Optimal design of a future hydrogen supply chain using a multi-timescale, spatially-distributed model

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Energy Systems Engineering

Development of integrated energy system models

- Energy conversion technologies
- Supply infrastructure
- Temporal and spatial characteristics
- Strategic and operational aspects

Examples

1. Hydrogen Supply Chain (HSC) model

2. Biomass Value Chain Model (BVCM)
   - Potential of producing hydrogen from biomass
HSC model elements: spatial layout

- Great Britain is divided into 34 grid squares of equal sizes
HSC model elements: time

- Modelled using hierarchical non-uniform time discretisation

Five 6-year periods

- 6 identical years in a period
- 4 seasons in a year
- 13 identical weeks in a season
- 7 days in a week
- Four 6-hour periods in a day
HSC model elements

**Raw materials**
- Natural gas
- Coal
- Biomass
- Electricity

**Production technologies**
- Steam methane reforming
- Coal gasification
- Biomass gasification
- Electrolysis

**Form**
- Liquid hydrogen
  - Tanker truck
  - Railway tanker car
  - Liquid hydrogen storage
  - Tanker truck
  - Railway tanker car

**Primary distribution**
- Compressed gaseous hydrogen
  - Tube trailer
  - Railway tube car
  - Compressed hydrogen gas storage
  - Tube trailer
  - Railway tube car

**Storage facilities**
- Pipeline
  - Pipeline

**Secondary distribution**
- Fuelling stations (liquid)
  - Fueling stations (gas)

**Dispensing technologies**
Case study: Possible optimal network structure

Summer 2015-2020

Summer 2039-2044

- Rail transport
- Truck transport
- No. of storage facilities
- No. of production plants
- Location of existing facilities
Snapshot of London and the South East (grid 29) in 2039-2044

1-year hydrogen inventory profile

Week
Hydrogen production from renewables

Solar Energy

- Wind/Geothermal/Ocean/Hydro
- Photovoltaics

Mechanical energy
- Concentrated solar power

- Thermolysis

- Electricity

Biomass
- Biochemical
- Thermochemical

Conversion

- Electrolysis

- Photolysis

Hydrogen
Biomass Value Chain Model (BVCM)

- Can be used to understand how bioenergy systems can be implemented without negative sustainability-related impacts
- Models pathway-based bioenergy systems over five decades (from 2010 to 2050)
- Supports decision-making around land use, interactions with food production and acceleration of bioenergy technologies

Energy demand
Resource, technology and logistic data

Optimal bioenergy value chain structure
- allocation of crops to available land
- choice of technologies
- energy provision (electricity, heat, hydrogen, biofuels, biomethane)
- transport networks required
Model Elements: Time, Space and Climate

• **Time**
  – 5 decades
  – Up to 4 seasons per year

• **Spatial representation**
  – UK divided into 157 square cells of length 50km

• **Climate scenarios**
  – Low and medium scenarios
Model Elements: Land Use

Four levels of land “aggression”

• Level 1 as “easy, established technology”
  – Arable land
  – Heterogeneous agricultural land (e.g. Non-permanent crops associated with permanent crops)
• Level 2 as “pioneering plant establishment”
  – Shrub and/or herbaceous vegetation association, e.g. natural grassland
  – Open spaces with little or no vegetation
• Level 3 as “challenging techno-ecological and economic land use change”
  – Permanent crops, e.g. fruit trees and berry plantations
  – Pastures
• Level 4 as “last resort”
  – Forests
  – Artificial non-agricultural vegetated areas (e.g. green urban areas and parks)
Model Elements: Bioresources

- Biomass data (yield, cost, and emissions) have been typically estimated at high resolution (1x1km)
- High resolution data have been aggregated at a scale adequate for optimisation (50x50km)
Model Elements: Technologies

• The BVCM currently includes 72 distinct technologies, some with multiple scales:
  – pre-treatment and densification technologies
  – technologies for hydrogen production
  – technologies for liquid and gaseous fuel production
  – technologies for heat, power, and combined heat and power generation
  – waste to energy technologies
  – carbon capture and storage technologies
Model Elements: Bioresources

