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Biomass and biofuels for sustainable energy future

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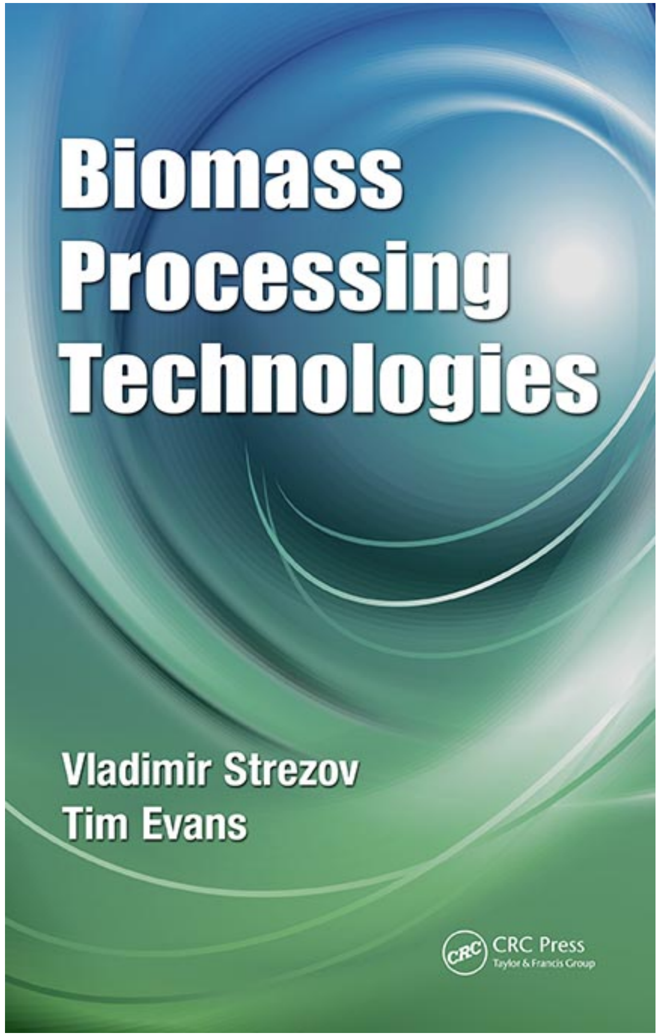
Outline

- Energy and sustainability
- Biomass properties
- Biomass processing technologies
- Production of biofuels
- System engineering of biomass applications



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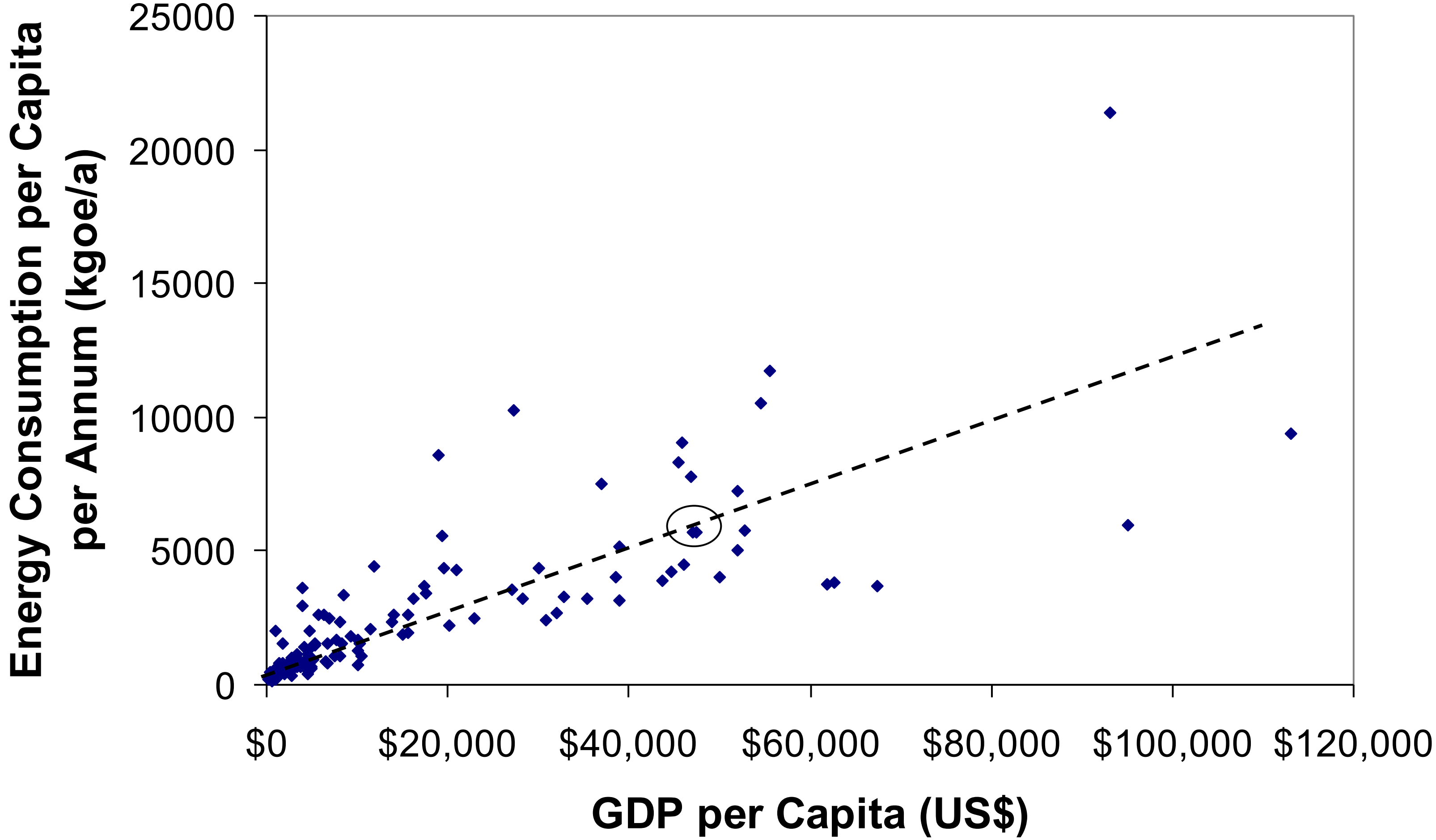
Energy Use and Economy



