Karlsruhe Institute of Technology

Model based investigation of biomass utilization paths for different regions in Germany, Sweden and Chile

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Evaluation and planning of biofuel production chains

- Background: Development of various biomass utilization processes
- Researchers, politics and industry demand for economic assessment regarding production costs and investments
- Relevant aspects
  - Number and locations of plants
  - Different production steps (e.g. crushing, cleaning, conversion, separation) at an integrated or at different locations
  - Capacity planning regarding economies of scale and transportation costs
  - Provision of energy, e.g. by using of waste heat or by burning of biomass
  - Regional framework conditions, e.g.
    - Types, masses and distribution of biomass
    - Road and electricity network

Approach for the regional assessment of utilization paths

I. Techno-economic assessment of the utilization path	II. Modeling of regional framework conditions
I.1 Determination and technical characterization of process units	II.1 Splitting of the region into a grid and determination of potential production sites
I.2 Identification of locally separable production steps	II.2 Identification and allocation of biomass potentials
I.3 Economic assessment of the process units	II. 3 Definition of the sinks and the target product quantities
	II.4 Determination of regional specific economical data

III. Calculation of the cost-optimal structure, locations and capacities for a utilization path in a given region

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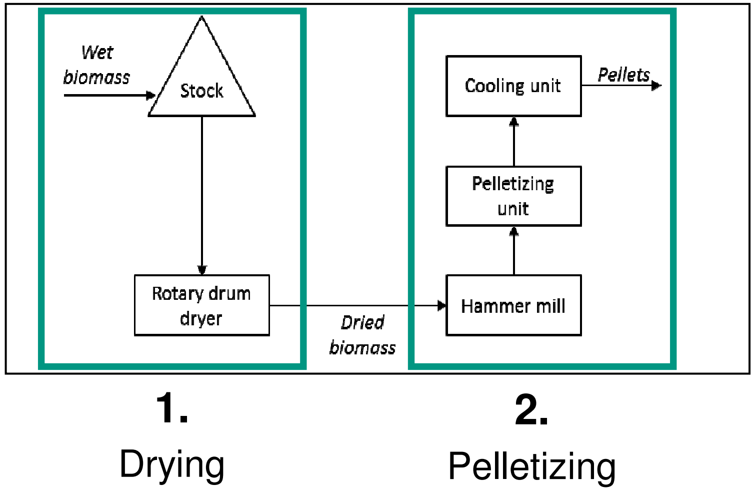
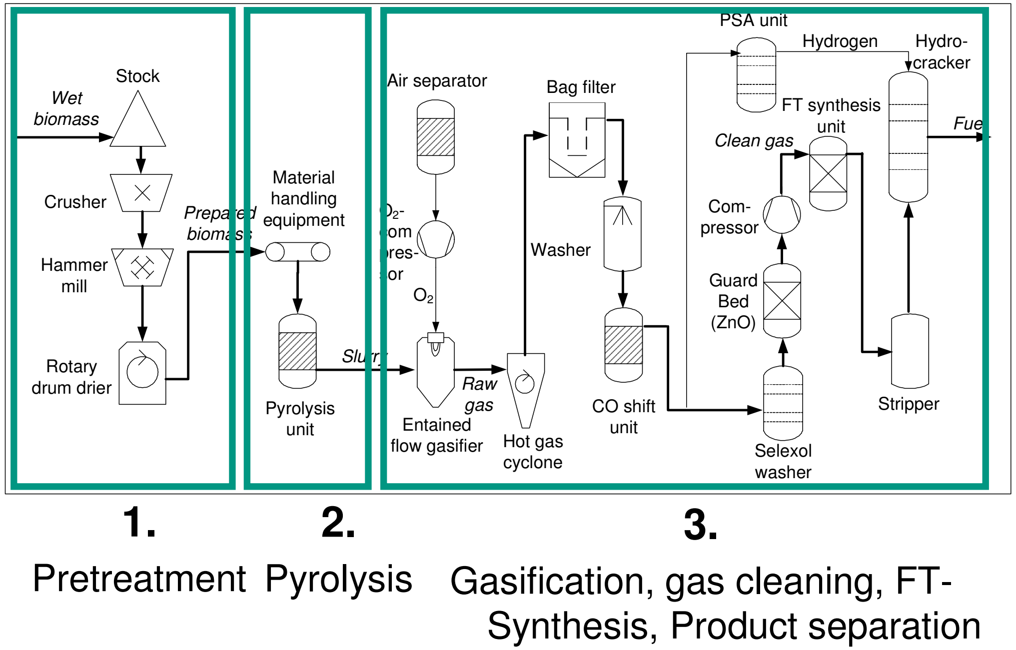
I.1+2 Determination & technical characterization of process units of two example utilization paths

- Pellet production



- Biofuel production



- Determination of technical figures
  - Material conversion of process units
  - Energy demands, waste energy and by-products
- Identification of locally separable production steps
  - Transportation of biomass limited by weight → separation after drying
  - Slurry is transportable, and has a higher energy density than biomass
  - No transportation of gas

Approach for the regional assessment of utilization paths

I. Techno-economic assessment of the utilization path

I.1 Determination and technical characterization of process units

I.2 Identification of locally separable production steps

I.3 Economic assessment of the process units

II. Modeling of regional framework conditions

II.1 Splitting of the region into a grid and determination of potential production sites

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I.2 Economic assessment of the process units

$$I_i^{S1} = \underbrace{\sum_{u \in \Upsilon^{S1}} \sum_{b=1}^{B} I_u^{basis} \cdot \left(\frac{\kappa_{b,i,u}^{target}}{\kappa_u^{basis}} \right)^{R_u}}_{} \cdot \underbrace{\left(1 + A_u \cdot \left(\frac{\kappa_{b,i,u}^{A,target}}{\kappa_u^{A,basis}} \right)^{R_u^A} \right)}_{} \cdot \underbrace{(1+B)}_{} \quad \forall i \in \{1, ..., I\}$$

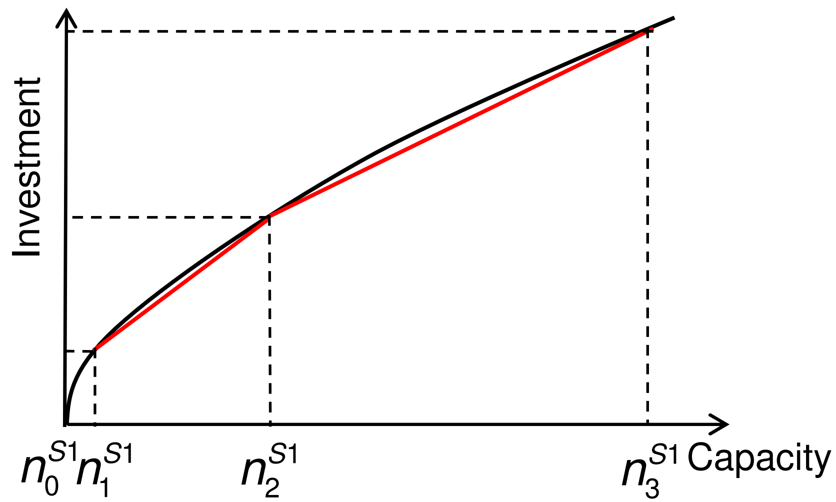
Investments for main units
→ Concave, strictly monotonic increasing function of the capacity with $R_u \geq 0$

Direct subitems
→ Convex, strictly monotonic decreasing function of the capacity with $R_u^A \leq 0$

Indirect subitems
→ Linear function of the investments battery limits

I_u^{basis}	Basis investment
κ_u^{basis}, $\kappa_u^{A,basis}$	Basis capacity
$\kappa_{b,i,u}^{target}$, $\kappa_{b,i,u}^{A,target}$	Target investment

