Torrefaction – The Big Picture

Framtiden för fasta biobränslen?
27 January 2026 Vasa

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Presentation Outline

- About our group
- What’s the point?
- The story and historic claims
- A little torrefaction chemistry
- The evidence
- Conclusions

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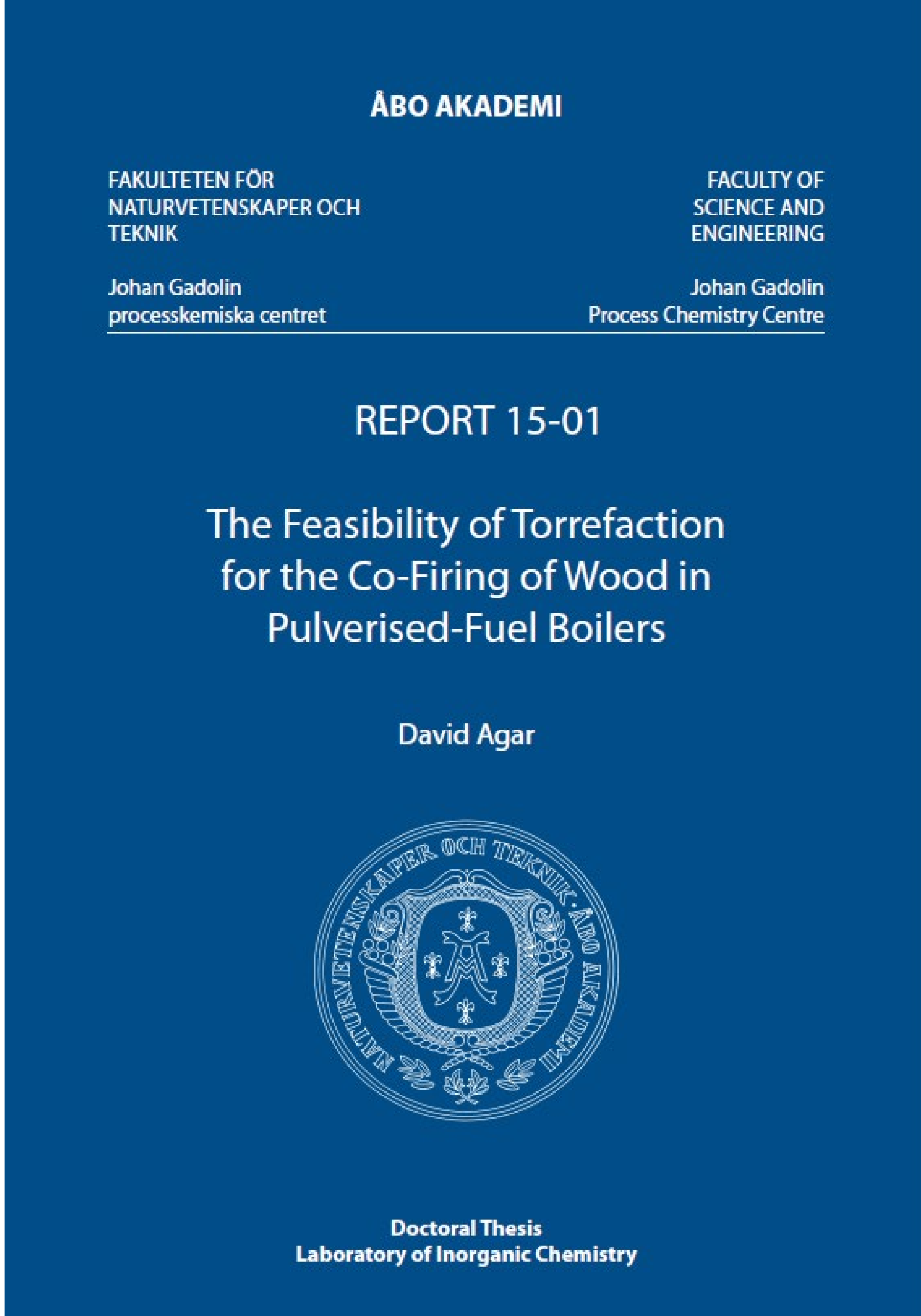

ÅBO AKADEMI

FAKULTETEN FÖR NATURVETENSKAPER OCH TEKNIK

Johan Gadolin processkemiska centret

FACULTY OF SCIENCE AND ENGINEERING

Johan Gadolin Process Chemistry Centre

REPORT 15-01

The Feasibility of Torrefaction for the Co-Firing of Wood in Pulverised-Fuel Boilers

David Agar

Doctoral Thesis
Laboratory of Inorganic Chemistry

Biomass Technology and Chemistry Division

Our research focuses on creating value from industrial biomass residues for energy, materials and chemicals

Division Head

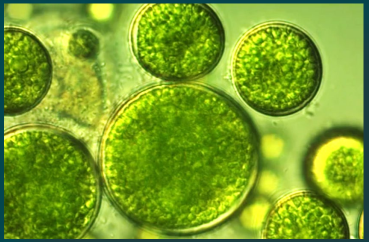
David A. Agar

Associate Prof.







SCIENCE AND EDUCATION FOR SUSTAINABLE LIFE

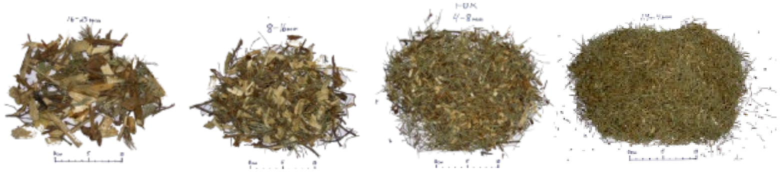
Biomass Technology Centre in Umeå, Sweden











Chipping →  Drying →  → Fractioning ↓

Well-defined materials






← Densification ←  ← Milling ← Thermal treatment

What’s the point?