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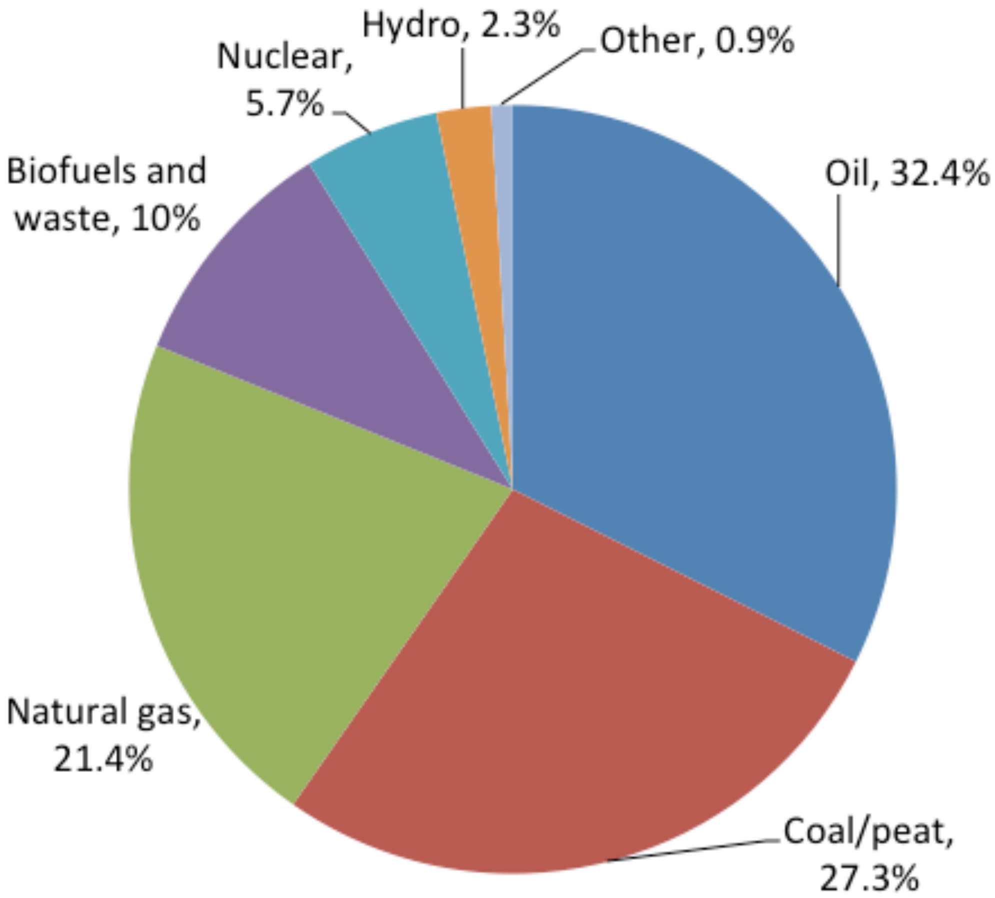
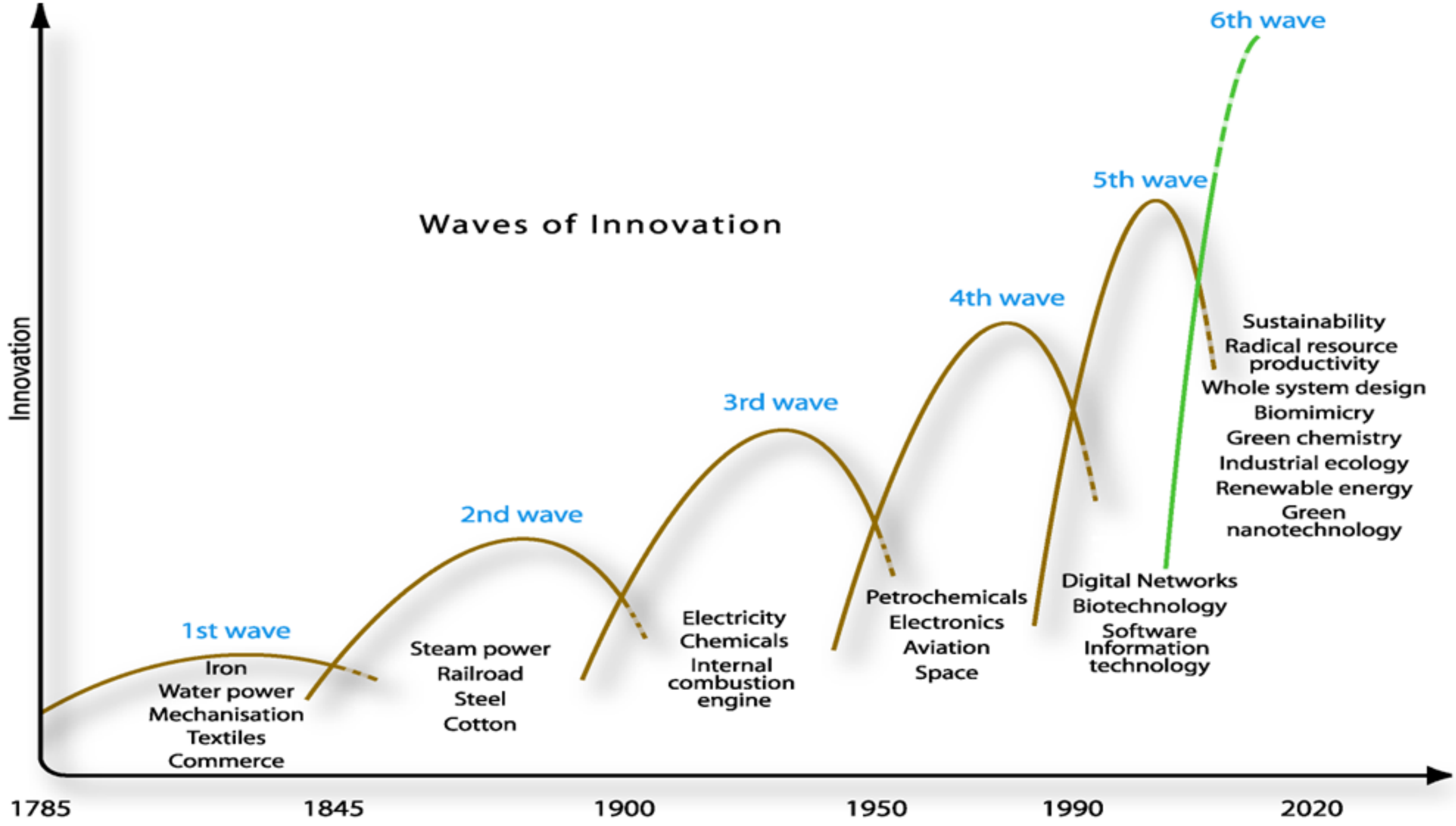
Total world primary energy production



