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Bioenergy yield from cultivated land in Denmark – competition between food, bioenergy and fossil fuels under physical and environmental constraints

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Carlsberg Academy, Copenhagen, Denmark
Bioenergy past

Danish Energy Agency, 2006
Renewable energy future

Danmarks energifremskrivning frem til 2030
[Energy projection to 2030]
Danish Energy Agency, 2009
Domestic bioenergy?

• What is the potential biomass supply in PJ yr\(^{-1}\)?
• What is the monetary cost?
• Energy efficiency?
• Land availability and suitability for annual crops, short rotation forest (willow) and plantation spruce forest?
• Consequences for nitrogen load
Model overview

Cultivation
- Starch crops
- Oil crops
- Sugar crops
- Grass crops
- Willows (SRF)
- Forest

Conversion
- Ethanol 57%
- Heat/CHP 90%
- RME 70%
- 1G/2G ethanol 54%
- Biogas 54%
- Biogas 54%
- Heat/CHP 81%
- Heat/CHP 69%

Substitution of fossil fuels

Nitrogen load:
- \( \text{N}_2\text{O} \)
- \( \text{NO}_3^- \)
Model parameters

- Denmark, total area 4309 kha
- Amounts and costs of seeds, machine operations, pesticides, fuels, fertilisers and lime.
- Bioenergy conversion types: district heating, heat and power, biogas, biodielsel (RME), bioethanol (data from AEBIOM, 2005)
Minimize fuel cost

• Cost minimization model
• Linear programming – a technique developed within operations research
• Objective function: \( \text{Min } Y = cX \)
• Constraints: \( aX \leq b, X \geq 0, X \sim X_1 \cdots X_n \)

• Energy mix of bioenergy and diesel oil

\[
\min_a \sum_i \left\{ p_{ic(oil)} \times x_{itc} \times a_{it} + p_{oil} \times (E - E_{bio}) \right\}
\]

\( a \sim \text{area, } i \sim \text{crop representative, } c \sim \text{commodity, } t \sim \text{soil type, } \text{oil} \sim \text{oil price} \)
Model constraints I

• Physical
  – Cultivated land area 3200 kha (2005)
  – Forest area: 600 kha
  – Soil types: 48% sandy, 52% loamy

• Agronomy – crop rotations
  – e.g. oilseed rape every 4 years~max 25%

• Environmental: biodiversity ~area reservation for permanent grassland, limits on willow area
Oil price and commodity prices

• Oil price range from index 25 to index 200
  – Index 100 ~2005~9.4€ GJ$
## Scenario constraints

### Scenario A

<table>
<thead>
<tr>
<th>Type</th>
<th>Model constraints</th>
<th>Physical Cultivated land</th>
<th>Physical Minimum forest area</th>
<th>Physical Maximum forest area PK 8</th>
<th>Physical Maximum forest area PK 12</th>
<th>Landscape Permanent grass (out of rotation)</th>
<th>Landscape Maximum area of annual crops and SRF area</th>
<th>Soil quality JB 1-3 + JB 11 (humus) of land area.</th>
<th>Soil quality JB 4-10 and 12 (calcareous) of land area.</th>
<th>Crop rotation Rape seed area of annual crop land (loamy)</th>
<th>Crop rotation Rape seed area of annual crop land (sandy)</th>
<th>Landscape Minimum share of clover grass, in rotation</th>
<th>Landscape Maximum area of SRF (willow), kha</th>
<th>Crop rotation Area limitation on sugar beet (and soil quality)</th>
<th>Landscape and biodiversity Crop mix, annual crops, sandy soils</th>
<th>Landscape and biodiversity Crop mix, annual crops loamy soils</th>
<th>Ground water N leaching (k t N/yr)</th>
<th>GHG N2O emission from cultivated land (kt N2O-N/yr)</th>
<th>Carbon balance - soil humus Straw for feed/animal husbandry</th>
<th>Social Timber/construction wood</th>
<th>Social Wheat grain reserved for food and feed, PJ</th>
<th>Social Oil seed rape reserved for food and feed, PJ</th>
<th>Social Sugar beets for sugar production, PJ</th>
<th>Social Grass for feed, PJ</th>
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<td><strong>Type</strong></td>
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<td><strong>6</strong></td>
<td><strong>11</strong></td>
<td><strong>38</strong></td>
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</tbody>
</table>

### Scenario B

- **Food & feed 50% of scenario A**
- **Willow < 25% area**
- **Permanent grass 275 kha**
Crop yields

Net energy harvest yield

- W-wheat, sandy
- W-wheat, loamy
- Oilseed rape, sandy
- Oilseed rape, loamy
- Sugar beet
- Grass/clover
- Willow, sandy
- Willow, loamy
- Spruce, low yield
- Spruce, avg. Yield

GJ ha⁻¹ Yr⁻¹
Energy output:input ratio

- W-wheat, sandy
- W-wheat, loamy
- Oilseed rape, sandy
- Oilseed rape, loamy
- Sugar beet
- Grass/clover
- Willow, sandy
- Willow, loamy
- Spruce, low yield
- Spruce, avg. Yield
Biomass feedstock cost

- Rape, sandy: 25.0 €/GJ
- Wheat, sandy: 20.0 €/GJ
- Sugar beet: 15.0 €/GJ
- Rape, loamy: 10.0 €/GJ
- Wheat, loamy: 5.0 €/GJ
- Wood, sandy: 0.0 €/GJ
- Wood, average: 0.0 €/GJ
- Willow, sandy: 0.0 €/GJ
- Willow, loamy: 0.0 €/GJ
- Diesel oil index (2005=100)
Bioenergy yield

Scenario/ oil index

100%food&feed 50%food&feed

- Biogas
- RME
- Ethanol
- CHP

100% food & feed
50% food & feed
Nitrogen load from cultivated land

- Reduction in N use and thus in N leaching and in N$_2$O losses

[Graph showing nitrogen load from cultivated land with labels for nitrogen use, NO3-N leaching, and N2O-N emission.]
## Bioenergy future scenarios

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<td>PJ yr⁻¹</td>
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<td><strong>Current</strong></td>
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<td><strong>Scenario</strong></td>
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<td><strong>EEA, 2006</strong></td>
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<td>2010</td>
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<td>2030</td>
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<td>92</td>
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<td><strong>Our study, Oil index 100</strong></td>
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<td>100%FF</td>
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<td>53</td>
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<tr>
<td>50%FF</td>
<td>6</td>
<td>125</td>
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</tbody>
</table>
Biomass in EU27

Potential self sufficiency (2030 supply vs 2005 consumption)

Total: 8 – 25 EJ yr⁻¹

After deWit et al. 2009, figure 6, Biomass & bioenergy
The Refuel project, www.refuel.eu
Conclusion

- More biomass for bioenergy at increasing oil prices
- Domestic bioenergy potentials are limited due to land and environmental constraints (~20% of primary energy use)
- Increased biomass imports necessary to meet strategic goals of bioenergy supply
- Large N load reductions possible by growing more short rotation forest (willow) or by planting high forest
More about the model

Optimization of bioenergy yield from cultivated land in Denmark

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