Unit u	I_u^{basis}	κ_u^{basis}	R_u	A_u	R_u^A
Grinding	0.48 M €	33.5 t/h	0.6	0.33	-0.82
Drying	8.5 M €	33.5 t/h	0.8	0.33	-0.82
Pyrolysis	7.52 M €	70 MW	1	0.33	-0.82
Gasifier	90.1 M €	78 t/h	0.7	0	1
CO shift	12.2 M €	8.82 kmol/h	0.65	0.81	1
Guard bed	240 T €	8 m³	1	2	1
FT synthesis	17 M €	208 t/h	1	0.3	1
Pelletizing	470 T €	5 t/h	0.8	0.33	-0.82



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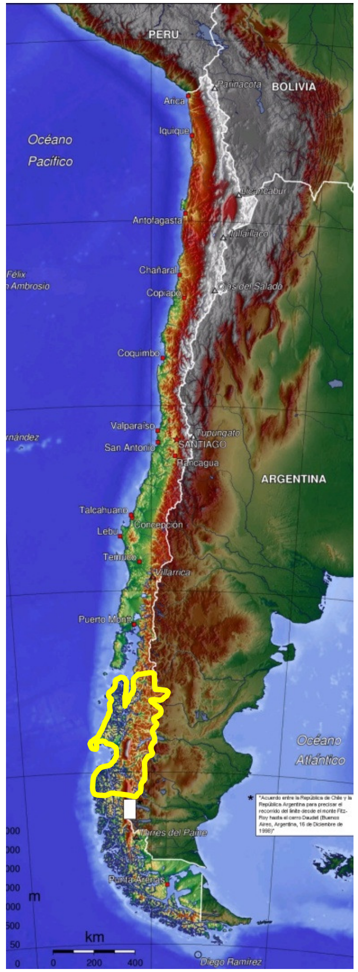
Investigation of three example regions

Germany

Sweden

Chile



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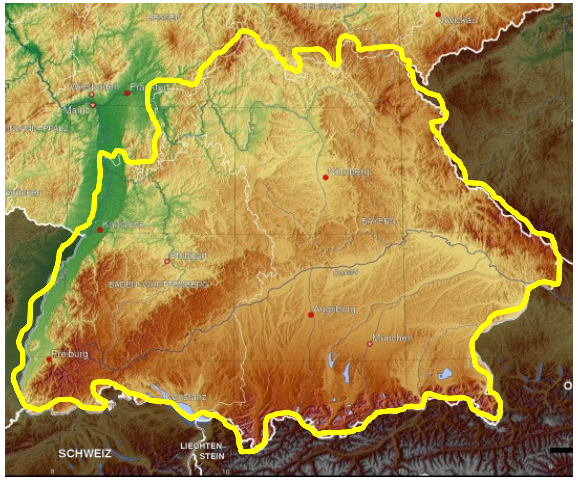
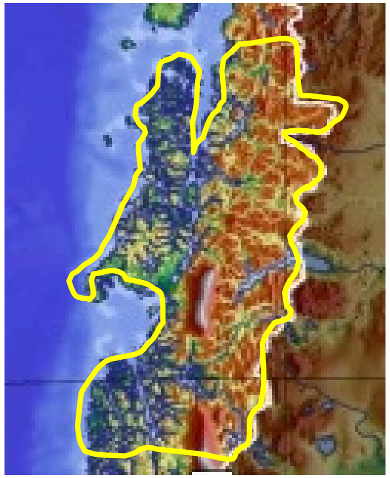
Main charaterstics of the regions





	South Germany	South Sweden	Aysén in Chile
Relevant geographical characteristics	▪ Alps & mountain ranges	▪ Thousands of islands ▪ Numerous lakes and rivers	▪ Andes ▪ Islands, rivers and lakes ▪ 45% forest, 23% grass/wetland ▪ 28% snow, no vegetation
Surface [km²]	106,303	114,190	106,982
Inhabitants [-]	23,254,921	4,583,815	91,492
Densitiy [Inh./km²]	219	40	1
Communes	3,157	167	10
Cities > 100,000	17	7	-

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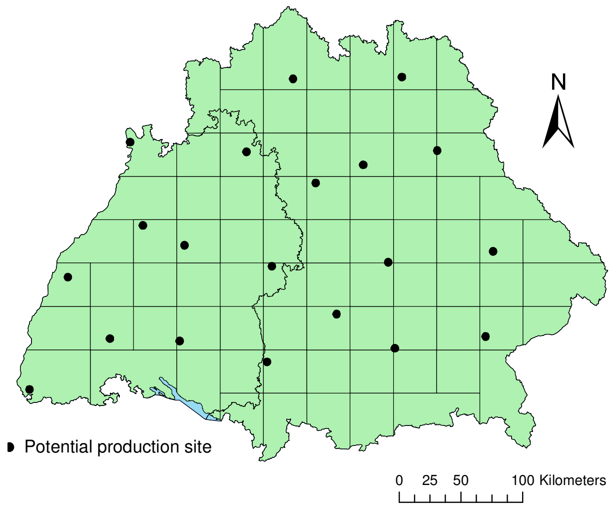
II.1 Splitting of the region into a grid and determination of potential production sites

- Edge length of cells: 35 km
- Fusion of small cells at the borders



South Germany
▪ Lake Constance excluded
80 cells
• No locations in mountain regions

II.1 Splitting of the region into a grid and determination of potential production sites

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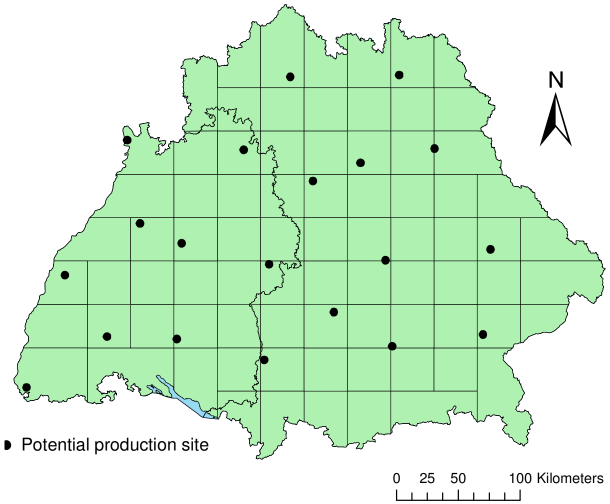
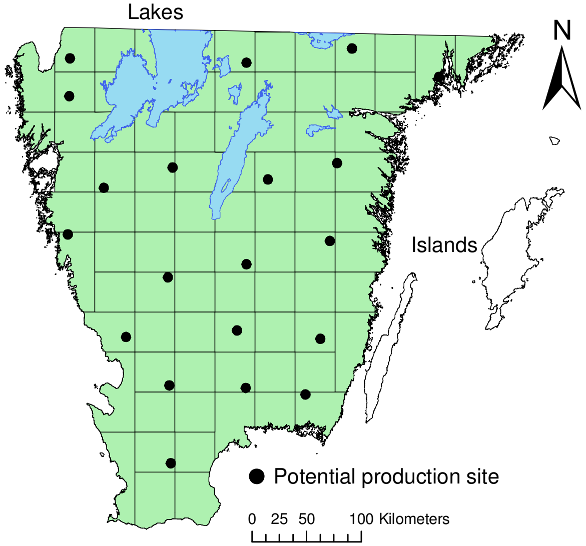
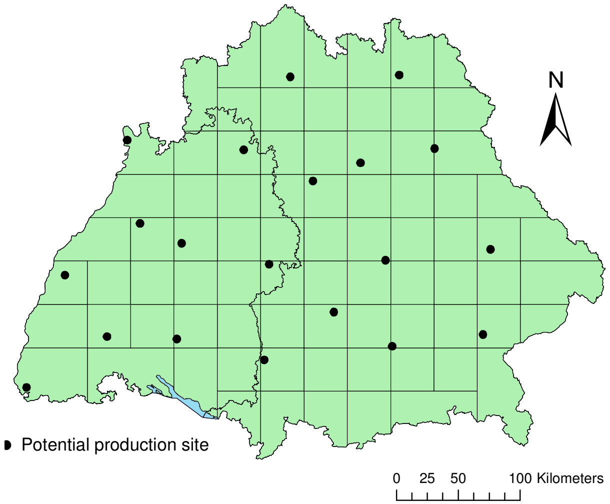