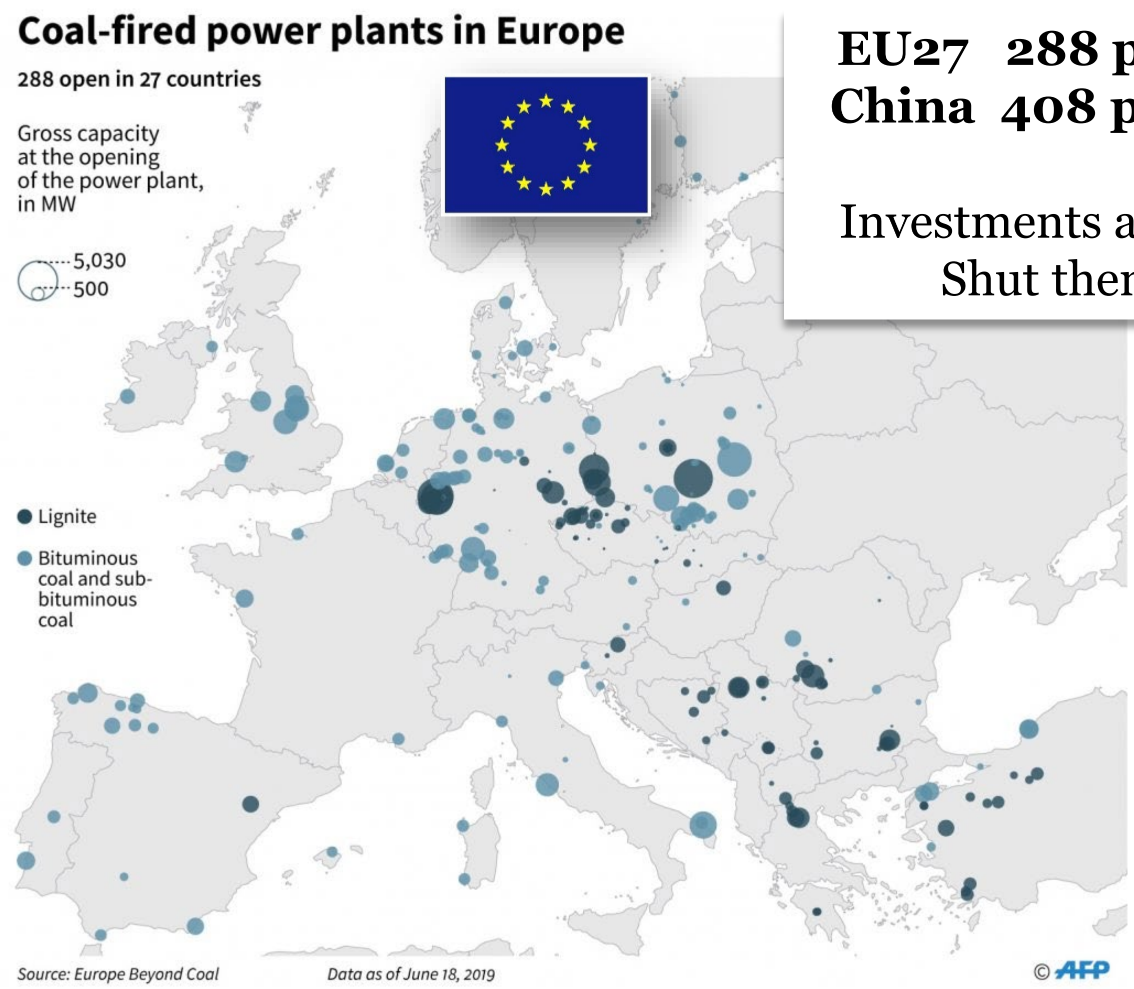
Torrefaction – What's the Point?

- Fast-track CO2 cutting (pelleting desirable)
- Replace coal in existing pulverised-coal boilers
- Untreated biomass co-firing limited to 5-10 %

- Key properties after torrefaction (280◦C)
  - ➢ Much easier to pulverise
  - ➢ Improved heating value
  - ➢ Lower moisture content

