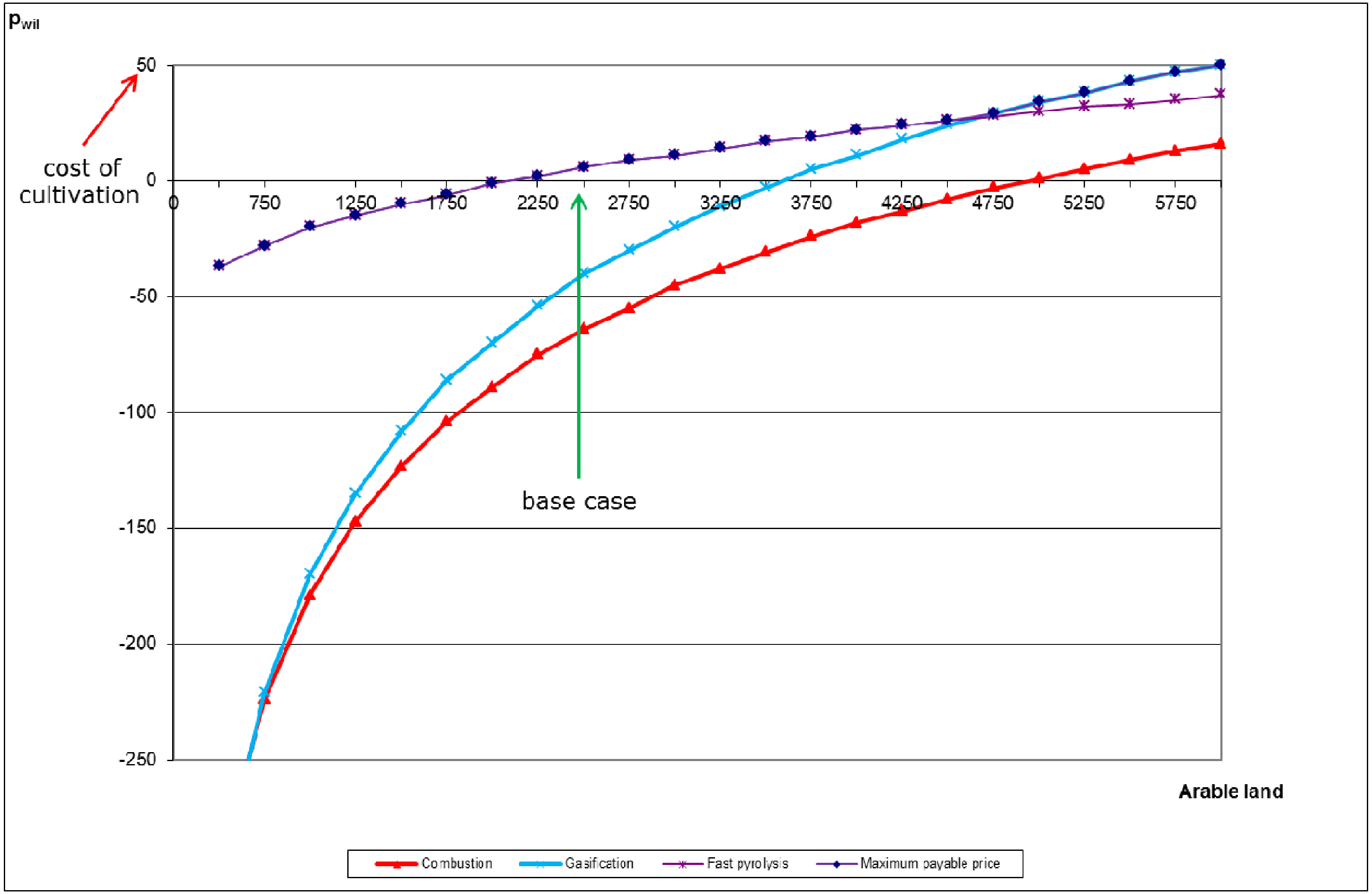
Risk analysis

Exploration of the willow price taking into account uncertainties

- minimum
  - = cultivation cost incurred by farmers
  - = 50 EUR t_{dm}^{-1}
- maximum
  - = price that can be paid by an investor in electricity production using willow as a feedstock, taking into account uncertainties by means of Monte Carlo simulations, i.e. P(NPV>0) ≥ 95 %