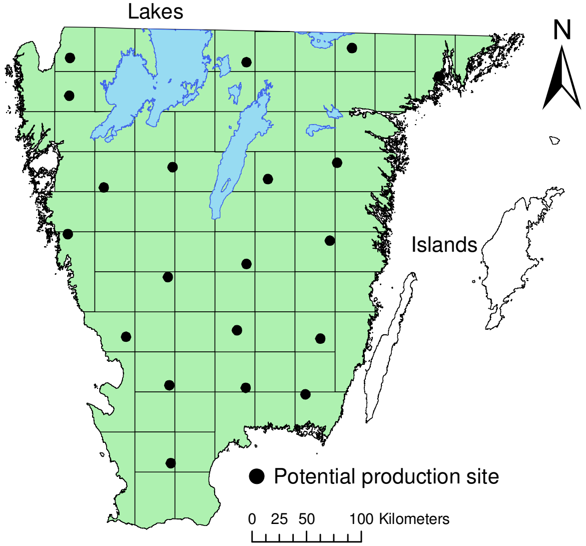


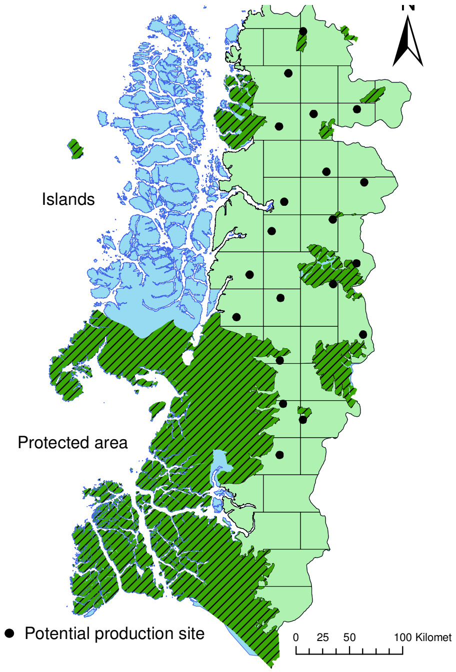
South Germany	South Sweden
▪ Lake Constance excluded	▪ *Lakes Vänern, Vättern, Roxern, Glan* and *Hjälmaren* excluded
80 cells	77 cells
• No locations in mountain regions	• Locations near to cities / villages

II.1 Splitting of the region into a grid and determination of potential production sites

- Edge length of cells: 35 km
- Fusion of small cells at the borders







South Germany	South Sweden	Aysén, Chile
▪ Lake Constance excluded	▪ *Lakes Vänern, Vättern, Roxern, Glan and Hjälmaren* excluded	▪ 43 % national parks / reservations protected by SNASPE (*Sistema de Nacional de Áreas Silvestres Protegidas del Estado) and islands exluded*
80 cells	77 cells	45 cells
• No locations in mountain regions	• Locations near to cities / villages	• Locations close to main roads near cities / colonies in plain areas

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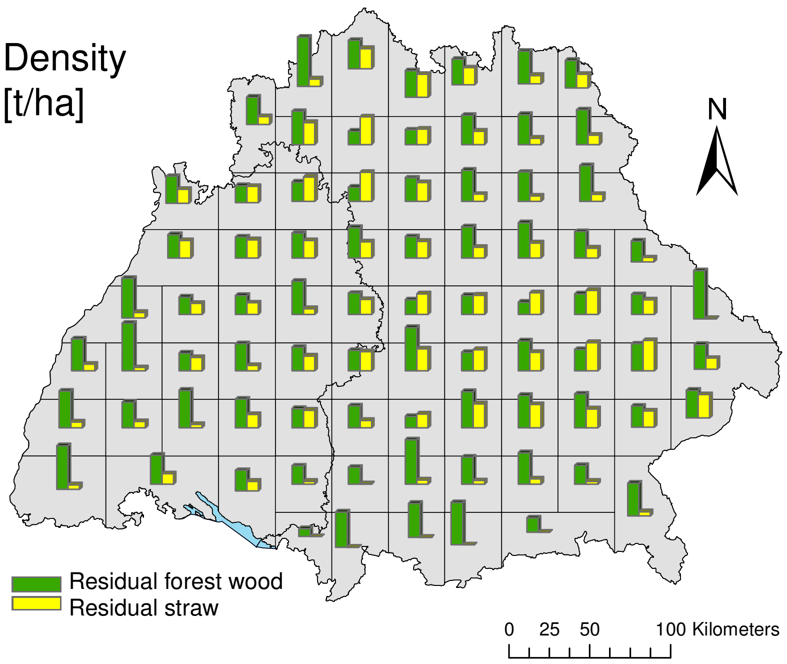
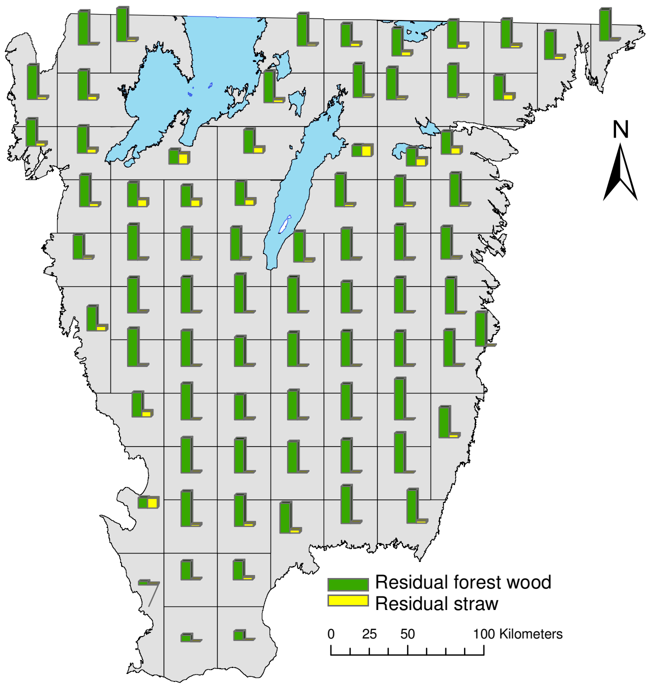
II.2 Identification and allocation of biomass potentials

Density [t/ha]





Basis: Land use data

	South Germany	South Sweden	Aysén, Chile
Types	Residual forest wood and residual straw		Wood from native forests
Distribution	▪ High density of wood in the south and south-west ▪ Highest density of straw in Bavaria	▪ Wood equally distributed (except the very south) ▪ Only little straw between the lakes	▪ Three regions with high densities ▪ Low density in the east