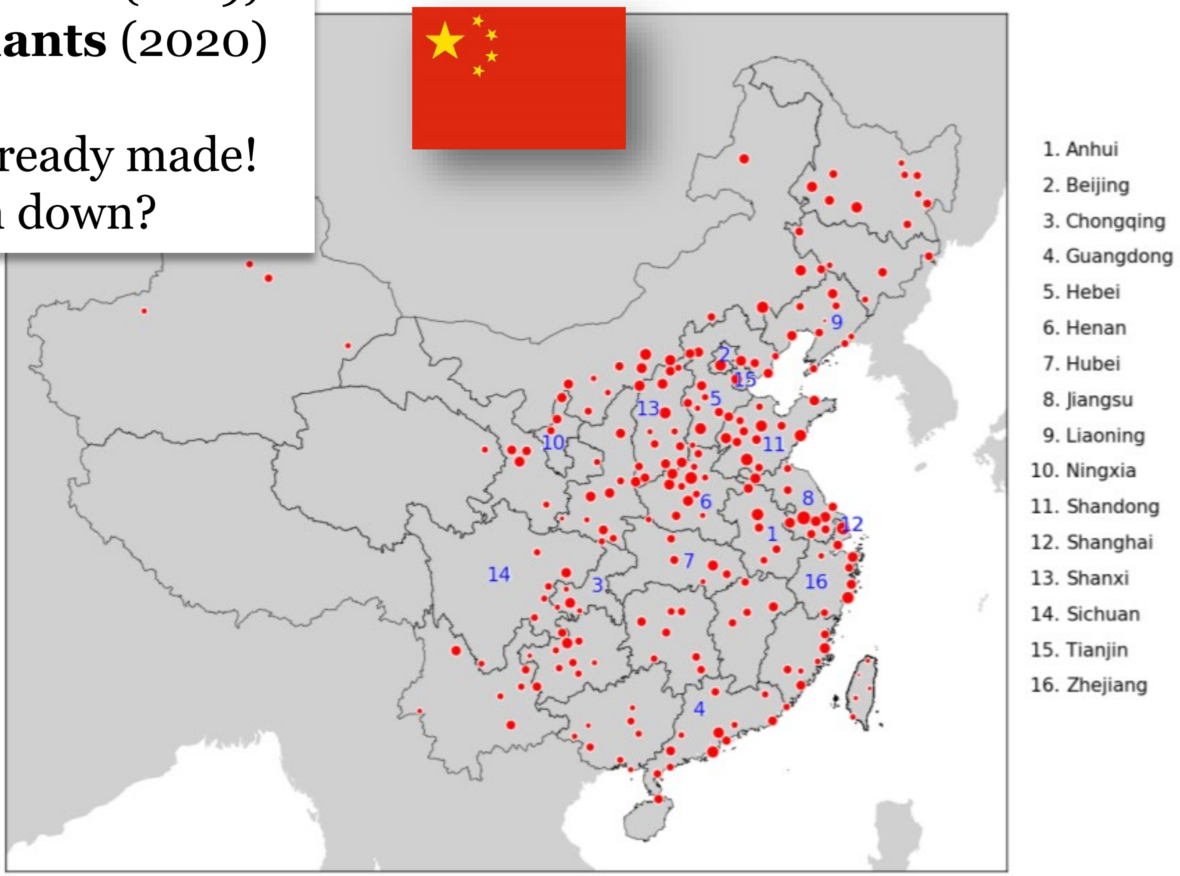
Like *coffee roasting*

Coal-fired plants in EU27 and China



EU27 288 plants (2019)
China 408 plants (2020)

Investments already made!
Shut them down?



Van der A RJ, Mijling B, Ding J, Koukouli ME, Liu F, Li Q, et al. Cleaning up the air: effectiveness of air quality policy for SO2 and NOx emissions in China. Atmos Chem Phys. 2017

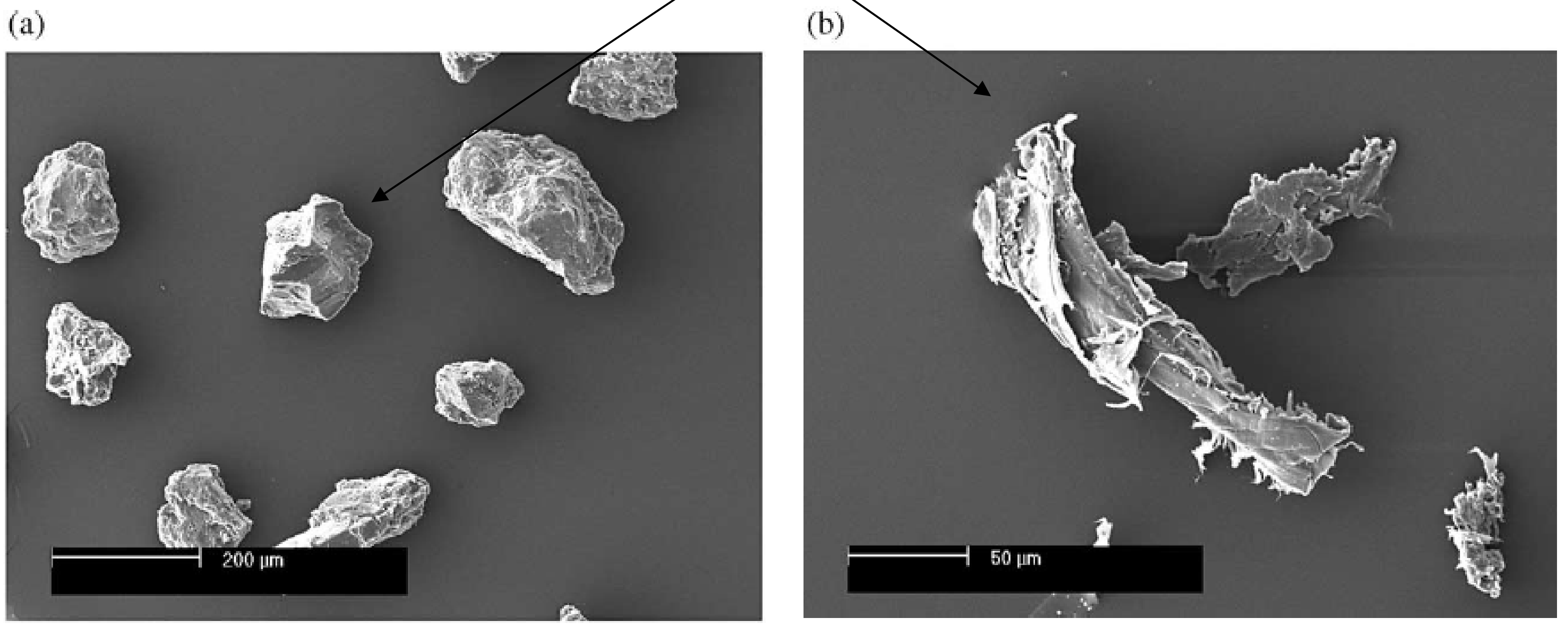
Size reduction bottleneck

Milling energy requirements of biomass versus coal

- Biomass*: **240 kWh/t**
- Coal: **23 kWh/t**

(Phanphanich 2011)
**forest residues*

Flow Properties: spherical particles versus needle-like particles



Scanning electron microscope images of (a) coal and (b) sawdust (Zulfiqar, 2006)