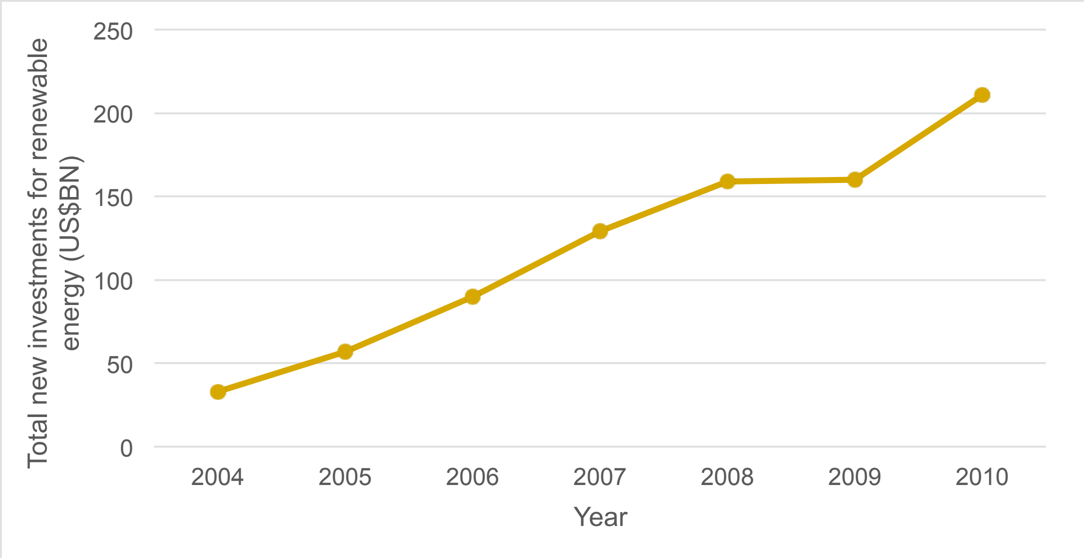
Source: IEA, International Energy Agency, Biofuels and Waste, 2013