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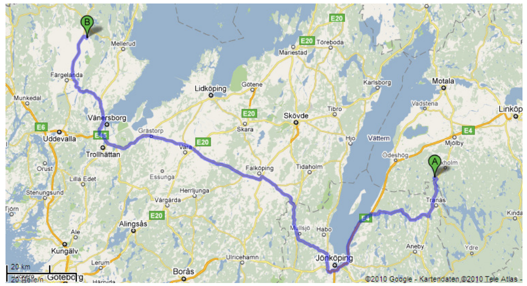
II. 3 & 4: Sinks, target product quantities and regional economic data

- Production quantities
  - Pellet production in Chile: 20,000-400,000 tons
  - Biofuel production: utilization of 70 % of the available biomass → 400 m liter in Germany and Sweden; → 200 m liter in Aysén
- Sinks and Transportation
  - Products
  - Germany / Sweden: Utilization by the population
    → Transport to the grid cells according to share of inhabitants
  - Aysén: Exportation of the products → transportation to the port
  - Transportation costs on existing roads: highest in Aysén
  - Transportation distances: real road distances
  - Additional: road construction costs in Aysén
  - Limitation of truck arrivals and departures to 20 per hour at each location



- Further economic parameters
  - Biomass acquisition
  - Waste disposal, auxiliary materials, selling and buying of electricity
  - Interests, amortization, maintenance, repair, insurances, taxes, administration, labor: depending on the investment

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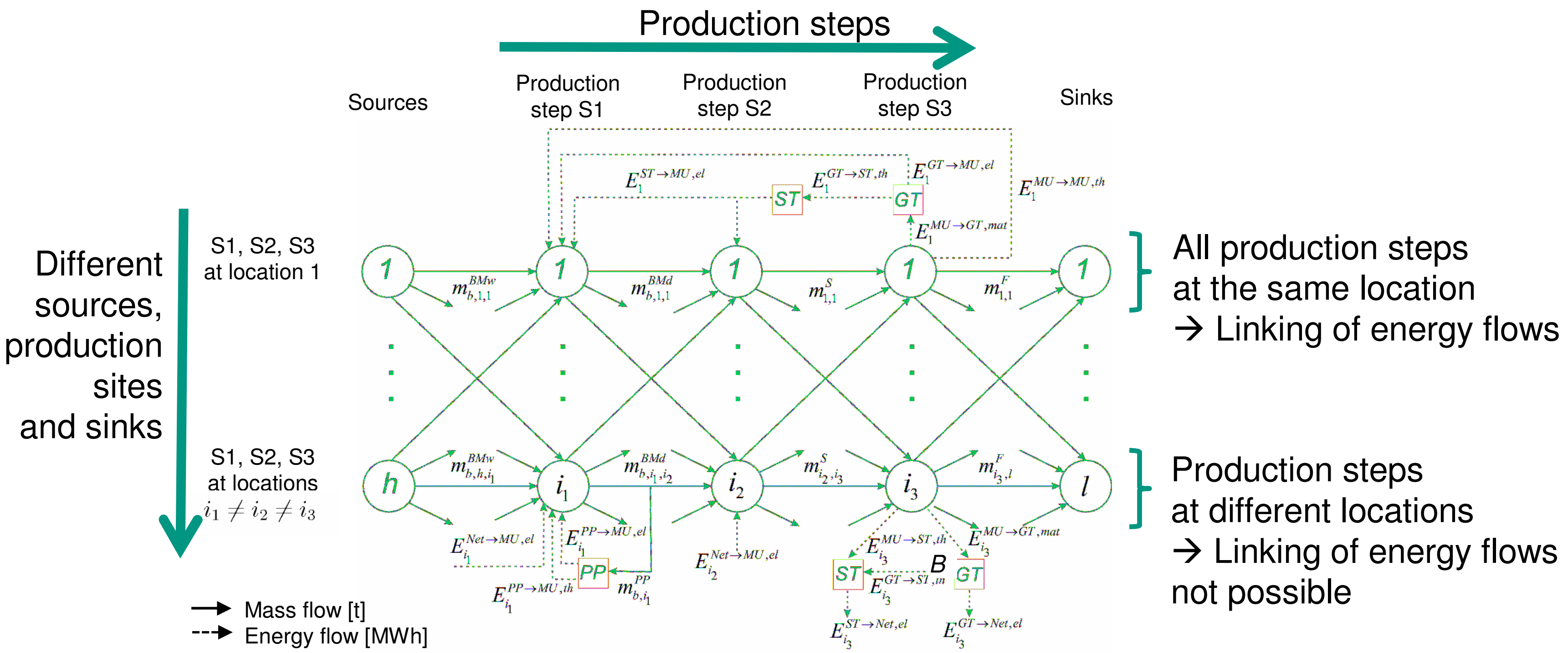
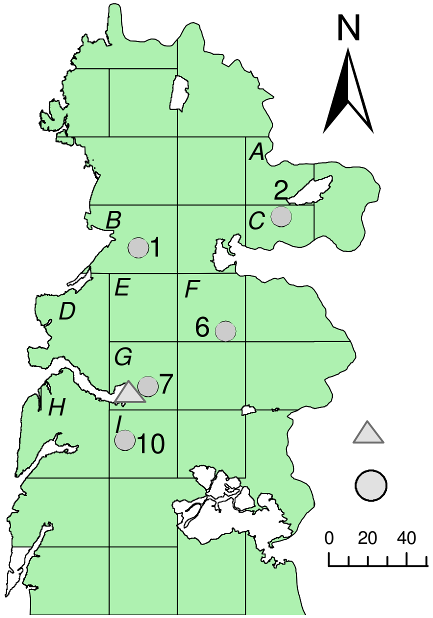
III. Calculation of the cost-optimal structure, locations and capacities

- Application of the ECLIPTIC Model:

  Modeling of **E**nergy **C**onversion and **L**ocal framework for the **I**ntegrated **P**lanning of **T**ransportation, **I**nvestment and **C**apacities
- Consideration of the presented technical and economical aspects

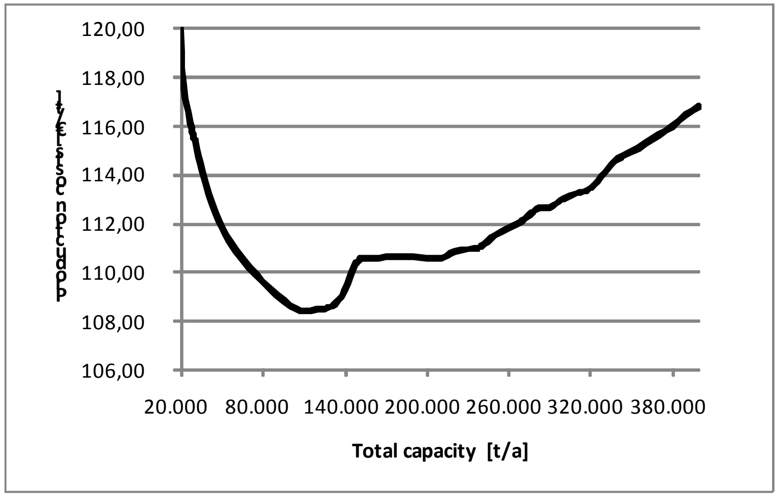


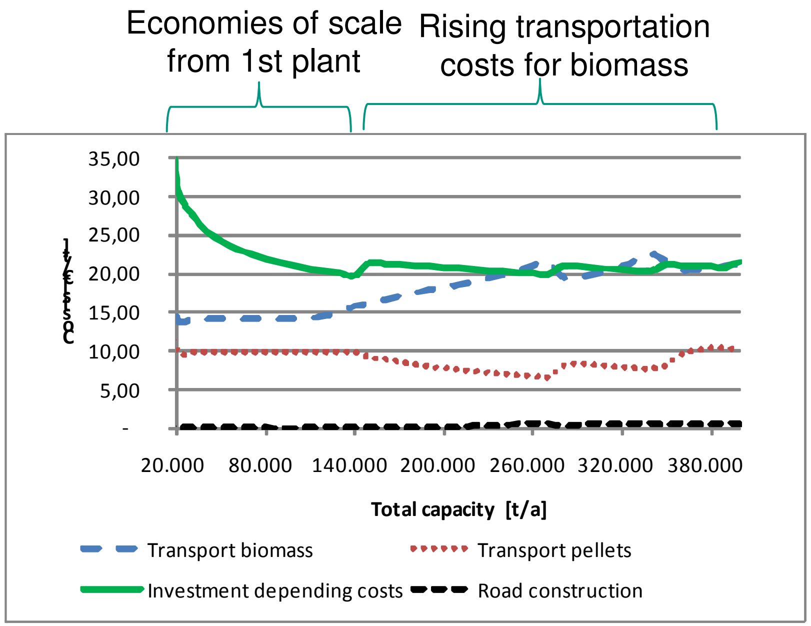
Results: Pellet production in Aysén, Chile