The Story and Historic Claims

Energy Centre Netherlands Report 2005

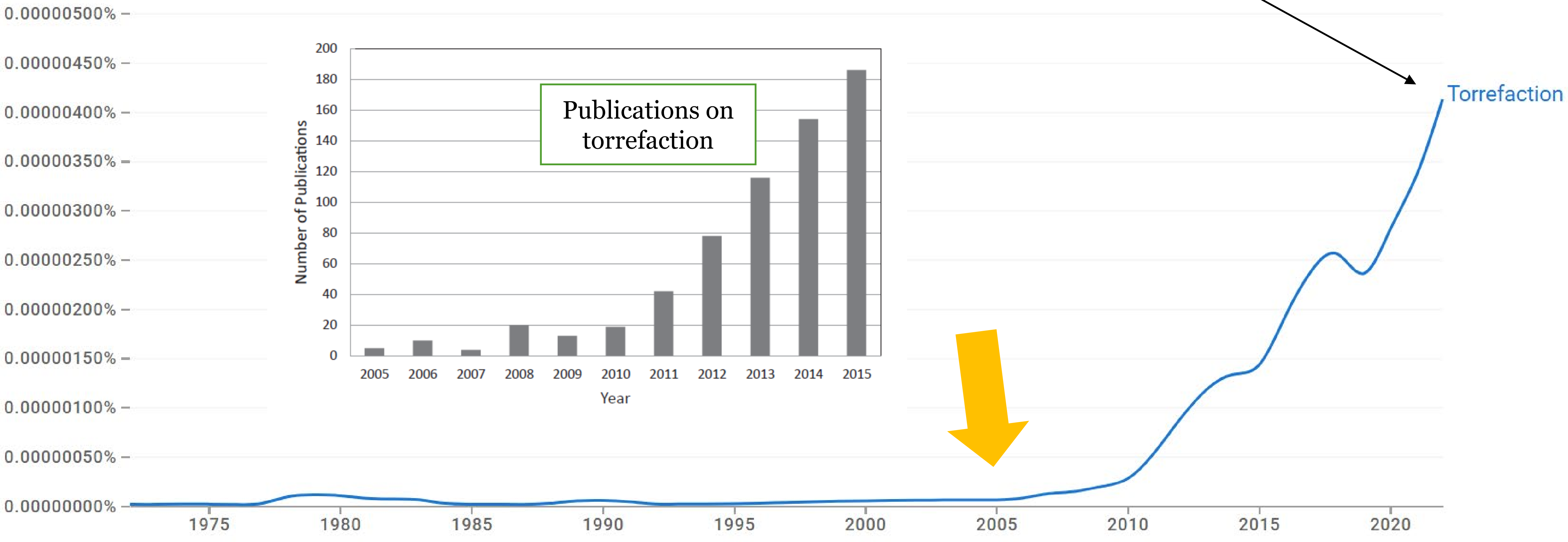
An ECN report* was catalyst for torrefaction development

Report claims on torrefied pellets:

- Easy to make pellets
- Bulk density **750 to 850** kg/m3
- Net calorific value **19 to 22** MJ/kg (as received)
- Volumetric energy density **14 to 19** GJ/m3
- Hydrophobic: can be stored outdoors

* *Combined torrefaction and pelletisation - The TOP process (2005)*

”Torrefaction” usage in Google Ngram viewer



2005

SLU

Torrefaction technology developers 2011

Reactor technology	Technology developers
Rotary drum	CDS (UK), Torrcoal (NL), BioEndev (SE), ACB (AU), BIO3D (FR), CENER/List (ES)
Multiple hearth furnace	CMI-NESA (BE)
Screw reactor	BTG (NL), Biolake (NL), FoxCoal (NL)
Torbed reactor	Topell (NL)
Moving bed reactor	ECN (NL), Thermya (FR), Bühler (CH)
Belt reactor	Stramproy (NL)

Kiel J, Torrefaction for upgrading biomass into commodity fuel, 2011.

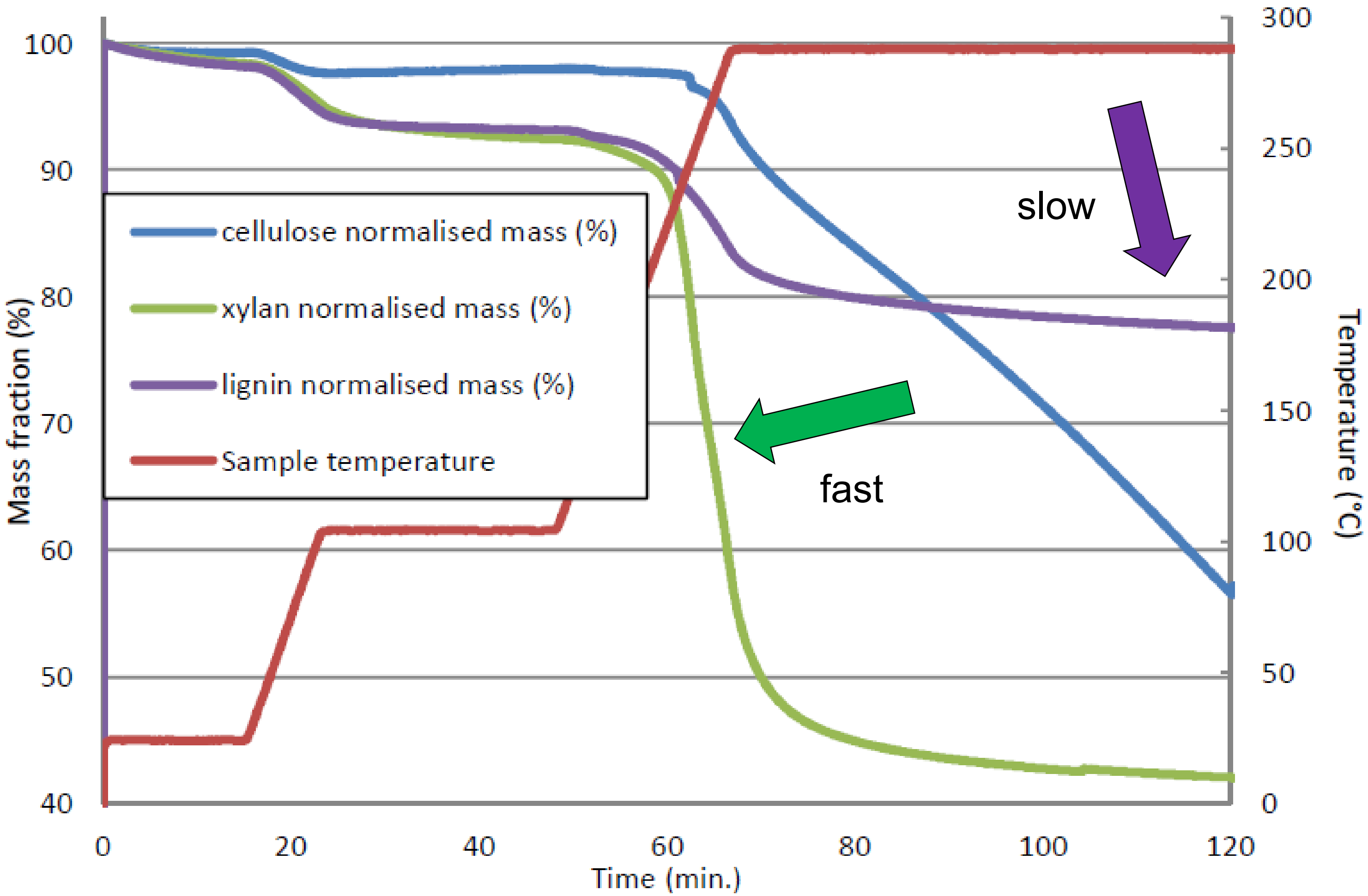
"It has been hard to fully prove the claims made earlier on product characteristics, and several companies have gone bankrupt due to inability to produce good quality product or due to a lack of buyers."