- Miscanthus
- Short Rotation Coppice (SRC) – Willow
- Winter wheat
- Oilseed rape
- Sugar beet
- Short Rotation Forestry (SRF)
- Long Rotation Forestry (LRF)

The BVCM currently includes 94 resources, comprising bioresources, intermediates, final products, by-products and wastes.
Example of a Resource-Technology Chain: SRC Willow

**Gaseous fuels**
- Anaerobic digestion
- Biogas upgrading
- Gasification
- Gasification + syngas
- Gasification + DME
- Gasification + H2
- Gasification + FT diesel
- Gasification + syngas fermentation
- Pyrolysis oil upgrading
- Pyrolysis oil
- Sugar extraction

**Heat & power**
- Boiler combustion (heat)
- Syngas boiler
- Biodegraded steam cycle (CHP)
- Biodegraded steam cycle (electricity)
- Co-fired steam cycle (CHP)
- Co-fired steam cycle (electricity)
- Stirling engine
- Organic Rankine cycle
- IC engine
- Gas turbine
- Dedicated biomass IGCC
- Co-fired IGCC

**Liquid fuels**
- First gen ethanol
- First gen biodiesel
- First gen butanol
- Lignocellulosic ethanol
- Lignocellulosic butanol
- Gasification + FT diesel
- Gasification + methanol catalysis
- Gasification + mixed alcohol process
- Gasification + syngas fermentation
- Pyrolysis oil upgrading
- Pyrolysis oil
- Sugar-to-diesel
- Wood-to-diesel

**Pretreatment**
- Chipping
- Pelletising
- Torrefaction
- Torrefaction + pelleting
- OI extraction
- Pyrolysis

**Legend**
- Harvested resource
- Intermediate resource
- Agricultural co-product
- Final product
- Technology
Model Elements: Logistics

- 4 transport modes: ship, road, rail, inland waterways
Pathways from biomass to hydrogen

- Reforming of methane (produced from biomass) to hydrogen
- Electrolysis using electricity produced from biomass
Key questions

• How much hydrogen can be produced from locally-available biomass resources without undermining food production?

• How much would it cost to meet the transport fuel demand using carbon neutral hydrogen from biomass?

• What is the optimal pathway to produce hydrogen from biomass?
Transport fuel demand

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Transport Fuel Demand (TWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010s</td>
<td>7.13</td>
</tr>
<tr>
<td>2020s</td>
<td>28.52</td>
</tr>
<tr>
<td>2030s</td>
<td>71.30</td>
</tr>
<tr>
<td>2040s</td>
<td>121.20</td>
</tr>
<tr>
<td>2050s</td>
<td>142.59</td>
</tr>
</tbody>
</table>
Case study 1: Hydrogen from locally-available biomass

- Maximise H\(_2\) production

- Land constraint: allocate 2% of land available in Level 1 and 15% in Levels 2-4 to bioenergy (2.35 out of 22.28 Mha)

- No import of resources abroad
Case study 1: Hydrogen from locally-available biomass (cont...)

No constraint on GHG emissions

Carbon neutral

<table>
<thead>
<tr>
<th>Year</th>
<th>Bioenergy Mix</th>
<th>Total Cost (Bn£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010s</td>
<td>10%</td>
<td>32.7</td>
</tr>
<tr>
<td>2020s</td>
<td>40%</td>
<td>73.7</td>
</tr>
<tr>
<td>2030s</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>2040s</td>
<td>90%</td>
<td>100%</td>
</tr>
<tr>
<td>2050s</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Total cost comparison:
- No constraint: Bn£ 73.7
- Carbon neutral: Bn£ 32.7
Case study 1: Hydrogen from locally-available biomass (cont...)
Case study 1: Hydrogen from locally-available biomass (cont...)

No constraint on GHG emissions

Carbon neutral
Case study 1: Hydrogen from locally-available biomass (cont...)

Land area allocated to SRC Willow and H₂ Gasification plants built

Carbon neutral case

- Total area allocated for crops
- Area for SRC Willow

- H₂ Gasification
- H₂ Gasification with CCS

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<tr>
<th>Year</th>
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<th>2020s</th>
<th>2030s</th>
<th>2040s</th>
<th>2050s</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ Gasification</td>
<td><img src="image" alt="2010s H₂ Gasification" /></td>
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<td>H₂ Gasification with CCS</td>
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Case study 1: Hydrogen from locally-available biomass (cont...)

