A Survey of
International Fuel-Pellet Research

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University of Jyväskylä
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  – Quality problems
  – Pelletisation
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◆ Summary
Purpose

◆ Obtain an overview of pellet-related research
◆ Identify active research institutions, groups and key individuals in the field of pellet research
◆ To present some examples of current publications
◆ To understand the direction of research and development in the fuel-pellet industry
◆ To use the findings to strengthen the pellet R&D sector in Central Finland and in forming competitive research clusters
Scope

- Review of international pellet-related publications with a focus on raw materials and basic research
- Journal and institutional publications
- Domestic (Finnish) publications not included
Pellet-Related Recent Publications

Reviewed International Fuel-Pellet Publications
(42)

number of publications

2 4 6 8 10 12

year of publication

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

2 2 1 6 4 11 4 10 2 2
<table>
<thead>
<tr>
<th>Publication Type</th>
<th>Count</th>
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<tr>
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<td>10</td>
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<tr>
<td>Institutional Reports</td>
<td>6</td>
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<tr>
<td>Fuel Processing Technology</td>
<td>3</td>
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<td>Bioresource Technology</td>
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<td>Environmental Chemistry Letters</td>
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<td>Applied Engineering in Agriculture</td>
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<td>Forest Products Research Journal</td>
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<td>Canadian Biosystems Engineering</td>
<td>2</td>
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<td>Conference Proceedings</td>
<td>2</td>
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<td>Analytical &amp; Applied Pyrolysis</td>
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<td>American Chemical Society</td>
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<td>Energy for Sustainable Development</td>
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<td>Fuel Chemistry Division Preprints</td>
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<td>Energy</td>
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<td>Radiation Physics and Chemistry</td>
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Publication Based on Country

- CA: 10
- SE: 9
- AU: 3
- ES: 1
- FR: 2
- EU: 1
- BR: 1
- IN: 1
- NL: 6
- USA: 3
- DK: 2
- UK: 1
- BR: 1
- EU: 1
- AU: 3
- ES: 1
- FR: 2
- SE: 9
- USA: 3
- DK: 2
- UK: 1
- ES: 1
- NL: 6
Limitations of Publication Survey

- Access to journals
- Non-English publications not accessible (i.e. German speaking world)
- Networking limited (i.e. conferences & contacts)
- Limited period (3-4 months)
- Companies often conduct own research
- Conventional pellets are quite practical (i.e. recipes may not be documented externally)
Prominent Research Organisations
(based on publications)

- Biomass & Bioenergy Research Group, University of British Columbia (UBC), Vancouver, BC. Canada
- Unit of Biomass Technology & Chemistry, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
- Biomass, Coal & Environmental Research Unit, Energy Research Centre of the Netherlands (ECN), Petten, the Netherlands
- Institute for Resource Efficient & Sustainable Systems, Graz University of Technology, Graz, Austria
Scope of Research

Raw Materials
- Various types
- Additives
- Acquisition
- Pre-treatment

Pelletisation
- Theory & modelling
- Pellet mill design
- Combined processes
- Economics

Combustion &c.
- Storage
- Durability
- Emissions
- Boiler types
- Small vs. Large-scale
General Challenges in (non-wood) Biomass Usage for Fuel

- Scattered resource – unlike oil, coal, peat & wood
- Low energy & mass density – expensive to transport and often very wet
- Storage problems – needs shelter and degradation occurs
- Combustion – volatile compounds, high ash content, low ash-melting point, emissions
- Large & small-scale not likely
Biomass Raw Materials
Depend on geographical location & other industries

- Sawdust & wood shavings (softwoods, hardwoods)
- Straw (wheat, barley, rye, rice &c.)
- Peat
- Forest residues
- Tree bark
- Short-rotation coppice (willow, hazel &c.)
- Corn stover
- Reed canary & other grasses
- Infested round wood
- Hemp

Pellet additives: plastic waste (RDF), oils & fats, hydrated lime, bentonite, corn/rye flours, molasses, lignosulfonate, steam, coal, black liquors &c.
The Special Case of Wood Pellets

- Raw material is by-product of a huge industry
- Resource already concentrated at mills etc.
- Therefore, relatively low-cost and dispersed
- Homogeneous (pine & spruce)
- Pelletising works with proper techniques
- Clean and easy burning
- Small-scale technology suitable
Conventional Wood Pellet Research

Publications can be grouped into four groups:

- Raw materials
- Quality problems
- Pelletisation
- Combustion
Raw Materials

- Studies have mapped available resources from existing industries (forestry, agriculture, food production)
- European and North American
- These are also general biomass studies
Raw Materials

- Available European (EU25) Biomass Resources are estimated to be about 4.1 exajoules ($10^{17}$)
- If present European pellet consumption is roughly 10 million tons or 0.17 EJ
- About 4% of available resource being used
General Conclusions: Raw materials available in Europe but production costs too high and combustion problematic. Passalacqua, F. Et al. (2004)
Raw Materials


General Conclusions: No resource limitations in Europe to meet white paper goals set by European Commission (1997).
Quality Problems

Producers would like to produce the best quality of pellets with the lowest production costs. Pellet quality is a function of:
- Durability
- Moisture
- Bulk Density
- Material type
- Particle size
- Sawdust maturity
- Energy content
- Combustion characteristics
Quality Problems

- Real-time analysis of raw materials at pellet factory
- Near Infrared Spectroscopy (NIR)
- Uses 780 – 2500 nm detectors
- Sensors record spectral data of passing material

Publication: Torbjörn L. Et al. NIR techniques create added values for the pellet and biofuel industry (2009)
Quality Problems

Process variables:
- Moisture content
- Species blend (spruce/pine)
- Press energy consumption
- Drying temperature

Torbjörn L. Et al. NIR techniques create added values for the pellet and biofuel industry (2009)
Quality Problems

Prediction of sawdust blends (pine/spruce)

Fig. 3. Amount of spruce and pine raw sawdust in the process flow predicted day 5–9 during the experiment for the test set values and day 1–5 before the running of the experiment (open circle, ○) and predicted values for the calibration set values (filled circle, ●) of the different runs indicated by the arrows.
Quality Problems

System predicted some 91% of power consumption

![Graph showing electrical current prediction](image)

Fig. 4. Observed and predicted electrical current measured in ampere per unit input of biomass in the pellet press. *Figure legend:* cross (×), 90% pine at ca. 11%; circle (○), centre points at ca. 9%; plus (+), 90% pine at ca. 7%; diamond (◇), spruce at ca. 11%; square (□), spruce at ca. 7% moisture content.
Quality Problems

Problem: Emission of volatile organic compounds from softwood pellets and sawdust. Can result in:

- Odour problems
- Spontaneous heating of stored materials/pellets
- General problem for biomass storage
Quality Problems

Electron beam treatment of pine sawdust irradiated at 10 MeV linear accelerator

- They found that e-beam treated sawdust pellets had 2% higher density and up to 14% higher compression strength
- They suggest method for controlled aging/maturation of raw materials.

Finell, M. et al., Laboratory-scale production of biofuel pellets from electron beam treated Scots pine (Pinus silvestris L.) sawdust (2009)
Quality Problems
Study of Emissions from Softwood Pellets

Experienced with fresh & stored sawdust in pellet making. They found that:

- Under certain conditions, pellets emit high levels of volatile compounds (Aldehydes, pentanal & hexanal among others)
- Amount determined by raw material and drying temperature
- The composition of emissions change during storage
- Lipid content seems to be a good indicator of sawdust maturity

Arshadi, M. et al., Emission of volatile compounds from softwood pellets during storage (2005)
Pelletisation

Basic research areas using laboratory-scale single pellet press if fairly widespread. Areas of research include:

- Pellet quality (durability, moisture, mechanical properties)
- Optimal dye temperatures
- Pellet & compression theory models
- Density & heating values of products
- Pellet recipes using mixed materials
- Effects of additives
- Particle size distribution
- Input energy consumption
Pelletisation

This process is modelled with the single pellet press.

This zone is modelled by sequential loading of single pellet press.

Figure 1. Matrix channel and roller. The pressures at the top of the pellet are depicted.

Holm, J.K., Experimental Verification of Novel Pellet Model Using Single Pelleteer Unit (2007)
Pelletisation

Figure 2. Single pelletter unit. Setup for pellet production (A). Setup for the measurement of back pressure (B).

Holm, J.K., Experimental Verification of Novel Pellet Model Using Single Pellette Unit (2007)
Pelletisation

Figure 4. Pellet length versus pellet weight with single or sequential loading. (◇) One loading. (●) Sequential loading. (・・・) Linear trend line of sequential loading. The equation and $R^2$ of the trend line for sequential loading are given in the figure.