Risk analysis



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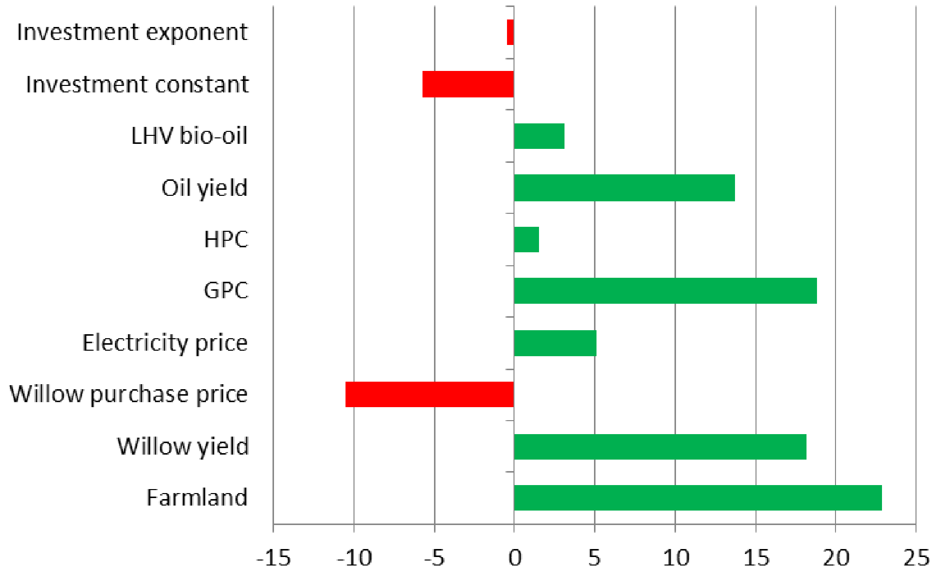
Risk analysis

Maximum price for a fast pyrolysis plant with combined heat and power production

Scale		Maximum possible willow price ($EUR\ t_{dm}^{-1}$)		$p_{willow} - c_{willow}$
ha	$kt_{dm}\ yr^{-1}$	Electricity production only	Combined heat and power	Price/cost difference
500	4	-37	-2	-52
1500	12	-10	38	-12
2500	20	6	51	1
3500	28	17	60	10
4500	36	26	66	16
5500	44	33	70	20

Risk analysis

Which uncertainties explain the variability of the net present value of cash flows?



Risk reduction strategies

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Risk reduction by changing inputs

- Risk reduction strategies in general:
  - modification of the firm's operations
  - change of the capital structure
  - employment of financial instruments (e.g. insurance)

Risk reduction by changing inputs

- Risk reduction strategies in general:
  - modification of the firm's operations
  - change of the capital structure
  - employment of financial instruments (e.g. insurance)

- Reduction of the dependence on:
  - scale
  - the value of the green power certificates
  - oil yield

  → by changing inputs (feedstock)

  → by changing outputs (pyrolysis products)

Risk reduction by changing inputs

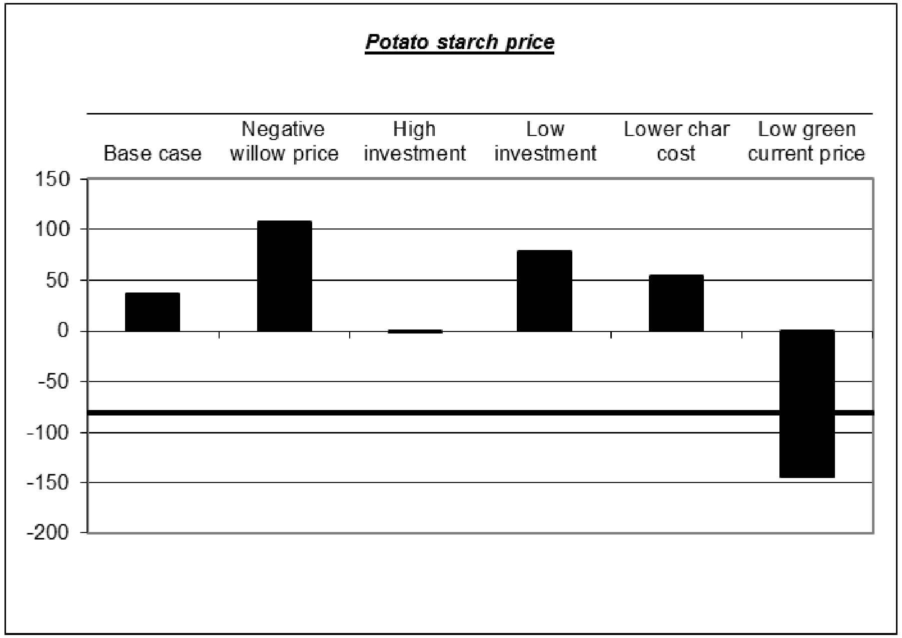
- Fast co-pyrolysis of willow and biopolymer waste:
  - increase of the scale of operation
    → cost advantage
  - processing waste can result in a *gate fee*, as biopolymer waste now is composted at a cost of 80 EUR t_{dm}^{-1}
  - decrease of the water content of the oil
  - other synergistic effects (e.g. higher oil yield)
  - change of oil composition
    → cf. presence of high value chemicals