CO2 capture, transport and sequestration, and waste utilisation

Carbon neutral case

- CO2 captured
- CO2 transport
- CO2 sequestered

Waste wood utilisation

2010s  2020s  2030s  2040s  2050s
Case study 2: 100% transport fuel demand from bio-hydrogen

<table>
<thead>
<tr>
<th>No constraint on GHG emissions</th>
<th>Carbon neutral</th>
</tr>
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<tbody>
<tr>
<td><strong>Bioenergy system costs [Bn£(2010)]</strong>&lt;br&gt;(Cumulative 2010s - 2050s)</td>
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</tr>
<tr>
<td>Crop production</td>
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</tr>
<tr>
<td>Tech. Capital</td>
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</tr>
<tr>
<td>Tech. Operation</td>
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<tr>
<td>Transport</td>
<td>Transport</td>
</tr>
<tr>
<td>Storage capital</td>
<td>Storage capital</td>
</tr>
<tr>
<td>Storage operation</td>
<td>Storage operation</td>
</tr>
<tr>
<td>Resource purchase</td>
<td>Resource purchase</td>
</tr>
<tr>
<td>Resource imports</td>
<td>Resource imports</td>
</tr>
<tr>
<td>Co-products</td>
<td>Co-products</td>
</tr>
<tr>
<td>Forestry CO2 sequestration</td>
<td>Forestry CO2 sequestration</td>
</tr>
<tr>
<td>CCS Infrastructure</td>
<td>CCS Infrastructure</td>
</tr>
<tr>
<td>Waste utilisation</td>
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</tr>
</tbody>
</table>

| Total = Bn£ 51.5 | Total = Bn£ 62.9 |

<table>
<thead>
<tr>
<th>Top 10 technology investments&lt;br&gt;(Cumulative 2010s - 2050s, excluding existing assets)</th>
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<tr>
<td>Gasification + H2 - Large</td>
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</tr>
<tr>
<td>Gasification + H2 - Medium</td>
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</tr>
<tr>
<td>Biodiesel + combustion + bio...</td>
<td>Gasification + H2 + CCS - Medium</td>
</tr>
<tr>
<td>Gasification + H2 + CCS - Large</td>
<td>Gasification + H2 + CCS - Medium</td>
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Case study 2: 100% transport fuel demand from bio-hydrogen

Carbon neutral case
What about biofuels?

Least cost, carbon neutral scenario if biofuels were to satisfy 100% of transport fuel demand

**Bioenergy system costs [Bn£(2010)]**

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost (Bn£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop production</td>
<td>7</td>
</tr>
<tr>
<td>Tech. Capital</td>
<td>27</td>
</tr>
<tr>
<td>Tech. Operation</td>
<td>0</td>
</tr>
<tr>
<td>Transport</td>
<td>0</td>
</tr>
<tr>
<td>Storage capital</td>
<td>0</td>
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<td>0</td>
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*Total = Bn£ 71.6*

**Biofuel mix**

- Naphtha
- Hydrotreated renewable jet (HRJ)
- FT jet
- FT diesel
- Butanol
- Higher alcohols
- Ethanol
- DME
- Upgraded pyrolysis oil (UPO)
- Methanol

**Top 10 technology investments**

- Gasification + methanol catalysis
- Gasification + DME
- Pyrolysis - Unique
- Gasification + pyrolysis oil upgrading
- Biorefining + H2 - CCS
- Gasification + mixed alcohol
- Mechanical Biological Treatment

**Feedstock energy mix (Total)**

- Total UK-grown
- Total imports
- Total waste
- Total energy

Energy (PJ/yr)
Conclusions

• Carbon neutral hydrogen produced from locally-available biomass can meet up to 44% of the transport fuel demand in 2050 without significant impact on food production.

• CCS technologies and waste play an important role in meeting the demands for carbon neutral hydrogen from biomass.

• SRC Willow and gasification plants will most likely be used in producing hydrogen from biomass.

• Import of resources is necessary if we are to satisfy all transport fuel demand using hydrogen from biomass.