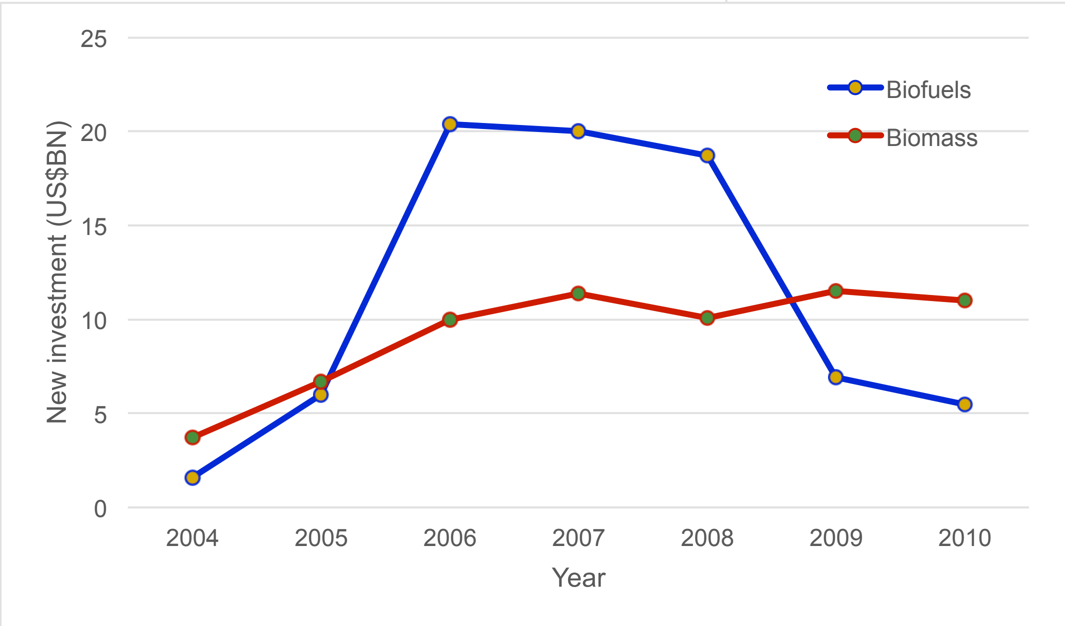
Innovation is the central issue in economic prosperity.
Michael Porter, Harvard Business School



Source: The Natural Edge Project
The Natural Advantage of Nations (Vol.I): Business Opportunities, Innovation and Governance in the 21st Century
http://www.naturaledgeproject.net/

Investments in renewable and biomass energy





Source: *McCrone, et al., Global Trends in Renewable Energy Investment 2011*

Definition of biomass

- any renewable material sourced from a biological origin and includes anthropogenic-modified material including products, by-products, residues and waste from agriculture, industry and the municipality

$CO_2 + H_2O + hv \rightarrow \{CH_2O\} + O_2$

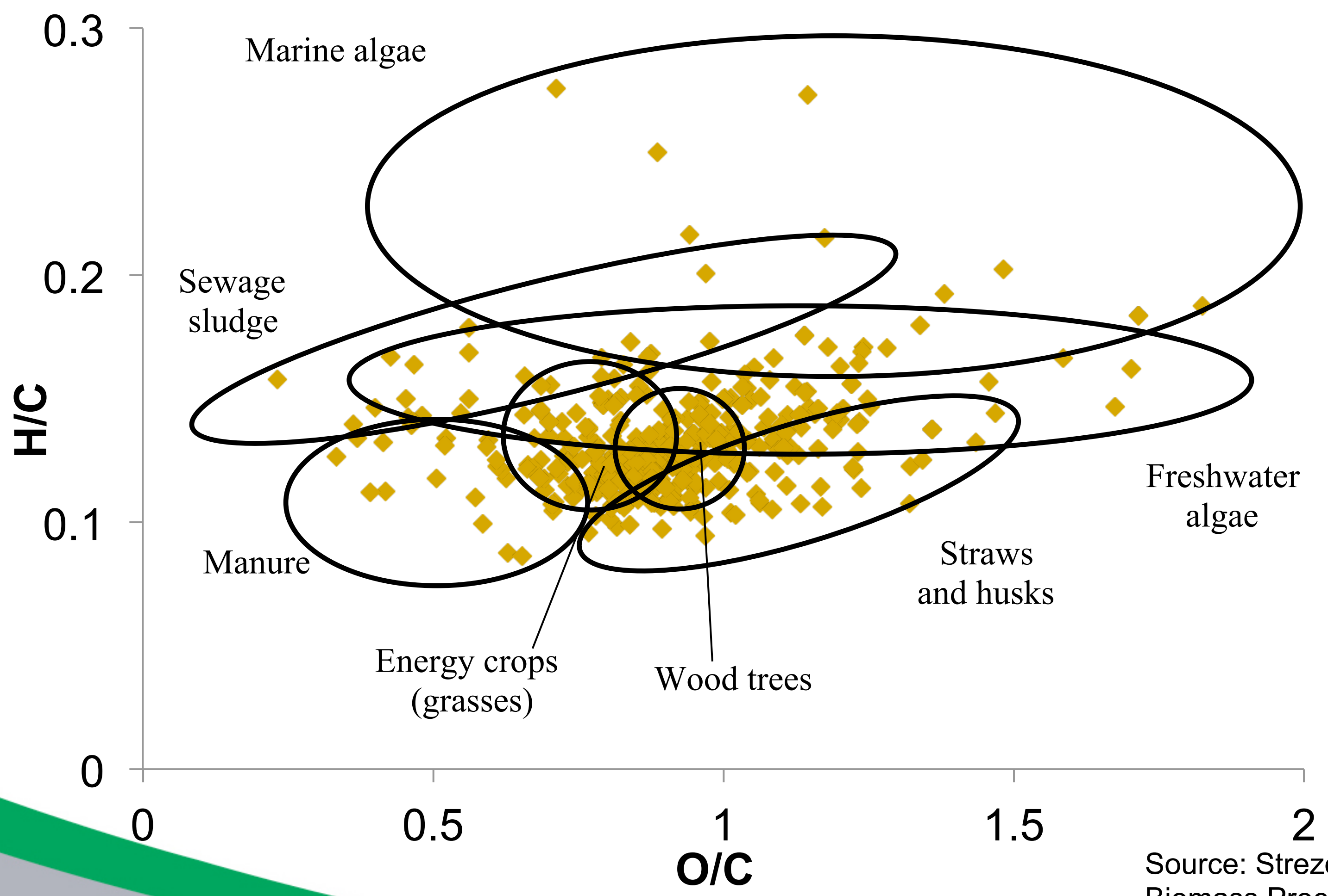
Where *hv* is the energy from the sun and