Holm, J.K., Experimental Verification of Novel Pellet Model Using Single Pelleter Unit (2007)
Fig. 1. Single pellete unit.

Mani, S., Evaluation of compaction equations applied to four biomass species (2004)

Pelletisation

Pelletisation
Experimental compression data fit to standard compaction models for powders (pharmaceuticals)

Fig 2. Typical compression curve of biomass grinds.

Mani, S., Evaluation of compaction equations applied to four biomass species (2004)
Pelletisation

other research

Pelletisation research includes other areas:

- Crushing & milling of raw materials
- Drying processes
- Mixing of feedstocks
Combustion
Research concerning biomass combustion in general

- In general, pellet fuels should be produced in two separate classes
- High-quality domestic pellets for small users
- Industrial pellets for large users
- Easier to burn problematic biofuels in large power plants
- This topic is not in the scope of the review
Combustion
Available raw materials

Summary of fuel challenges:

• Forest residues (reactive Cl, ash content, K, lack of protective elements S, Al, Si)

• Crop residues (Cl, K, ash content)

• Bark (high Mn content can easily exceed EU co-incineration directives

What is needed in biomass fuel supply chain?

Nature has prepared homogeneous fossil fuels over long durations of time.
Figure 2.1 A typical mass- and energy balance of the torrefaction process on as received basis.

Symbols: E = energy unit, M = mass unit
Torrefaction

Dehydration Zone
- $\text{H}_2\text{O} + \text{C} = \text{C}$
- $\text{CO}_2$
- Methanol
- $\text{H}_2\text{O}$

Retification Zone
- Levoglucosan (far)
- Max. decomposition
- Oligosaccharides

Torrefaction Zone
- Phenols, Furans
- Aromatic groups

Carbonization Zone
- Alkyl Furans, Aromatics
- $\text{CO} + \text{CO}_2$
- Condensed Aromatics
- Max. Decomposition
- Biocarbon
- Increasing Aromaticity
- Carbon Content Rises

Source: http://alternaenergy.ca/
The TOP process – for biomass upgrading into solid fuel

Three steps: drying, torrefaction and pelletisation

Torrefaction: temperature treatment 200-300 deg C without oxygen

Volatile compounds are released and used in drying process

**Figure 4:** Process flow diagram of BO₂-technology. Only the integrated drying-torrefaction part of the process is shown (not size reduction and pelletisation).

(Kiet et al. 2008)
Torrefaction
straw, willow, reed canary grass

Fig. 2. Mass loss of wheat straw, reed canary grass and willow during torrefaction at 563 K.

Bridgeman, T.G. et al., Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties (2007)
Benefits of Torrefied Biomass

Heterogeneous Input  →  More homogenous output

- Improves energy density of biomass
- Improves grindability (reduces energy requirements)
- Resistance to biodegradation
- Better durability, handling and storage properties (outdoor)
- Basic result = biomass becomes more coal-like!

Figure 2: Torrefaction mass yields as a function of feedstock and temperature, generally increased hemicellulose content in direction of arrow

(Kiel et al. 2008)
Benefits of TOP Pellets

Table I: Overview of BO₂ pellet properties

<table>
<thead>
<tr>
<th>Properties (typical values)</th>
<th>Wood chips</th>
<th>Torref. Wood</th>
<th>Wood pellets</th>
<th>BO₂ pellets</th>
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<tbody>
<tr>
<td>Moisture wt%</td>
<td>35</td>
<td>0</td>
<td>10</td>
<td>3</td>
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<tr>
<td>LHV kJ/kg</td>
<td>17.7</td>
<td>20.4</td>
<td>17.7</td>
<td>20.4</td>
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<tr>
<td>Dry</td>
<td>10.5</td>
<td>20.4</td>
<td>15.6</td>
<td>19.9</td>
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<tr>
<td>As received</td>
<td>10.5</td>
<td>20.4</td>
<td>15.6</td>
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<td>Bulk density kg/m³</td>
<td>475</td>
<td>230</td>
<td>650</td>
<td>750</td>
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<tr>
<td>GJ/m³</td>
<td>5.0</td>
<td>4.7</td>
<td>10.1</td>
<td>14.9</td>
</tr>
</tbody>
</table>