IEA, Status overview of torrefaction technologies 2015

A Little Torrefaction Chemistry

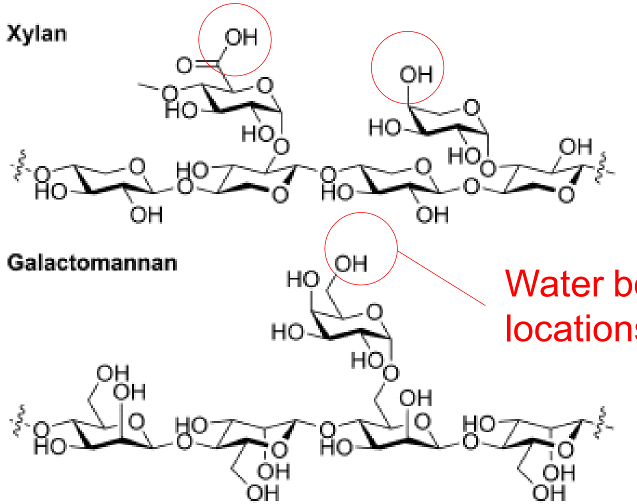
Wood-component degradation during pyrolysis

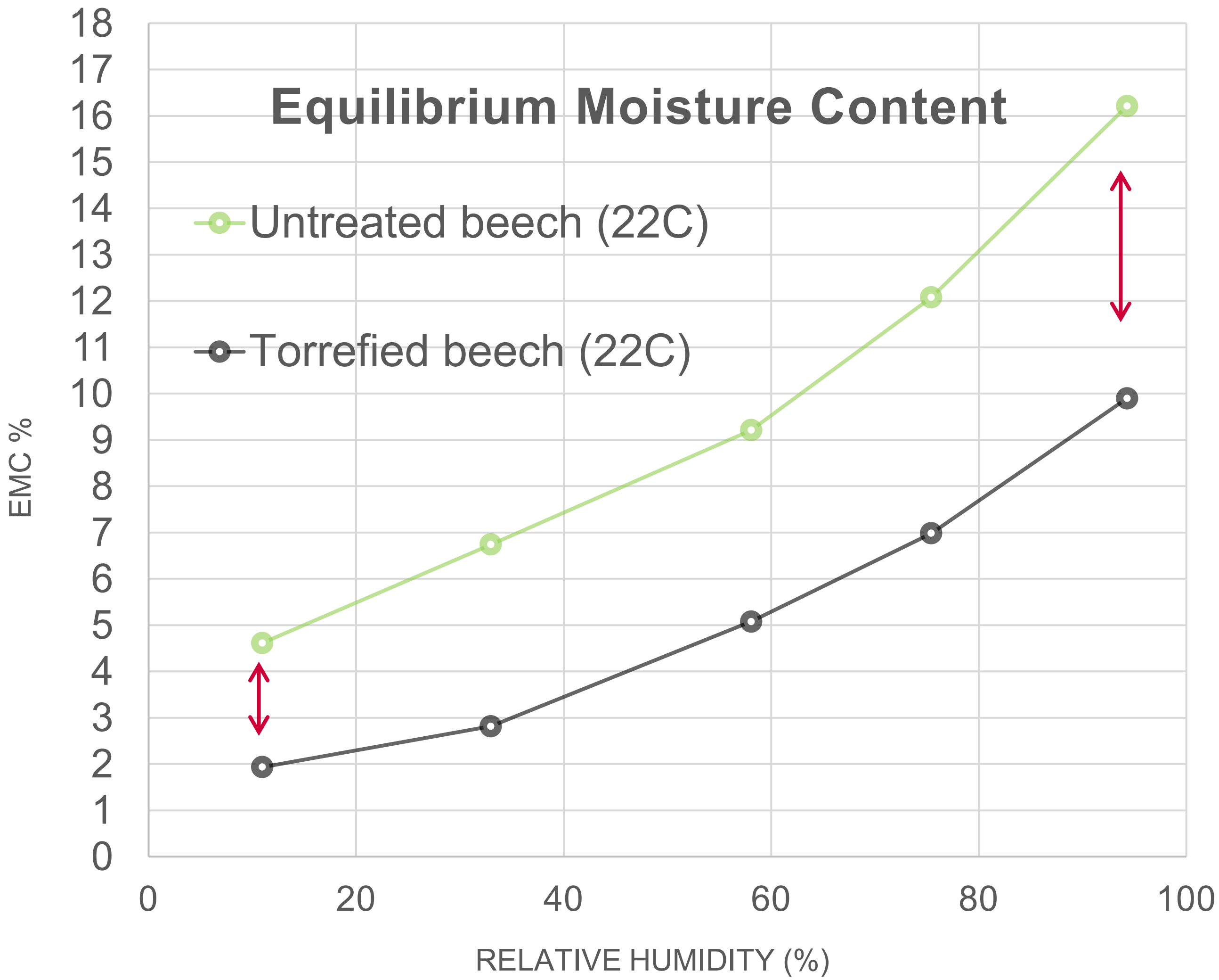
- Cellulose, lignin and hemicellulose have different sensitivities to heat
- Hemicellulose is most reactive (xylan)
- Lignin most stable



Hemicellulose and equilibrium moisture content

Hemicellulose affects moisture content as water binds easily to hydroxyl groups (OH)





Järvinen T & Agar D. Fuel 129; 330-339 (2014).