$\{CH_2O\}$ is the organic plant material with the basic form accepted to be that of glucose $C_6H_{12}O_6$

Source: McKendry, *Bioresource Technology*, 83, 37-46, 2002

Biological origin	Plants	Terrestrial	Wood	Roots		
				Trunk		
				Leaves		
			Non-wood	Herbaceous plants		
				Grasses		
			Fruit	Soft fruit		
				Seeds		
				Hard shells		
		Aquatic	Freshwater algae			
			Saltwater	Microalgae		
				Macroalgae		
	Animals	Tallow				
		Manure				
	Human	Sewage				
Biomass production route	Accidental (wastes and residues)	Weeds				
		Agricultural wastes				
		Forest wastes				
		Industrial and commercial wastes				
	Deliberately cultivated (energy crops)	Cultivation conditions	Soil	Biomass cultivated on agricultural soils		
				Biomass cultivated on marginal soils and degraded land		
			Water	Freshwater	Natural (creeks, rivers, lakes, sea, ocean)	Photobi reactor
				Saltwater		
		Edible properties	Edible (food crops)			
			Non-edible			
	Natural biomass	Biomass replanted after harvesting	Short regrowth rates			
			Long regrowth rates			
		Biomass not replaced after harvesting	Biomass regenerated naturally			
			Biomass regeneration suppressed by other plants and weeds			

H:C to O:C diagram

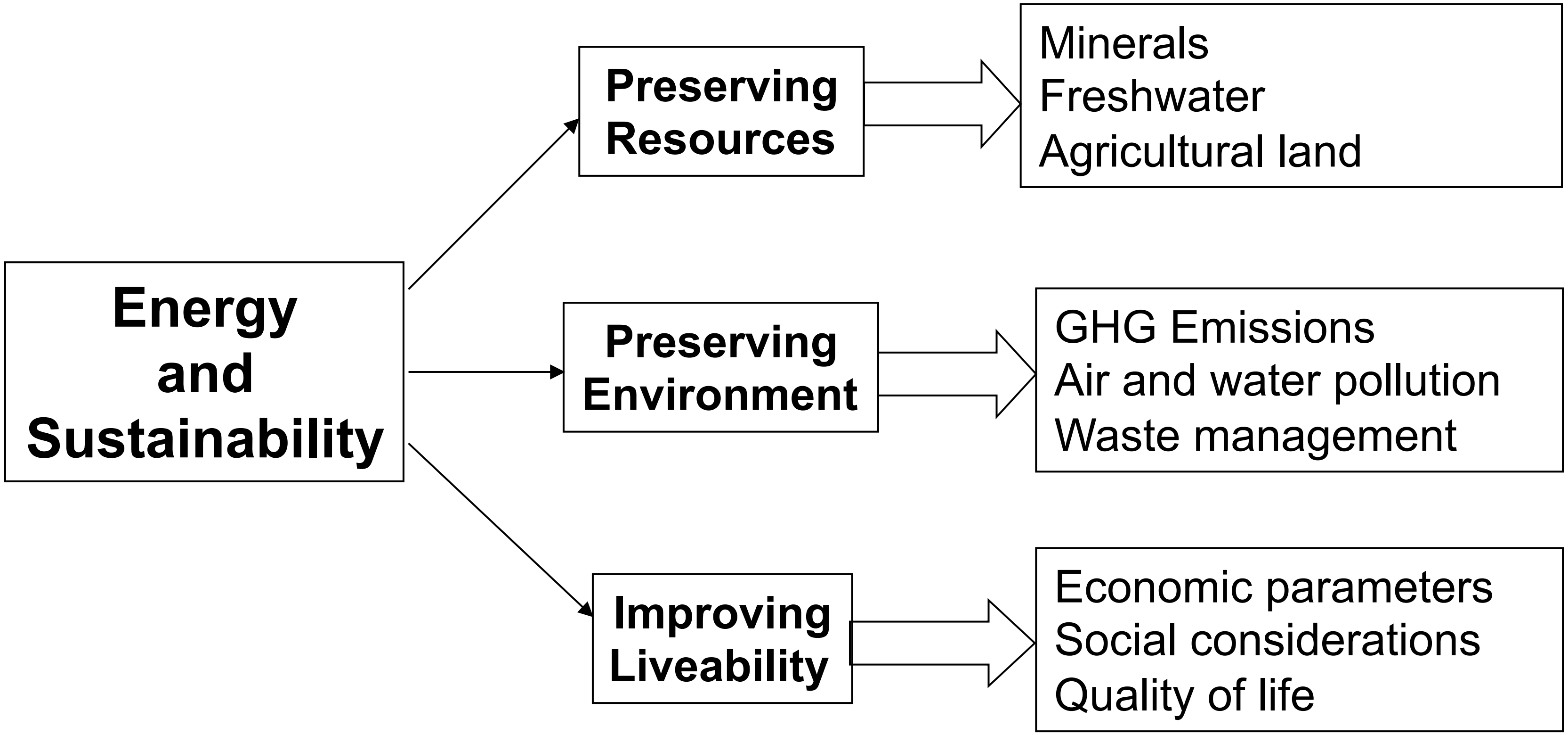


Source: Strezov and Evans, Biomass Processing Technologies, 2014

Biomass fuel quality

- Lipid to carbohydrate ratio (L/C)
  - L/C >0.5 suitable for biodiesel production
  - African oil palm L/C = 4.7
- Carbohydrate to fibre ratio (C/F)
  - C/F>5 indicates suitability for fermentation
- Moisture to Fixed Carbon ratio (moist/FC)
- Ash to Fixed Carbon ratio (ash/FC)
- Mineral matter properties
- Grindability