(Kiel et al. 2008)
Torrefaction
By Any Other Name

- Torrified biomass
- Bio coal
- E-coal
- Green coal

Currently six companies starting up operations
NL(2), B(1), USA(2), CA(1):

www.BO2GO.eu
http://alternaenergy.ca/
www.topell.nl/index.htm
http://4energyinvest.com
www.integrofuels.com
www.newearth1.net
Publication


www.ecn.nl
Contents of Economic Analysis

- Capital investment & production costs
- Analysis of logistical & transport costs
- Profitability analysis
- Internal rate of return & payback period
Economic Analysis in Publication

- Comparison of conventional wood pellet production with TOP pellets
- Both processes use same raw material (wet sawdust)
- Investment & production costs (pellet factory)
- Logistics & transport costs (from production in South Africa and market in Northwest Europe)
- Profitability analysis based on market price for both co-firing and domestic market
- Internal rate of return & payback period calculated
- Note: publication also treats pellets made from green wood but it is not presented here
Assumptions in Publication

- Working capital amounts not specified for each process
- Investments cost estimated using factorial method (Peters & Timmerhaus, 1991) not supplied
- Mass and energy balance modelling done in cooperation with a pellet production company (GF Energy), therefore not supplied in publication (confidential?).
- Depreciation period = estimated lifetime of drying and reactor equipment (10 years)
- Financing rate = 5%
- Factory is continuously operating (8760 hrs/year) with three shifts per day and five employees (salary 50,000 €/year)
- Units of utility consumption use MW (power not energy)
Technical Parameters Used in Analysis
(based on pilot experiments at ECN)

Table 2.2  Technical performance characteristics of conventional pelletisation process and the TOP process. The reported net efficiencies are based on electricity generated with an efficiency of 40%

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Conventional pelletisation</th>
<th>TOP process</th>
<th>Conventional pelletisation</th>
<th>TOP process</th>
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</thead>
<tbody>
<tr>
<td>Feedstock</td>
<td></td>
<td>Sawdust</td>
<td>Sawdust</td>
<td>Green wood chips</td>
<td>Green wood chips</td>
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<tr>
<td>Feedstock capacity</td>
<td>kton/a</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
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<tr>
<td>Moisture content</td>
<td>wt.</td>
<td>57%</td>
<td>57%</td>
<td>57%</td>
<td>57%</td>
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<tr>
<td>LHV&lt;sub&gt;ar&lt;/sub&gt; feed (ar)</td>
<td>MJ/kg</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
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<tr>
<td>Production capacity</td>
<td>kton/a</td>
<td>80</td>
<td>56</td>
<td>80</td>
<td>56</td>
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<tr>
<td></td>
<td>Mm&lt;sup&gt;3&lt;/sup&gt;/a</td>
<td>133</td>
<td>70</td>
<td>133</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>MW&lt;sub&gt;th&lt;/sub&gt; fuel</td>
<td>44</td>
<td>40</td>
<td>44</td>
<td>40</td>
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<tr>
<td>Moisture content</td>
<td>% wt.</td>
<td>9</td>
<td>3</td>
<td>9</td>
<td>3</td>
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<tr>
<td>LHV&lt;sub&gt;ar&lt;/sub&gt; product</td>
<td>MJ/kg</td>
<td>15.8</td>
<td>20.8</td>
<td>15.8</td>
<td>20.8</td>
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<tr>
<td>Cooling water</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;/ton product</td>
<td>-</td>
<td>16.7</td>
<td>-</td>
<td>16.7</td>
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<tr>
<td>Steam</td>
<td>ton/ton product</td>
<td>0.025</td>
<td>-</td>
<td>0.025</td>
<td>-</td>
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<tr>
<td>Utility fuel</td>
<td>MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>10.4</td>
<td>3.9</td>
<td>11.3</td>
<td>4.7</td>
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<tr>
<td>Power consumption</td>
<td>MWe</td>
<td>1.26</td>
<td>0.83</td>
<td>1.84</td>
<td>1.01</td>
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<tr>
<td>Thermal efficiency</td>
<td>LHV(ar)</td>
<td>93.9%</td>
<td>98.5%</td>
<td>92.2%</td>
<td>96.5%</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>LHV(ar)</td>
<td>88.0%</td>
<td>93.7%</td>
<td>84.0%</td>
<td>90.8%</td>
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</tbody>
</table>
General Input Data for Evaluation