Heating value: function of moisture content

Effective or lower heating value used in real applications and used on dry basis (db) and at moisture content M, also called “as received” value

$$LHV(ar) = LHV(db) \times \left(\frac{100 - M}{100}\right) - 0.02443 \times M$$

LHV(db) = lower heating value, dry basis (MJ/kg)

LHV(ar) = lower heating value, as received (MJ/kg)

M = moisture content

NOTE: LHV (ar) determines the price of the fuel in real life!

The Evidence

The feasibility of torrefaction: the evidence

FP7 SECTOR

FP7 BIOCLUS

H2020 MOBILE FLIP

2012

Bio-coal, torrefied lignocellulosic resources - Key properties for its use in co-firing with fossil coal - Their status.

2014

Experimentally determined storage and handling properties of fuel pellets made from torrefied whole-tree pine chips, logging residues and beech stem wood.

2015

Torrefied versus conventional pellet production – A comparative study on energy and emission balance based on pilot-plant data and EU sustainability criteria.

2016

Influence of elevated pressure on the torrefaction of wood.

2017

A comparative economic analysis of torrefied pellet production based on state-of-the-art pellets.

2021

Pelleting torrefied biomass at pilot-scale – Quality and implications for co-firing.

Improved grindability (easy to mill)

Table 3 – Selected experimental results on the grindability of torrefied materials.

Material	T (°C)	t (min.)	Initial particle size	Final particle size	E_g (kWh t^{-1})	E'_g (kWh t^{-1})	ΔE_g [a] (%)	Equipment specification	Fraction of heating value[b] (%)	Ref.
Beech	280	5	2–4 mm	d_{50} = 140 µm	840	90	−89	Retsch XMI mill,	2 (LHV)	[15]
Spruce	280	5		d_{50} = 93 µm	750	150	−80	500 µm sieve	2.8 (HHV)	[15]
Pine	275	30	20.94–70.59 ×	d_{50} = 270 µm	241[c]	52.0	−78	Retsch SM2000 mill,	1.0 (HHV)	[13]
Logging residues	275	30	15.08–39.70 × 1.88–4.94 mm	d_{50} = 460 µm	242[c]	78.0	−68	1.5 mm sieve	1.5 (HHV)	[13]

a Change in grinding energy $\Delta E_g = 100(E'_g - E_g)\,[E_g]^{-1}$.
b Used heating values (expressed as MJ kg^{-1}) were Spruce 19.0 [16], Pine 18.46, Logging residues 18.79 [13] and Beech 17.0 [15].
c Values calculated by fitted equation from reference at 25 °C.

Bio-coal, torrefied lignocellulosic resources – Key properties for its use in co-firing with fossil coal – Their status

D. Agar[a,], M. Wihersaari[b]*

Improved heating value (7 to 21% increase)

Table 2 – Selected experimental results on torrefaction of biomass raw materials from recent literature.

Material	Mass yield (%)	Energy yield (%)	Heating value (MJ kg^{-1})	Δq^a (%)	T (°C)	t (min.)	Volatiles (%)	Fixed carbon (%)	Ref.
Willow	78.6[b]	91.9[c]	17.7/20.7 (LHV)	16.9	270	15	n/a	n/a	[6]
Beech	73.8[b]	88.1[c]	17.0/20.3 (LHV)	19.4	280	30	n/a	n/a	[6]
Willow	79.8	85.8	20.0/21.4 (HHV)	7.00	270	30	79.3	18.6	[8]
Willow	81.6	89.9	19.8[c]/21.8 (HHV)	10.2	290	10	72.4[d]	23.3[d]	[9]
Wheat straw	71.5	78.2	18.9/20.7 (HHV)	9.52	270	30	65.2	26.5	[8]
Rice straw	36.6	39.9[c]	17.1/18.7 (HHV)	9.11	300	30	n/a	n/a	[10]
Rape stalk	25.3	29.1[c]	18.8/21.6 (HHV)	15.1	300	30	n/a	n/a	[10]
Loblolly pine	74.2	83.1	19.55/21.80 (HHV)	11.5	275	80	83.0	16.4	[11]
Loblolly pine	60.5	73.2	19.55/23.56 (HHV)	20.5	300	80	82.3	17.0	[11]
Miscanthus	75.7	81.0	20.2[c]/21.6 (HHV)	6.98	290	10	63.8[d]	32.6[d]	[9]
Eucalyptus	80	90	19.4/22.2 (HHV)	14.4	240	30	75.4	21.8[e]	[12]
Pine chips	73	87	18.5/21.8 (HHV)	18.2	275	30	76.4	23.3	[13]
Southern yellow pine residues	70	82	18.8/22.0 (HHV)	17.2	275	30	71.4	26.7	[13]
Willow	n/a	n/a	17.6/21.0 (LHV)	19.3	300	10	n/a	n/a	[14]

a Relative heating value increase $\Delta q = 100(X' - X)[X]^{-1}$ where X' is the LHV or HHV of the torrefied solid product and X is LHV or HHV of the untreated material.
b Estimated from on-screen graphical data.
c Calculated value using heating value (LHV or HHV) according to energy yield definition given in [8].
d As received (not daf).
e Calculated from given data on ultimate analysis and (n/a) data not available.