Risk reduction by changing inputs

Impact on profitability

1:1 w/w ratio willow/biopolymer	NPV (MEUR)	Diff.
Pure willow	-10,610	
Willow/PLA	2,494	13,104
Willow/PHB (crotonic acid - chemicals)	341,764	352,375
Willow/Biopearls	4,571	15,182
Willow/Eastar	5,549	16,159
Willow/Potato starch	3,633	14,243

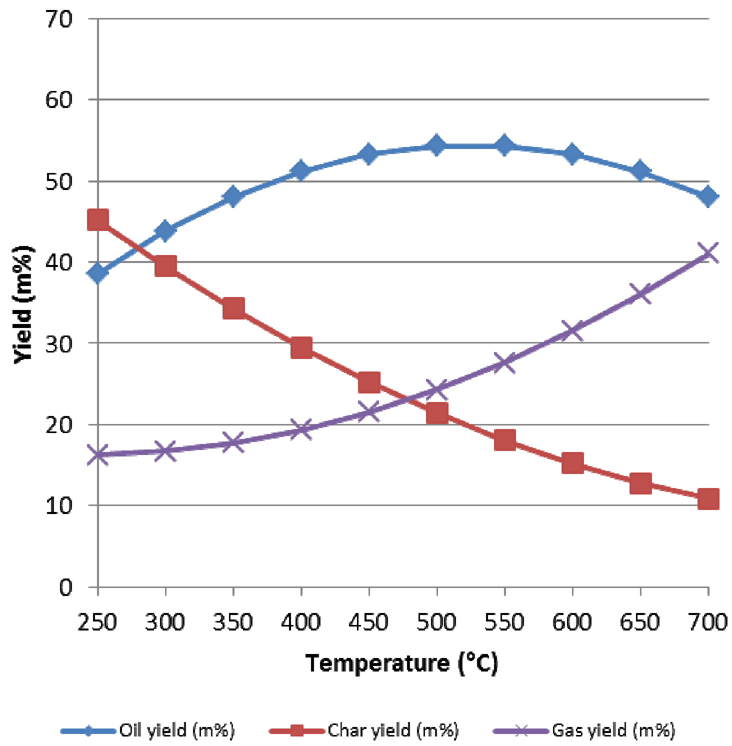
Price scenario analysis



- The use of biopolymers enhances the profitability of fast pyrolysis
- Fast co-pyrolysis of willow and biopolymers is an alternative to composting
- The presence of chemicals (cf. crotonic acid) might greatly increase profitability

Risk reduction by changing outputs

- Fast pyrolysis results in the production of oil, gas and char
- Process parameters (temperature and residence time) influence the product yields:
  - longer residence time favours char production
  - lower temperature favours char production too



Risk reduction by changing outputs

- Assuming subsequent processing of the pyrolysis products into marketable products:
  - char can be activated for production of active coal (filter medium)
  - oil can be combusted for combined heat and power production

  → conclusion:
    - active coal (AC) production is favoured as long as its selling price is higher than 2 kEUR t^{-1}
    - combined heat and power production is favoured when the AC price is below 1,4 kEUR t^{-1}

Conclusion and discussion

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Conclusion

- For small scale biomass conversion:
  fast pyrolysis > gasification > combustion
- Power production alone is loss making, only combined heat and power production is profitable and able to recover cultivation costs of willow
- The profitability is largely dependent on:
  - the scale of the pyrolysis plant
  - the value of green power certificates
- Economic risk can be reduced by:
  - changing the inputs: e.g. co-pyrolysis with bioplastics
  - changing the outputs: e.g. valorisation of the char

Future research

- Reverse the role of pyrolysis technology
  - Not as an output of phytoremediation
  - But as an input to soils for metal immobilisation

- Valuation of the environmental benefits (and costs)
  - Life cycle analysis of phytoremediating crops
  - Valuation of the outcomes

  → Motivates government interventions

Willing to collaborate?

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