No separation of production steps

Number	Steps	Max. capacity [t]	Installation overall capacity [t]	Sources
10	1+2	140,000	0	H, I
7	1+2	141.342	140,000	G, D, E
1	1+2	47,252	280,000	B
2	1+2	63,994	350,000	A, C
6	1+2	29,553	400,000	F





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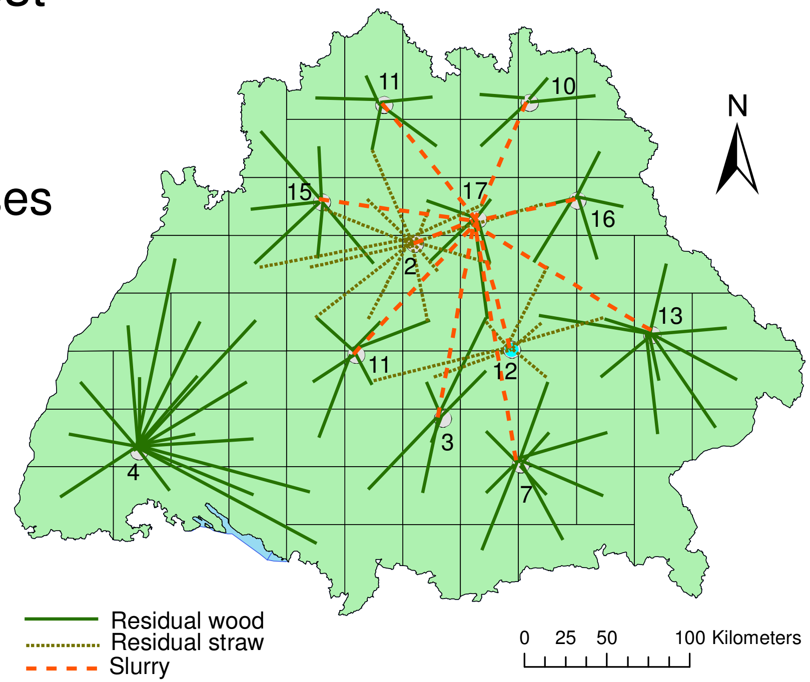
Results: Biofuel production in South Germany

- Central plant for wood from Black Forest
  - All 3 production steps
  - 94,893 t biofuel
  - Drying of biomass with energy surpluses
  - Selling of 9,7 MW_{el}



- Decentral system in Bavaria
  - 1 central location
    - all production steps
    - reaches maximum truck arrivals
    - 239,107 t biofuel
  - 10 locations with production step 1 and 2
    - 8 pyrolysis plants for wood, 2 for straw
    - Smallest : 102,000 t slurry, biggest : 251,000 t slurry
  - Energy
    - 64,742 tons wood burned for drying
    - 91 MW_{el} sold at central location, 46,6 MW_{el} bought at decentral locations

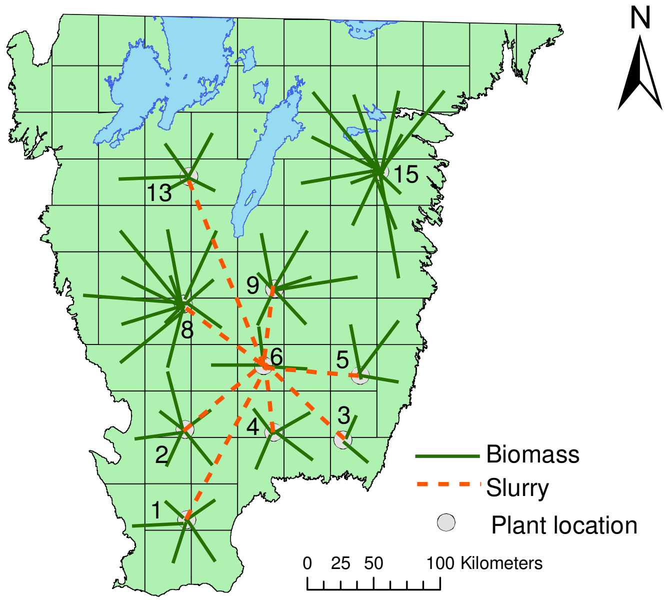
Biofuel production in South Sweden

- Only wood utilized
- 2 locations less than in South Germany
- No biomass from the north and between the lakes
- Three plants meet transportation limit (6,8,15)

- Two independent parts
  - Central plant for wood in the north-west
  - Decentral system in the middle

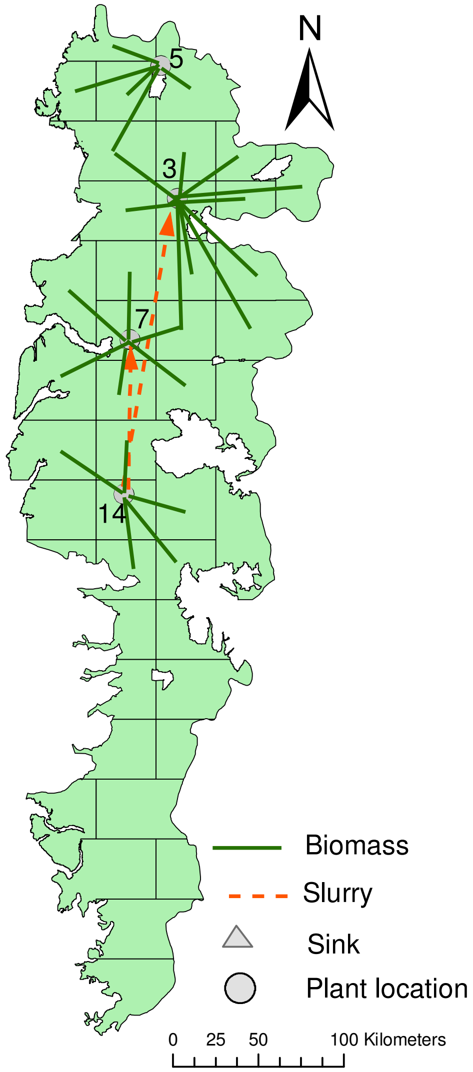
- Pyrolysis plant at location 8 processes 30% of the biomass

- Energy compared to South Germany
  - More energy for drying (no straw utilized)
  - → Less electric energy sold
  - Less electric energy bought at decentral locations (smaller capacities)



Biofuel production in Aysén, Chile

- No utilization of biomass from the south of Aysén
  - Very poor infrastructure
  - Long distance to the sink
- Only 4 production sites
  - 3 locations with all production step
  - 1 preparation and pyrolysis location
- Plants at location 3 and 7
  - Nearest to sink
  - 80 % of total capacity
  - Maximum transportation
  - Slurry delivery from the decentral pyrolysis plant
- Plant 5 uses high biomass density in the north
- Energy
  - High thermal demands (water content)
  - → Huge amounts of waste heat used for drying
  - → More central structure with higher transportation costs



Comparison of specific costs

- Biomass acquisition: lowest costs in Chile
- Biomass transportation: highest costs in Chile
- Slurry transportation : lowest in Chile due to central structure
- Investment depending costs: highest in Chile
  - Drying of biomass
  - Less economies of scale (lower capacities)

→ Highest production costs in Chile

→ Consideration of the impact of local framework conditions in Germany, Sweden and Chile

→ Delivering production costs, number, locations and capacities of production sites as well as structure of the production network.