Bio-coal, torrefied lignocellulosic resources – Key properties for its use in co-firing with fossil coal – Their status

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Hydrophobic? Rainfall simulation and water immersion (similar to wood pellets)

- Pellets exposed to 2.5 mm/hr (statistically heavy rain)
- Pellets were submersed for 15 min in water

Sample	Measured Values									
	$q_{V,gr,d}$ (MJ kg^{-1})	ρ_{ar} (kg m^{-3})	M_{ar} (%)	M_{emc} (%)	d_{ar} (%)	d^a (%)	h_{ar} (kg)	h^a (kg)	$M_{2.5}$ (%)	M_{15} (%)
Wood pellet	20.48	678.5	6.67	11.66	98.0	(98.2)[b]	20.9 (0.5)	(19)[b]	31	77
Pine 235	20.80	556.6	7.89	10.60	80.0	69.2	15.1 (4.7)	18.3 (3.1	33	66
Pine 245	21.77	633.1	5.49	9.50	92.0	86.6	20.7 (0.6)	19.4 (3.1	32	53
Pine 255	21.91	633.8	5.65	9.37	88.2	81.6	18.8 (3.6)	20.3 (1.8	32	51
Lres 240	21.59	681.3	7.09	9.41	89.1	84.3	17.8 (2.9)	18.6 (3.1	32	46
Lres 250	21.70	643.2	6.99	9.84	86.8	79.1	9.8 (1.7)	10.6 (3.5	33	50
Beech 270	21.60	702.3	4.99	8.93	97.1	95.5	19.7 (2.4)	20.4 (1.6	32	39

Järvinen T & Agar D. Fuel 129; 330-339 (2014).

Pelleting torrefied biomass at pilot-scale

Research questions:

- How does torrefaction affect the pelleting of biomass?
- How does pellet quality depend on production variables?
- What are the implications for coal replacement?

Pelleting Behaviour

Beech

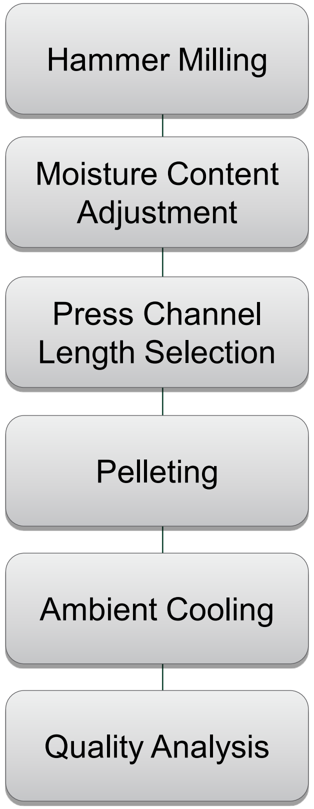
Wheat straw

Poplar

Corn/maize cob

Pilot-scale pelleting: from art to science

Multiple hearth torrefaction furnace
CEA Grenoble, France



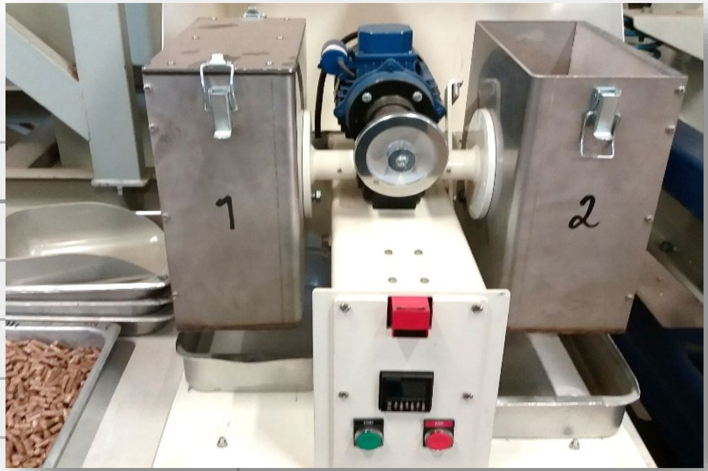
The pelleting process

- 2 Press Channel Lengths
- 4 moisture contents (MC)
- 3 replicate sampling periods
- **180 pellet batches**

Ring-die pellet press, Biomass Technology Centre

Pellet quality standards

Property	Unit	ENplus A1	ENplus A2	
Diameter	mm	6-8		
Length	mm	3.15 < L ≤ 40		
Moisture Content	% a.r	≤ 10		
Ash Content	% a.r	≤ 0.7	≤ 1.2	
Mechanical Durability	% a.r	≥ 98.0	≥ 97.5	
Fines (< 3.15 mm)	% a.r	≤ 1.0		
Net calorific value	MJ kg^{-1} a.r	≥ 16.5		
Bulk density	kg m^{-3}	≥ 600		
Additives	% a.r	≤ 2.0		
Nitrogen	% d.b	≤ 0.3	≤ 0.5	≤ 1.0
Sulphur	% d.b	≤ 0.04	≤ 0.05	
Chlorine	% d.b	≤ 0.02		≤ 0.03
Ash Deformation Temp.	°C	≥ 1200	≥ 1100	



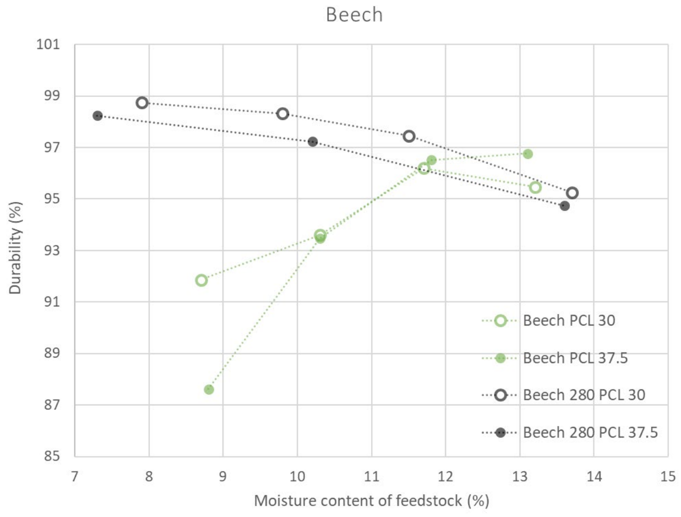
Pellet tumbler for durability testing

Symbols refer to a.r = as received, d.b = dry basis.