Table 3.1  Summary of general input data used for the economic evaluation

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>Depreciation period</td>
<td>Year</td>
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<td>Depreciation method</td>
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<tr>
<td>Financing</td>
<td>% of investment</td>
<td>5</td>
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<tr>
<td>Feestock (gate delivered)</td>
<td>€/ton (wet)</td>
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<tr>
<td>Utilities</td>
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<td></td>
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<tr>
<td>Electricity</td>
<td>€/KWh</td>
<td>0.065</td>
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<tr>
<td>Natural gas (NG)</td>
<td>€/Nm³</td>
<td>0.14</td>
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<tr>
<td>Cooling Water</td>
<td>€/m³</td>
<td>0.04</td>
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<tr>
<td>Air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>€/a per operator</td>
<td>50,000</td>
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<tr>
<td>Operator shifts</td>
<td># / day</td>
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(*Rates correspond to Dutch rates in 2004)
## Investment & Production Costs

<table>
<thead>
<tr>
<th></th>
<th>Convention Pellets</th>
<th>Top Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working capital (M€)*</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Total capital investment (M€)</td>
<td>3.9</td>
<td>5.6</td>
</tr>
<tr>
<td>Labour (M€/year)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Raw materials (M€)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Utilities (M€/year)</td>
<td>1.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Total (€/ton)</td>
<td><strong>37 (41)</strong></td>
<td><strong>42 (45)</strong></td>
</tr>
<tr>
<td>Total (€/GJ)</td>
<td><strong>2.3 (2.6)</strong></td>
<td><strong>2.0 (2.2)</strong></td>
</tr>
</tbody>
</table>

* Amount of assumed working capital is unclear in publication
Total Production Costs of Conventional and TOP Pellets (made from sawdust)

Energy required for heating & evaporating H2O

\[ E = (mc\Delta T) + (mL_v) = m(c\Delta T + L_v) \]

- \( m \) = mass of water (kg)
- \( c \) = specific heat capacity water (4186 J/kg C)
- \( \Delta T \) = change in temperature (100 deg C)
- \( L_v \) = latent heat of vaporisation water (2260000 J/kg)

Natural gas savings from torgas \( \approx 15 \) (€/ton product)
Logistics and Transport Analysis

- Pellet production in South Africa
- Delivery to markets in NW-Europe
Logistical and Transport Cost Analysis of Conventional and TOP Pellets

The diagram shows the costs (€/ton) for various stages of the production and transportation of conventional and TOP pellets. The costs are broken down into:

- Feedstock gate delivery
- Pellet production
- Road transport to harbour
- Harbour storage
- Transfer handling
- Sea transportation
- Transfer handling
- Harbour storage
- Water transport to user

The costs for conventional pellets are represented in orange, and for TOP pellets in green.

- Feedstock gate delivery: €10.5 for conventional, €15.0 for TOP
- Pellet production: €42.3 for conventional, €37.0 for TOP
- Road transport to harbour: €15.0 for conventional, €28.1 for TOP
- Harbour storage: €34.6 for conventional, €28.1 for TOP
- Transfer handling: €42.3 for conventional, €37.0 for TOP
- Sea transportation: €34.6 for conventional, €28.1 for TOP
- Water transport to user: €15.0 for conventional, €28.1 for TOP
# Logistics & Transport Cost

<table>
<thead>
<tr>
<th>logistics &amp; transport costs (M€)</th>
<th>Conventional pellets</th>
<th>TOP pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€/ton product</td>
<td>€/year</td>
</tr>
<tr>
<td>Feedstock gate delivery</td>
<td>10.5</td>
<td>840000</td>
</tr>
<tr>
<td>Pellet production</td>
<td>37.0</td>
<td>2962028</td>
</tr>
<tr>
<td>road transport to harbour</td>
<td>4.4</td>
<td>350000</td>
</tr>
<tr>
<td>Harbour storage</td>
<td>1.8</td>
<td>144000</td>
</tr>
<tr>
<td>Transfer handling</td>
<td>4.0</td>
<td>320000</td>
</tr>
<tr>
<td>Sea transportation</td>
<td>34.6</td>
<td>2769231</td>
</tr>
<tr>
<td>Transfer handling</td>
<td>4.0</td>
<td>320000</td>
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<tr>
<td>Harbour storage</td>
<td>2.1</td>
<td>168000</td>
</tr>
<tr>
<td>Water transport to user</td>
<td>2.0</td>
<td>160000</td>
</tr>
<tr>
<td><strong>total cost</strong></td>
<td>100</td>
<td>8033259</td>
</tr>
<tr>
<td><strong>cost (€/GJ)</strong></td>
<td>6.36</td>
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</tr>
</tbody>
</table>
Profitability Analysis