Energy and Sustainability



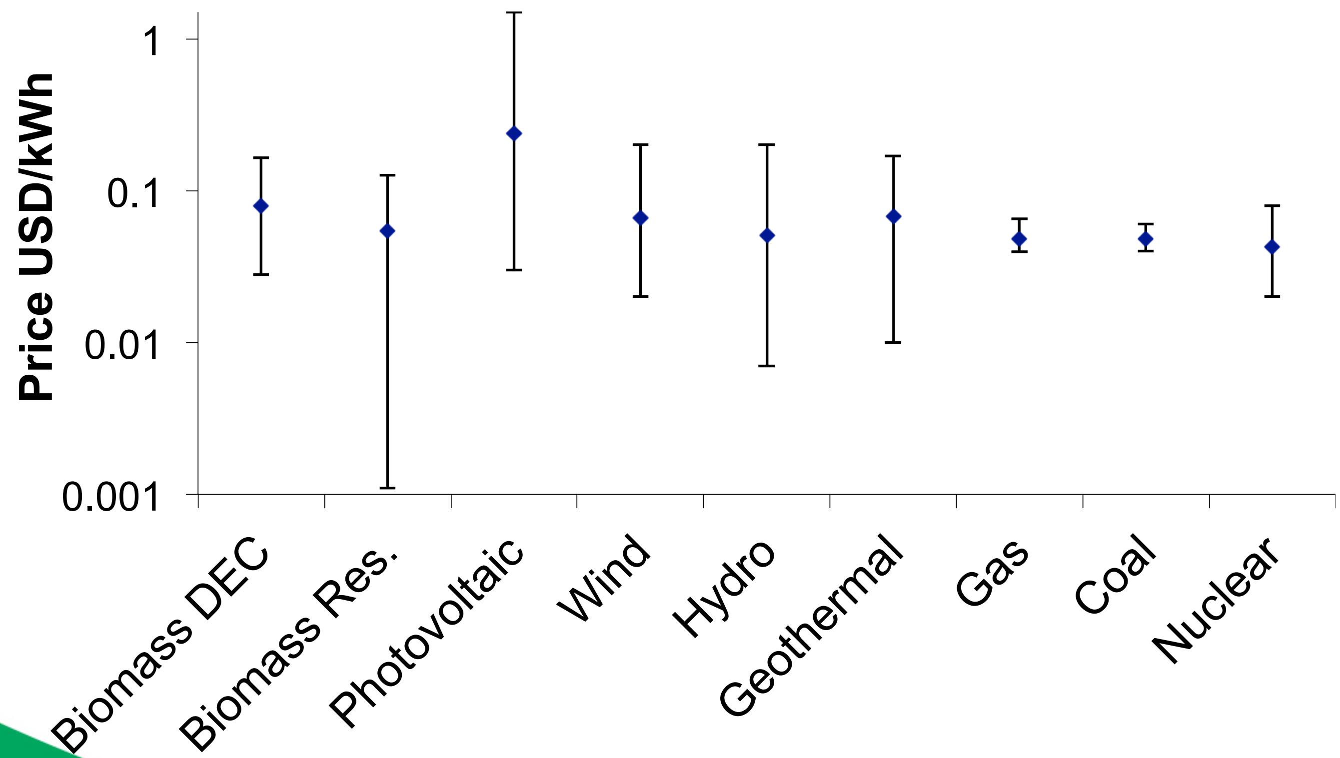
Sustainability Indicators for Power Generation Technologies

- Sustainability = Benefits / Risks

  Risk = Hazard + Outrage (P. Sandman, 1993)

- Parameters:
  - Cost of electricity
  - Greenhouse gas emissions
  - Availability of resources and technological limitations
  - Efficiency of energy generation
  - Land use
  - Water consumption
  - Social impacts