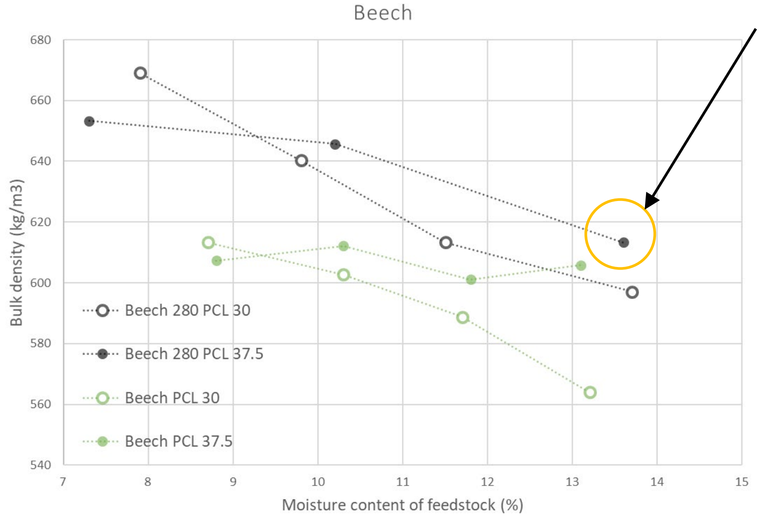
Observations example, beech vs. poplar

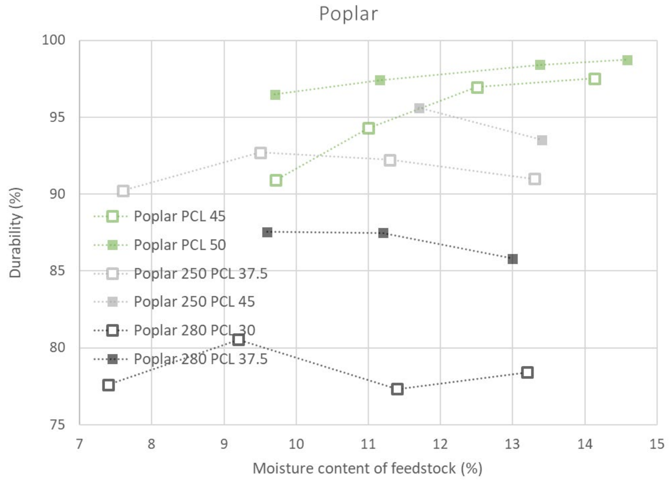
1 data point = average of 3 batches

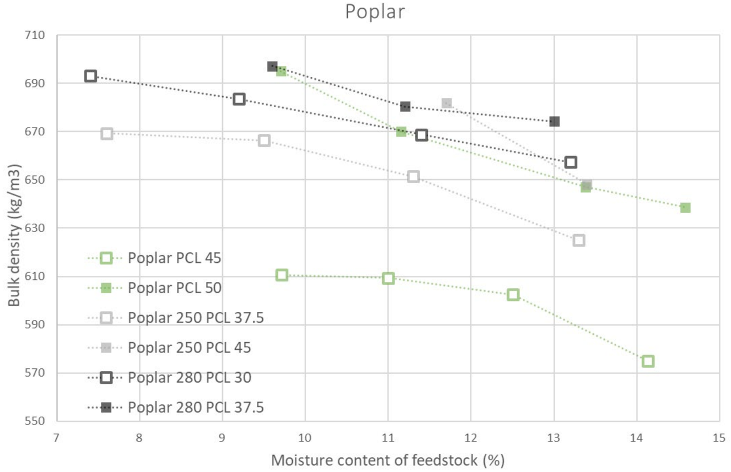
Durability



Bulk density







Pelleting behaviour

- Peak DU shifts to low MC
- Shorter press channel
- More friction
- More heat generated
- Material differences

Observations

Best results!

Durability

Bulk Density

Energy Density

Feedstock	Pelleting data					Pellet quality indicators					
	MC (%)	PCL (mm)	E (kWh t^{-1})	T_p (°C)	fines (%)	DU (%)	BD (kg m^{-3})	MC_{ar} (%)	LHV_{ar} (MJ kg^{-1})	σ_{ar} (GJ m^{-3})	ENplus A1* deficiencies
Beech 250	7.9 (-5.2)	30 (-7.5)	85.5 (+18)	140 (+30)	1.3 (-0.5)	98.7 (+1.9)	669 (+63)	3.4 (-4.2)	18.2 (+3.1)	12.2 (+3.0)	ash
Poplar 250	11.7 (-2.9)	45 (-5.0)	56.0 (-15)	112 (-6)	1.4 (+0.9)	95.6 (-3.1)	682 (+43)	7.5 (-2.3)	16.3 (+2.0)	11.1 (+2.0)	DU, (ash)
Poplar 280	9.6 (-5.0)	38 (-12)	77.6 (+6.2)	120 (+2)	20 (+19)	87.5 (-11)	697 (+58)	4.9 (-4.9)	20.2 (+5.9)	14.1 (+4.9)	DU, (ash)
Straw 250	11.7 (-3.0)	30 (-25)	99.6 (+53)	131 (+31)	1.5 (+0.4)	94.5 (+1.0)	671 (+120)	5.2 (-6.1)	17.7 (+2.7)	11.9 (+3.6)	DU, (ash, Cl)
Cob 260	8.4 (-1.1)	30 (-25)	82.1 (+19)	135 (+12)	2.0 (+1)	94.2 (-2.7)	662 (-56)	4.3 (-1.8)	19.0 (+3.3)	12.6 (+1.3)	DU, (ash)

Pelleting results

Comparative pelleting has shown that torrefaction has:

- Large mostly negative effect on pellet durability
- Large mostly positive effect on bulk density
- Energy density **11.9 to 14.1 GJ/m3** (vs. lignite 12.8 GJ/m3)
- 50% extra milling capacity needed (e.g. hard coal replacement with beech)
- Optimal torrefaction 250-280 C, 20-75 min

Conclusions on torrefaction

- Fast-track emission cutting option (lots of coal plants)
- Reduces milling energy significantly (60-80%)
- Reduces moisture content, increases heating value
- High energy density via pelleting: 14 GJ/m3 (lignite 12.8 GJ/m3)
- Torrefied fuels are **not hydrophobic** (dry storage needed)
- Torrefaction benefits limited by pellet durability
- ECN 2005 report: **not 100% evidence based** (~65 % true?)

References

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Thank You! Kiitos! Tack så Mycket!

Q: Is replacing coal the most sustainable thing we can do?

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