[€/t biofuel]	South Germany	South Sweden	Aysén
Biomass acquisition	430.1	418.5	326.2
Transportation:			
Wet biomass	137.5	105.9	261.5
Slurry	54.1	44.5	19.5
Biofuel	14.5	16.5	21.8
Road construction	-	-	5.5
Investment depending	664.0	659.8	780.9
Water and waste water	24.2	24.2	24.2
Slag disposal	1.0	0.8	1.3
Electric energy	-37.9	-22.4	21.8
Total costs	1,287.5	1,247.8	1,457.1

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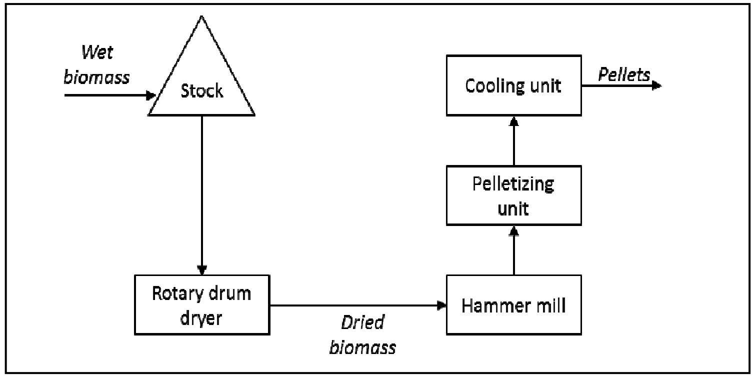
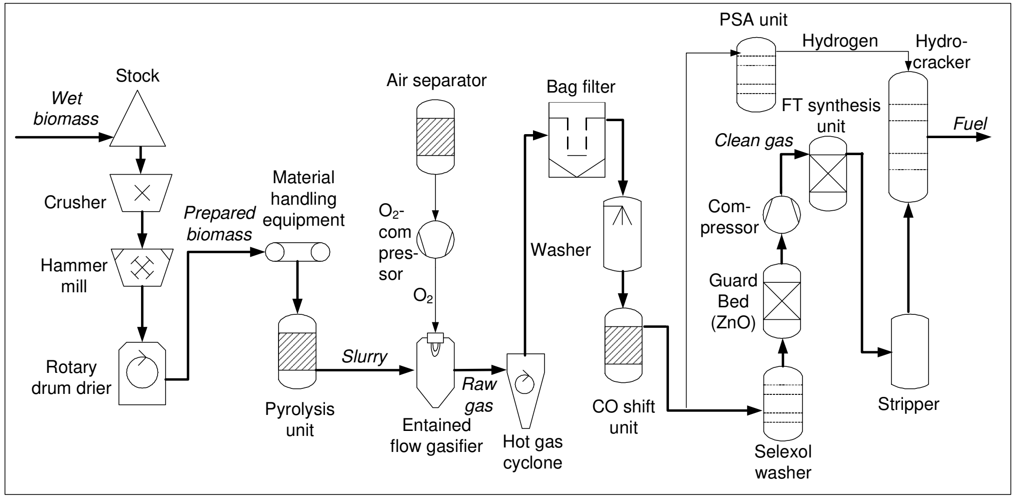
Data

Technical figures

Pellet production



Biofuel production



Important technical figures

Process unit	[t output/t input]	E_{el} [MWh/ t input]
Size reduction	1.000	0.02647
Drying	0.745	
Pyrolysis	0.72	0.135
Gasifier	0.480	0.2604
Cyclone	0.983	
Bag filter	0.995	
CO shift	1.148	
Selexol washer	0.415	
Guard bed	1.000	
FT Synthesis and stripper	0.747	

Biomass potentials

- Consideration of residual forest and residual straw in Eupope
  - Most important, today available types of biomass
- Corine Land Cover vector data of the European Environment Agency
  - Forest: broad-leaved, coniferous, mixed forest
  - Straw: non-irrigated arable land
- Aysén
  - Native forest is only partly cultivated
  - Strong legal limitations
  - Estimation of available wood basing growth and mortality rates of trees

	South Germany	South Sweden	Aysén Chile
Fraction grain fields of arable land	58%	38%	
Yield [t / ha]	5.5	3.51	
Straw generation ratio	1.3	1.3	
Fraction for animal feeding and soil stabilization	0.22	0.22	
Residual straw [T t/a]	2,613	0,535	
Water content	15%	15%	
Forest [km²]	38,12	60,34	48,16
Fraction protected area of forest	-	-	43%
Usable forest wood [t / ha]	0.72	0.72	2.56
Biomass from forests [T t/a]	2,712	4,360	3,645
Water content after drying at fresh air	35%	35%	60%

[Kappler 2008, Hamelinck et al. 2003]

Regional economic data

- Transportation costs on existing roads
- Road construction in Chile
  - Road from source to road network when biomass from the cell is utilized
  - Construction costs (amortization, interests, maintenance): 2.620 €/km
- Limitation of truck arrivals and departures to 20 per hour to prevent unrealistic frequency
- Further costs
  - Biomass acquisition (labor, interests, amortization, storage)
  - Investment depending (interests, amortization, maintenance, repair, assurance, taxes, administration, labor)
  - Disposal of waste
  - Auxiliary materials, electricity

Biomass		Europe	Chile
Wood	Fix [€/t]	2.34	4.60
	Var. [€/(t*km)]	0.13	0.2
Straw (15% H_2O)	Fix [€/t]	12,92	-
	Var. [€/(t*km)]	0,15	-
Liquid	Fix [€/t]	1,9	4.57
	Var. [€/(t*km)]	0.08	0.13

Cost category		Europe	Chile
Wood acquisition	[€/t dry substance]	83	45.13
Straw acquisition	[€/t dry substance]	63	-
Investment depending costs	[% of investment]	15.5	15.1

