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

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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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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
  - Grassy crops
  - Willow (SRF)
  - Forest

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

- 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, biodiesel (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: \( aX \leq b, X \geq 0, X \sim X_1 - X_n \)

- Energy mix of bioenergy and diesel oil

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

\(a\sim\text{area}, i\sim\text{crop representative}, c\sim\text{commodity}, t\sim\text{soil type}, oil\sim\text{oil price}\)
| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
| 03 | Social | Glazed cups revenue (farm land and fed. P) | 6 | 6 | 6 | 6 | FALSE | FALSE | FALSE | FALSE |
| 04 | Social | Sugar beet revenue (farm land and fed. P) | 11 | 11 | 11 | 11 | FALSE | FALSE | FALSE | FALSE |
| 05 | Social | Green Fruits revenue (farm land and fed. P) | 38 | 38 | 38 | 38 | FALSE | FALSE | FALSE | FALSE |
| 06 | Political | Incentive payments | 0 | 0 | 0 | 0 | 108 | 108 | 108 | 108 |
| 07 | Incentive payments | | 0 | 0 | 0 | 0 | 108 | 108 | 108 | 108 |

**Solve Parameters**

**Set Target Cell:** B217

**Equal To:** Max

**Objective of:** value of: 0

**By Changing Cells:** G143, H143, F91

**Subject to the Constraints:**

**Subject to:**

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**Options:** P500, P25, P25, P25

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**Options:** P500, P25, P25, P25

**Add:** P500, P25, P25, P25

**Options:** P500, P25, P25, P25
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$^{-1}$
## Scenario constraints

### Type Model constraints

<table>
<thead>
<tr>
<th>Type</th>
<th>Model constraints</th>
<th>P100</th>
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<tbody>
<tr>
<td>Physical</td>
<td>Cultivated land</td>
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<tr>
<td>Physical</td>
<td>Minimum forest area</td>
<td>600</td>
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<tr>
<td>Physical</td>
<td>Maximum forest area PK 8</td>
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<tr>
<td>Physical</td>
<td>Maximum forest area PK 12</td>
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<tr>
<td>Landscape</td>
<td>Permanent grass (out of rotation)</td>
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<tr>
<td>Landscape</td>
<td>Maximum area of annual crops and SRF area</td>
<td>2425</td>
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<tr>
<td>Soil quality</td>
<td>JB 1-3 + JB 11 (humus) of land area</td>
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<td>Soil quality</td>
<td>JB 4-10 and 12 (calcareous) of land area</td>
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<tr>
<td>Crop rotation</td>
<td>Rape seed area of annual crop land (loamy)</td>
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<tr>
<td>Crop rotation</td>
<td>Rape seed area of annual crop land (sandy)</td>
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<tr>
<td>Landscape</td>
<td>Minimum share of clover grass, in rotation</td>
<td>200</td>
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<tr>
<td>Landscape</td>
<td>Maximum area of SRF (willow), kha</td>
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<tr>
<td>Crop rotation</td>
<td>Area limitation on sugar beet (and soil quality)</td>
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</tr>
<tr>
<td>Landscape and biodiversity</td>
<td>Crop mix, annual crops, sandy soils</td>
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<tr>
<td>Landscape and biodiversity</td>
<td>Crop mix, annual crops loamy soils</td>
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<tr>
<td>Ground water</td>
<td>N leaching (k t N/yr)</td>
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<td>GHG</td>
<td>N2O emission from cultivated land (kt N2O-N/yr)</td>
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<tr>
<td>Carbon balance - soil humus</td>
<td>Straw for feed/animal husbandry</td>
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<tr>
<td>Social</td>
<td>Timber/construction wood</td>
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<tr>
<td>Social</td>
<td>Wheat grain reserved for food and feed, PJ</td>
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<tr>
<td>Social</td>
<td>Oil seed rape reserved for food and feed, PJ</td>
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<tr>
<td>Social</td>
<td>Sugar beets for sugar production, PJ</td>
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<tr>
<td>Social</td>
<td>Grass for feed, PJ</td>
<td>38</td>
</tr>
</tbody>
</table>

### Scenario A

**Food & feed 100% (=2005)**

- Willow < 0.2% area
- Permanent grass 175 kha

### Scenario B

**Food & feed 50% of scenario A**

- Willow < 25% area
- Permanent grass 275 kha
### Crop yields

#### Net energy harvest yield

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>GJ ha⁻¹·Yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-wheat, sandy</td>
<td>50</td>
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<tr>
<td>W-wheat, loamy</td>
<td>100</td>
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<tr>
<td>Oilseed rape, sandy</td>
<td>150</td>
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<tr>
<td>Oilseed rape, loamy</td>
<td>200</td>
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<tr>
<td>Sugar beet</td>
<td>250</td>
</tr>
<tr>
<td>Grass/clover</td>
<td>300</td>
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<tr>
<td>Willow, sandy</td>
<td>100</td>
</tr>
<tr>
<td>Willow, loamy</td>
<td>150</td>
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<tr>
<td>Spruce, low yield</td>
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<tr>
<td>Spruce, avg. Yield</td>
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</tbody>
</table>

[Diagram showing net energy harvest yield for various crop types.]
Crop area distribution

(a) 100% food&feed
(b) 50% food&feed

- Fallow + set-aside
- Wood, average
- Wood, sandy
- Willow, loamy
- Willow, sandy
- Clover grass (rotation)
- Sugar beet
- Rape, loamy
- Rape, sandy
- Wheat, loamy
- Wheat, sandy

Land area, kha

Oil index (2005=100)
Bioenergy yield

Scenario/ oil index

100%food&feed

50%food&feed

25 50 75 100-150 160-190

25 50 75-130 140-160 170-190

Pl yr⁻¹

0 20 40 60 80 100 120 140 160 180

Biogas
RME
Ethanol
CHP

100%food&feed
50%food&feed

DTU
Nitrogen load from cultivated land

- Reduction in N use and thus in N leaching and in N$_2$O losses
## Bioenergy future scenarios

<table>
<thead>
<tr>
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<th>FOR</th>
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<td><strong>Jørgensen, 2008</strong></td>
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<tr>
<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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<tr>
<td>2010</td>
<td>17</td>
<td>4</td>
<td>96</td>
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<td>2030</td>
<td>4</td>
<td>8</td>
<td>92</td>
<td>105</td>
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<tr>
<td><strong>Our study, Oil index 100</strong></td>
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<tr>
<td>100%FF</td>
<td>0</td>
<td>21</td>
<td>32</td>
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<tr>
<td>50%FF</td>
<td>6</td>
<td>125</td>
<td>18</td>
<td>149</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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