Typical Costs for Electricity Generation

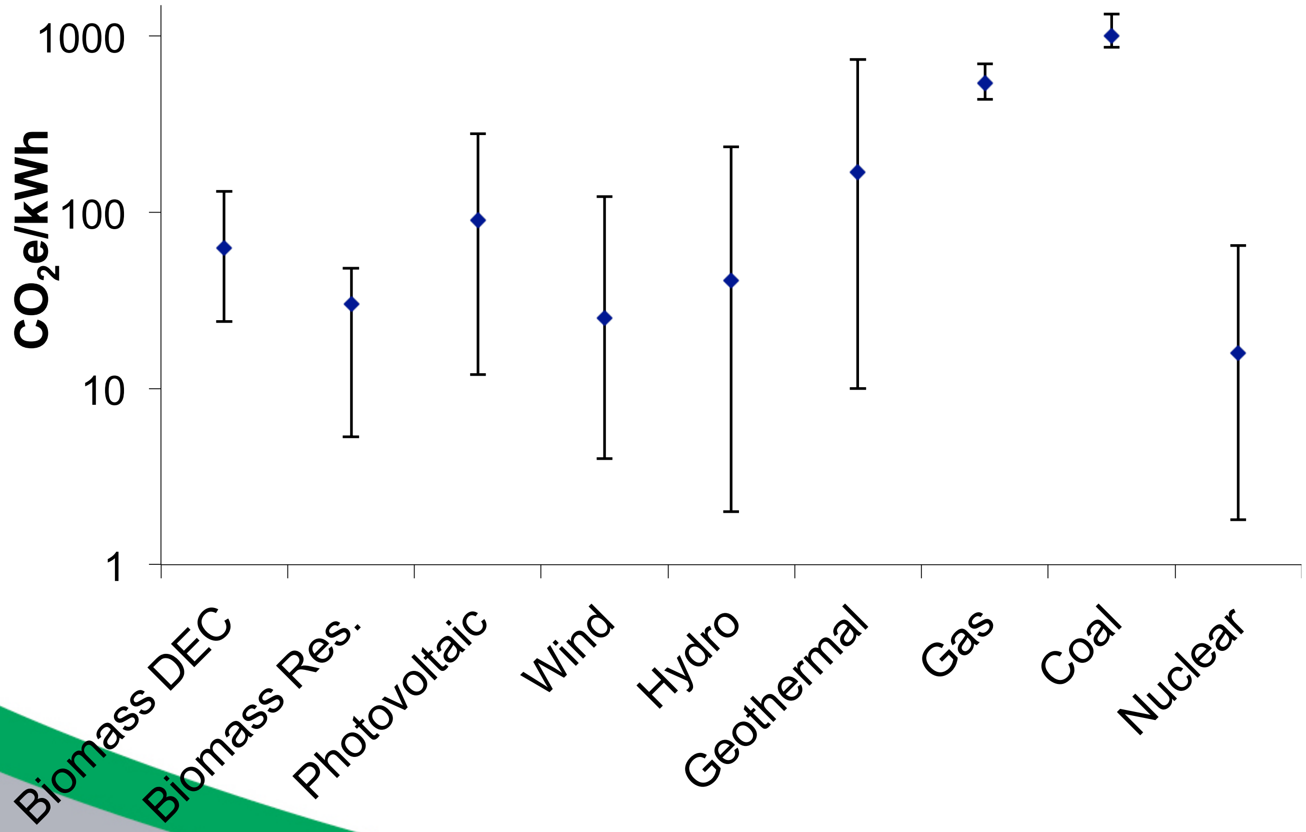


Mean Price USD/kWh:

Biomass	
DEC	$0.054
Res	$0.08
PV	$0.24
Wind	$0.07
Hydro	$0.05
Geoth	$0.07
Coal	$0.042
Gas	$0.048
Nucle	$0.043

Source: Evans et al., *Renewable and Sustainable Energy Reviews*, 13, 1082-1088, 2009

Greenhouse Gas Emissions for Electricity Generation



GHG emissions $gCO_{2\text{-}e}$/kWh:

Biomass	
DEC	62
Res	30
PV	90
Wind	25
Hydro	40
Geoth	170
Bioma	60
Coal	1000
Gas	543
Nucle	16

Source: Evans et al., *Renewable and Sustainable Energy Reviews*, 13, 1082-1088, 2009

Land Use and Water Consumption

Technology	Footprint m^2/kWh	Water use kg/kWh
Biomass DEC	0.553	90
Biomass Res.	0.001	78
Photovoltaic	0.045	0.01
Wind	0.072	0.001
Hydro	0.152	36
Geothermal	0.05	12
Gas	0.003	78
Coal	0.004	78
Nuclear	0.0005	107

Source: Evans et al., *Renewable and Sustainable Energy Reviews*, 13, 1082-1088, 2009

Survey

- Solar is the most popular technology by a significant margin with 50% of support
- Wind has high public support at 13%
- Geothermal and biomass are not well understood in Australia
- Hydro is favoured when existing dams are used, new dams are highly controversial
- 70% of Australians want to move away from coal and >75% do not want nuclear introduced

Sustainability Ranking

Ranking	Technology	Scaled Value
1	Wind	0.55
2	Hydro	0.57
3	Geothermal	0.70
4	PV	0.77
5	Biomass Residues	0.78
6	Gas	0.79
7	Nuclear	0.79
8	Coal	0.82
9	Biomass Crops	1

Sources:
Evans et al., *Renewable and Sustainable Energy Reviews*, 13, 1082-1088, 2009
Evans et al., *Renewable and Sustainable Energy Reviews*, 14, 1419-1427, 2010

Processing of biomass fuels

Thermochemical Processing	Combustion	Heat
		Steam
		Electricity
	Gasification	Steam
		Heat
		Electricity
		Methane
		Hydrogen
	Pyrolysis	Charcoal/biochar
		Biogas
		Bio-oil
	Hydrothermal processing	Charcoal
		Biogas
		Bio-oil
Biochemical Processing	Anaerobic digestion	Biogas
		Digestate
	Fermentation	Ethanol Fermentate
Physicochemical Processing	Esterification	Biodiesel

Biomass combustion

Cofiring with coal:
1) direct co-firing where biomass is pre-mixed with coal and then fed into the combustor along with coal;
2) parallel co-firing, where biomass and coal are combusted in separate combustors and the steam streams produced from different combustors then converge;
3) indirect co-firing, when the biomass fuel is firstly gasified separately and the produced gas is then combusted in the downstream coal boiler.