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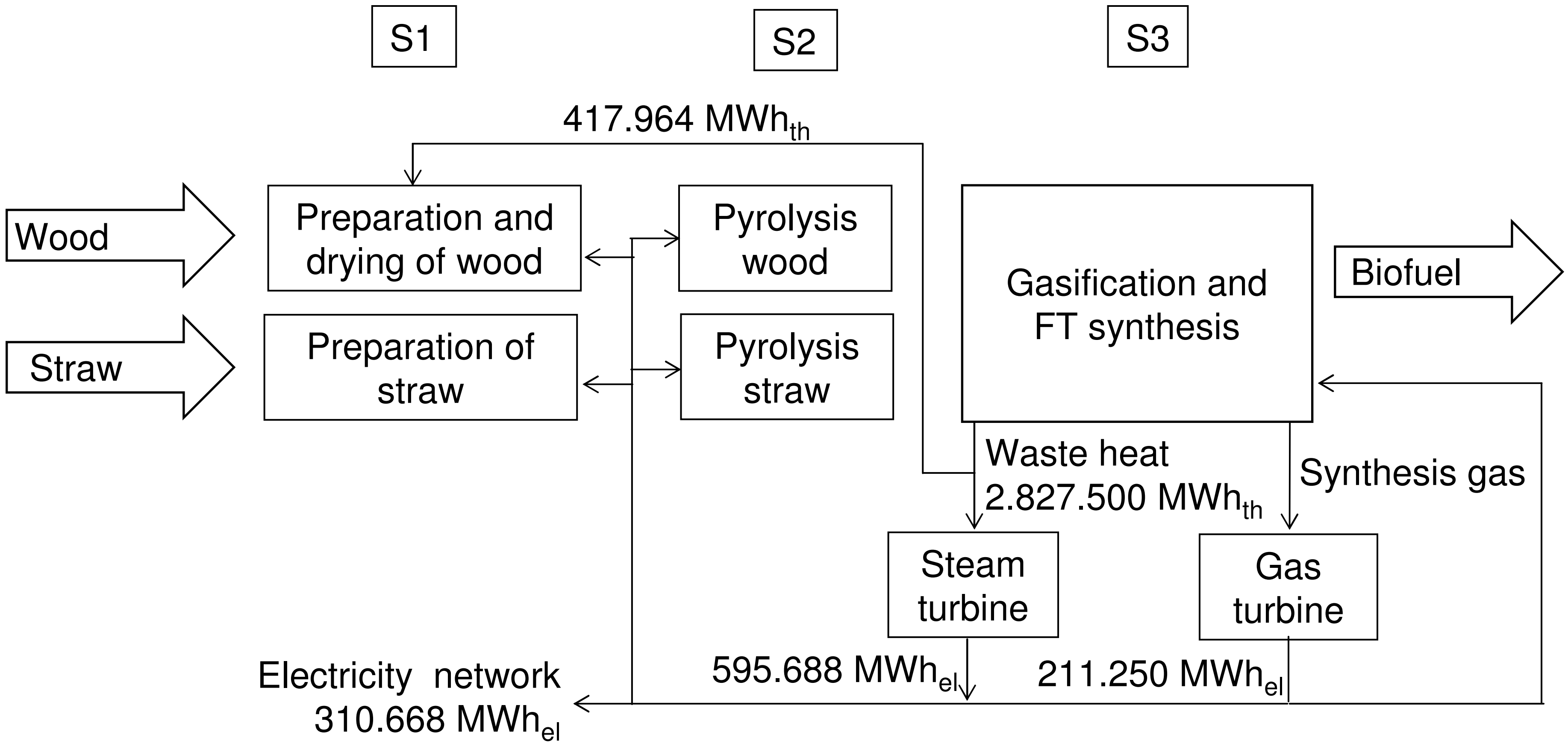
Energy

Results from the energy balances

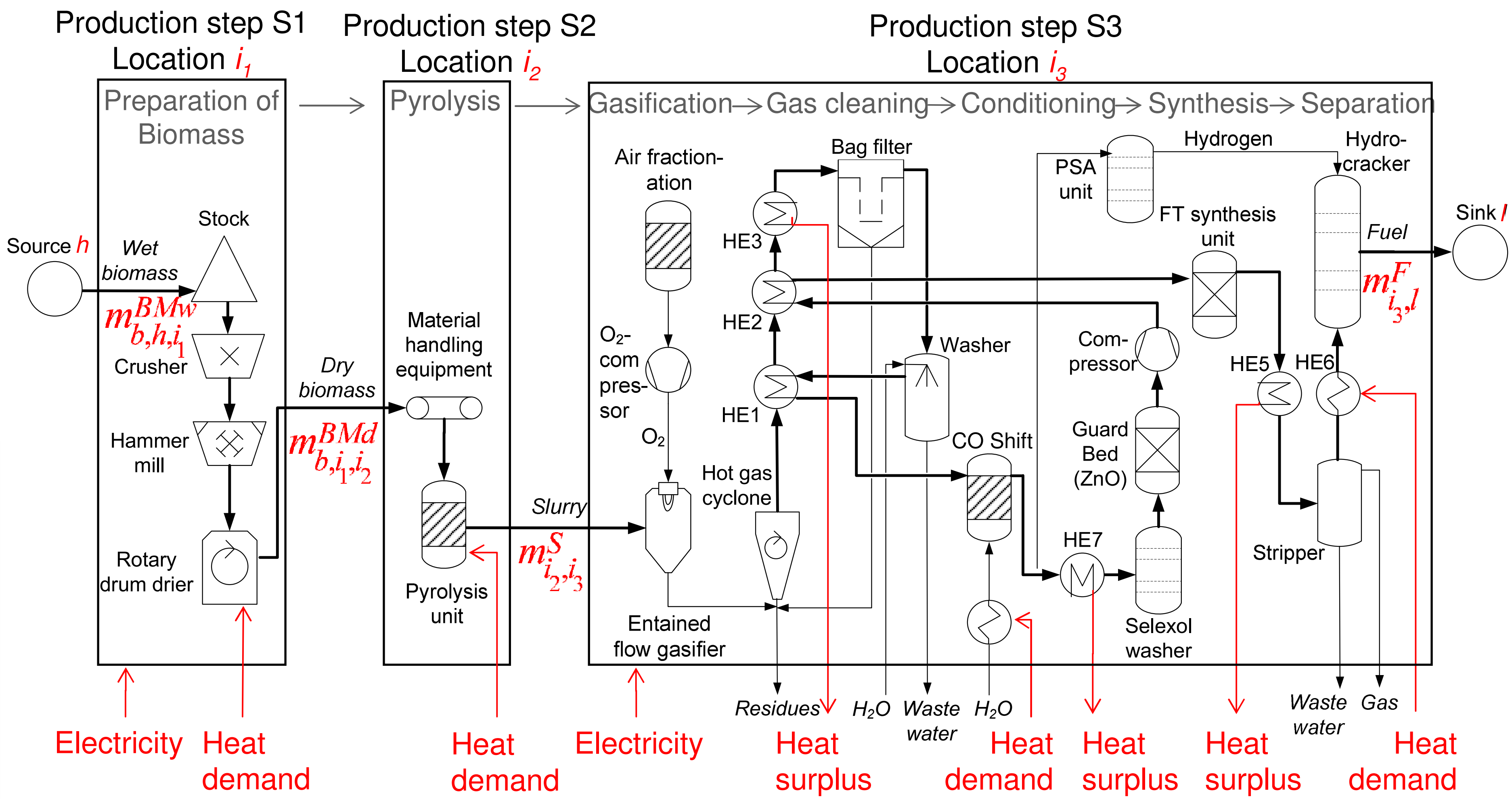
- Integrated location (No.2)



- Decentral plants for straw: 55.620 MWh_{el} from the electricity network

ECLIPTIC

Process flowsheet and model structure



Modelling of the energy provision for plants

- Electric and thermal energy demands and surpluses [MWh]
  - Estimation with specific energy demands of the main units

$$E_{i,e}^{De} = \sum_{b=1}^{B}\sum_{h=1}^{H}\sum_{u\in\Upsilon^{S1}} \gamma_{b,u,e}^{S1,De}\cdot m_{b,h,i}^{BMw} + \sum_{b=1}^{B}\sum_{i_1=1}^{I}\sum_{u\in\Upsilon^{S2}} \gamma_{b,u,e}^{S2,De}\cdot m_{b,i_1,i}^{BMd} + \sum_{i_2=1}^{I}\sum_{u\in\Upsilon^{S3}} \gamma_{u,e}^{S3,De}\cdot m_{i_2,i}^{S}$$

$\forall i \in \{1, ..., I\} \quad \forall e \in \{th, el\}$

$u \in \Upsilon^{s}$ Main units of $s \in \{S1, S2, S3\}$

  - Analogical for energy surpluses
  - Formulation of energy balances
    - Utilization of the energy surpluses!
    - Covering of the energy demands!