- Delivery to power station in NW-Europe (co-firing market not domestic market)
- Tax rate set to 35%
- Internal rate of return (IRR) is estimated based on ten year project lifetime (equal to depreciation period)
- Payback period estimated
Market Prices of Pellets

- Price is determined from energy content (LHV)
- Two different price levels: co-firing and domestic

<table>
<thead>
<tr>
<th></th>
<th>Co-firing market</th>
<th>Domestic market</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conv. pellets</td>
<td>TOP pellets</td>
</tr>
<tr>
<td>LHV* (GJ/ton)</td>
<td>15.8 (16.5)</td>
<td>20.8 (20.4)</td>
</tr>
<tr>
<td>Gate price (€/ton)</td>
<td>115 (120)</td>
<td>152 (148)</td>
</tr>
<tr>
<td>Gate price (€/GJ)</td>
<td>7.3</td>
<td>7.3</td>
</tr>
</tbody>
</table>

* Publication values of LHV differ from production estimates
# Cash-Flow Analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Calculation</th>
<th>Conv. Pellets (M€)</th>
<th>TOP pellets (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Revenues</td>
<td></td>
<td>9.2</td>
<td>8.5</td>
</tr>
<tr>
<td>B</td>
<td>Costs</td>
<td></td>
<td>8.0</td>
<td>5.7</td>
</tr>
<tr>
<td>C</td>
<td>Operational Income</td>
<td>A-B</td>
<td>1.2</td>
<td>2.8</td>
</tr>
<tr>
<td>D</td>
<td>Depreciation</td>
<td></td>
<td>0.39</td>
<td>0.56</td>
</tr>
<tr>
<td>E</td>
<td>Profit before tax</td>
<td>C-D</td>
<td>0.80</td>
<td>2.3</td>
</tr>
<tr>
<td>F</td>
<td>Tax (35%)</td>
<td>Tax rate*E</td>
<td>0.28</td>
<td>0.80</td>
</tr>
<tr>
<td>G</td>
<td>Net income</td>
<td>E-F</td>
<td>0.52</td>
<td>1.5</td>
</tr>
<tr>
<td>H</td>
<td>Cash flow</td>
<td>G+D</td>
<td>0.91</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Internal rate of return</td>
<td></td>
<td>19% (13%)</td>
<td>35% (30%)</td>
</tr>
<tr>
<td></td>
<td>Payback period</td>
<td>years</td>
<td>4.3 (6)</td>
<td>2.7 (3)</td>
</tr>
</tbody>
</table>
## Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>Conventional pellets</th>
<th>TOP pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production cost (€/ton)</td>
<td>37 (41)</td>
<td>42 (45) (50)</td>
</tr>
<tr>
<td>Production cost (€/GJ)</td>
<td>2.3 (2.6)</td>
<td>2.0 (2.2) (2.5)</td>
</tr>
<tr>
<td>Production transport &amp; logistics (M€)</td>
<td>8.0 (8.4)</td>
<td>5.7 (5.8)</td>
</tr>
<tr>
<td>Production transport &amp; logistics (€/GJ)</td>
<td>6.4 (6.6)</td>
<td>4.9 (5.0)</td>
</tr>
<tr>
<td>Market price (€/ton)</td>
<td>115 (120)</td>
<td>152 (148)</td>
</tr>
<tr>
<td>Market price (€/GJ)</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Cash flow (M€)</td>
<td>0.91 (0.72)</td>
<td>2.0 (1.8)</td>
</tr>
<tr>
<td>IRR</td>
<td>19 (13)</td>
<td>35 (30)</td>
</tr>
<tr>
<td>Payback period (years)</td>
<td>4.3 (6)</td>
<td>2.7 (3)</td>
</tr>
</tbody>
</table>
Conclusion of Economic Analysis

- TOP process appears feasible and, even an attractive alternative in terms of economics based on a raw material of wet sawdust, provided that the technical assumptions are valid.
- Significant cost advantages are achieved in the TOP process mainly due to the drying, size reduction and energy densification.
Summary

- International pellet research has the potential to be vast
- Active groups exist in countries where pellet production is significant (se, ca, nl, au, usa)
- Research is both theoretical and applied often related to local resources
- Torrefaction, if feasible, provides a promising route of utilising biomass resources.
Thank you!