- Facilities for the provision of energy (ST, SG, GT, PP)
  - Energy balances under consideration of degrees of efficiency
  - Assumption: biomass is used as fuel for the power plant
  - Calculation of capacities *P* [MW] in order to estimate investments

Estimation of investments (Ex: Production step S1)

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$$I_i^{S1} = \underbrace{\sum_{u \in \Upsilon^{S1}} \sum_{b=1}^{B} I_u^{basis} \cdot \left(\frac{\kappa_{b,i,u}^{target}}{\kappa_u^{basis}}\right)^{R_u}}_{\text{Investments for main units}} \cdot \underbrace{\left(1 + A_u \cdot \left(\frac{\kappa_{b,i,u}^{A,target}}{\kappa_u^{A,basis}}\right)^{R_u^A}\right)}_{\text{Direct subitems}} \cdot \underbrace{(1+B)}_{\text{Indirect subitems}} \quad \forall i \in \{1, ..., I\}$$

Investments for main units

→ Concave, strictly monotonic increasing function of the capacity with $R_u \geq 0$

Direct subitems

→Convex, strictly monotonic decreasing function of the capacity with $R_u^A \leq 0$

Indirect subitems

→ Depend linear on the investments battery limits

with $\kappa_{b,i,u}^{target} = \sum_{h=1}^{H} \alpha_{b,u}^{S1} \cdot m_{b,h,i}^{BMw}$

$$= \sum_{u \in \Upsilon^{S1}} \sum_{b=1}^{B} I_u^{basis} \cdot \left(\frac{\alpha_{b,u}^{S1}}{\kappa_u^{basis}}\right)^{R_u} \cdot (1+B) \cdot \left(\left(\sum_{h=1}^{H} m_{b,h,i}^{BMw}\right)^{R_u} + A_u \cdot \left(\frac{\alpha_{b,u}^{A,S1}}{\kappa_u^{A,basis}}\right)^{R_u^A} \cdot \left(\sum_{h=1}^{H} m_{b,h,i}^{BMw}\right)^{R_u^A + R_u}\right) \quad \forall i \in \{1, ..., I\}$$

I_u^{basis}	Basis investment
κ_u^{basis}, $\kappa_u^{A,basis}$	Basis capacity
$\kappa_{b,i,u}^{target}$, $\kappa_{b,i,u}^{A,target}$	Target investment
$\alpha_{b,u}^{S1}$, $\alpha_{b,u}^{A,S1}$	Conversion factors

Approach: Piecewise linear approximation

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- Supporting points $n_{g_{S1}}^{S1}$ with $g_{S1} \in \{0, ..., G_{S1}\}$ and weights $z_{b,i,g_{S1}}^{S1} \in [0;1]$
- Approximation with $\sum_{g_{S1}=0}^{G_{S1}} z_{b,i,g_{S1}}^{S1} = 1$

$$\sum_{h=1}^{H} m_{b,h,i}^{BMw} - \left(\sum_{g_{S1}=0}^{G_{S1}} n_{g_{S1}}^{S1} \cdot z_{b,i,g_{S1}}^{S1} \right) \cdot \kappa_b^{max,S1}$$

$$\left(\sum_{h=1}^{H} m_{b,h,i}^{BMw} \right)^{R_u} \approx \left(\sum_{g_{S1}=1}^{G_{S1}} (n_{g_{S1}}^{S1})^{R_u} \cdot z_{b,i,g_{S1}}^{S1} \right) \cdot \left(\kappa_b^{max,S1} \right)^{R_u}$$

$\forall i \in \{1, ..., I\}$
$\forall b \in \{1, ..., B\}$

- Special ordered sets of type 2
  - $G_{S1} - 1$ binaries $\mu_{b,i,g_{S1}}^{S1} \in \{0, 1\}$ with $\sum_{g_{S1}=0}^{G_{S1}-1} \mu_{b,i,g_{S1}}^{S1} = 1$
  - No plant / minimum capacity

    $$z_{b,i,g_{S1}}^{S1} \le \mu_{b,i,g_{S1}}^{S1} \quad \forall b \in \{1, ..., B\} \quad \forall i \in \{1, ..., I\} \quad \forall g_{S1} \in \{0, 1\}$$
  - Plants between minimum and maximum capacity

    $$z_{b,i,g_{S1}}^{S1} \le \mu_{b,i,g_{S1}-1}^{S1} + \mu_{b,i,g_{S1}}^{S1} \quad \forall b \in \{1, ..., B\} \quad \forall i \in \{1, ..., I\} \quad \forall g_{S1} \in \{2, ..., G_{S1} - 1\}$$
  - Maximum capacity

    $$z_{b,i,g_{S1}}^{S1} \le \mu_{b,i,g_{S1}-1}^{S1} \quad \forall b \in \{1, ..., B\} \quad \forall i \in \{1, ..., I\} \quad g_{S1} = G_{S1}$$

[Nemhauser and Wolsey 1988]
[Beale and Tomlin 1970]

Zielfunktion: Kostenminimierung

- Betriebsmittelverbrauchsabhängige Kosten
  - Biomasseerfassung und –transport

$$\sum_{b=1}^{B}\sum_{h=1}^{H}\sum_{i_1=1}^{I}\left(c_b^{BM}+c_b^{Tfix,BM}+c_b^{Tvar,BM}\cdot d_{h,i_1}\right)\cdot m_{b,h,i_1}^{BMw}$$

$$+\sum_{b=1}^{B}\sum_{h=1}^{H}\sum_{\substack{i_1=1\\h=i_1}}^{I}\sqrt{\frac{A_h^{Total}}{\pi}}\cdot 0.7\cdot c_b^{Tvar,BM}\cdot m_{b,h,i_1}^{BMw}$$

  - Transport von vorbehandelter Biomasse, Slurry und Kraftstoff
  - Kosten für Wasser, Abwasser und Reststoffe
  - Kosten und Erlöse elektrische Energie

$$\sum_{i=1}^{I}\left(F_i^{Net\to MU,el}\cdot c^{el}-\left(F_i^{ST\to Net,el}+F_i^{GT\to Net,el}\right)\cdot p^{el}\right)\cdot 1000$$

- Investitionsabhängige Kosten

$$\sum_{r=1}^{R}a_r\cdot\sum_{i=1}^{I}\left(I_i^{S1}+I_i^{S2}+I_i^{S3}+I_i^{PP}+I_i^{ST}+I_i^{GT}+I_i^{SG}\right)$$

Weitere Nebenbedingungen

- Stoffumwandlung mit Umwandlungskoeffizienten, z.B. Pyrolyse

$$H^{op} \cdot \sum_{b=1}^{B} \sum_{i_1=1}^{I} \beta_b^{S2} \cdot m_{b,i_1,i}^{BMd} = \sum_{i_3=1}^{I} m_{i,i_3}^{S} \qquad \forall i \in \{1, ..., I\}$$

- Biomassepotential

$$\sum_{i=1}^{I} m_{b,h,i}^{BMw} \leq A_{b,h} \cdot \epsilon_b \qquad \forall b \in \{1, ..., B\} \quad \forall h \in \{1, ..., H\}$$

- Kraftstoffdistribution, z.B. nach Einwohner pro Senke Inh_l

$$\sum_{i=1}^{I} m_{i,l}^{F} = \left(\sum_{i=1}^{I} \sum_{l'=1}^{L} m_{k,l'}^{F} \right) \cdot \frac{Inh_l}{\sum_{l'=1}^{L} Inh_{l'}} \quad \forall l \in \{1, ..., L\}$$