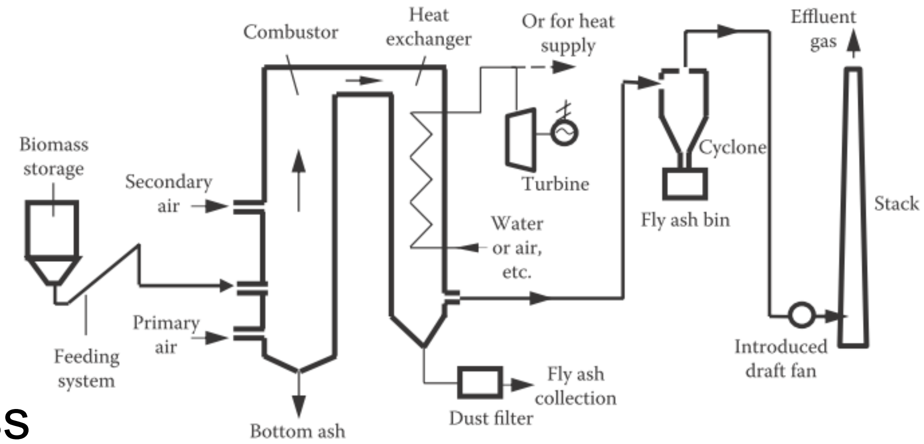
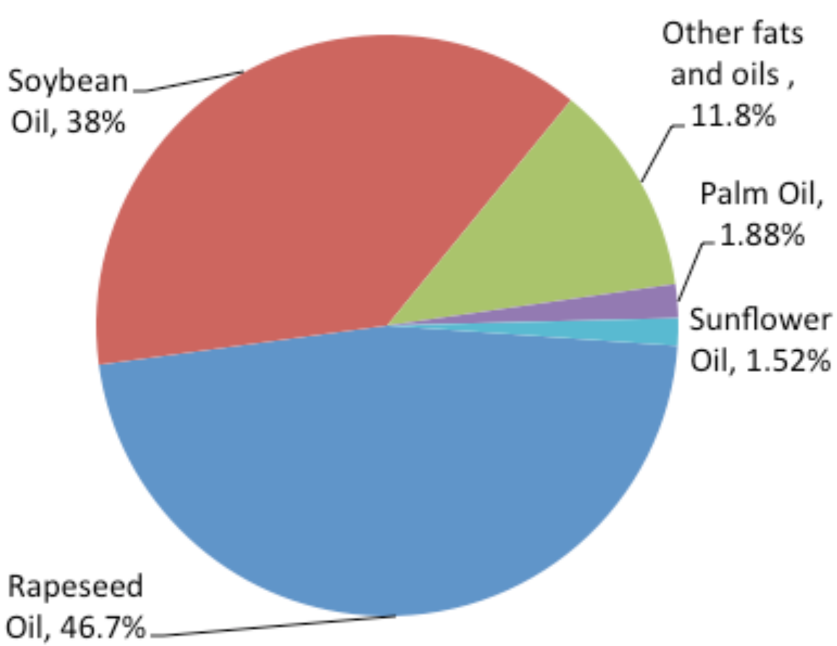


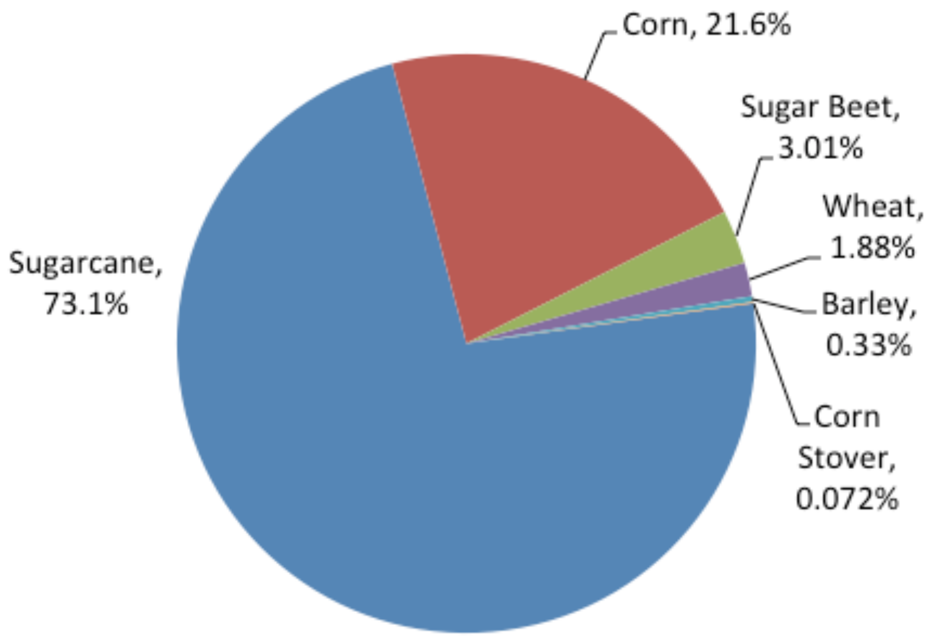
FIGURE 3.1
Basic components of an integrated boiler system for biomass combustion.

Source: Strezov and Evans, Biomass Processing Technologies, CRC Press, 2014

Biofuel production in 2012



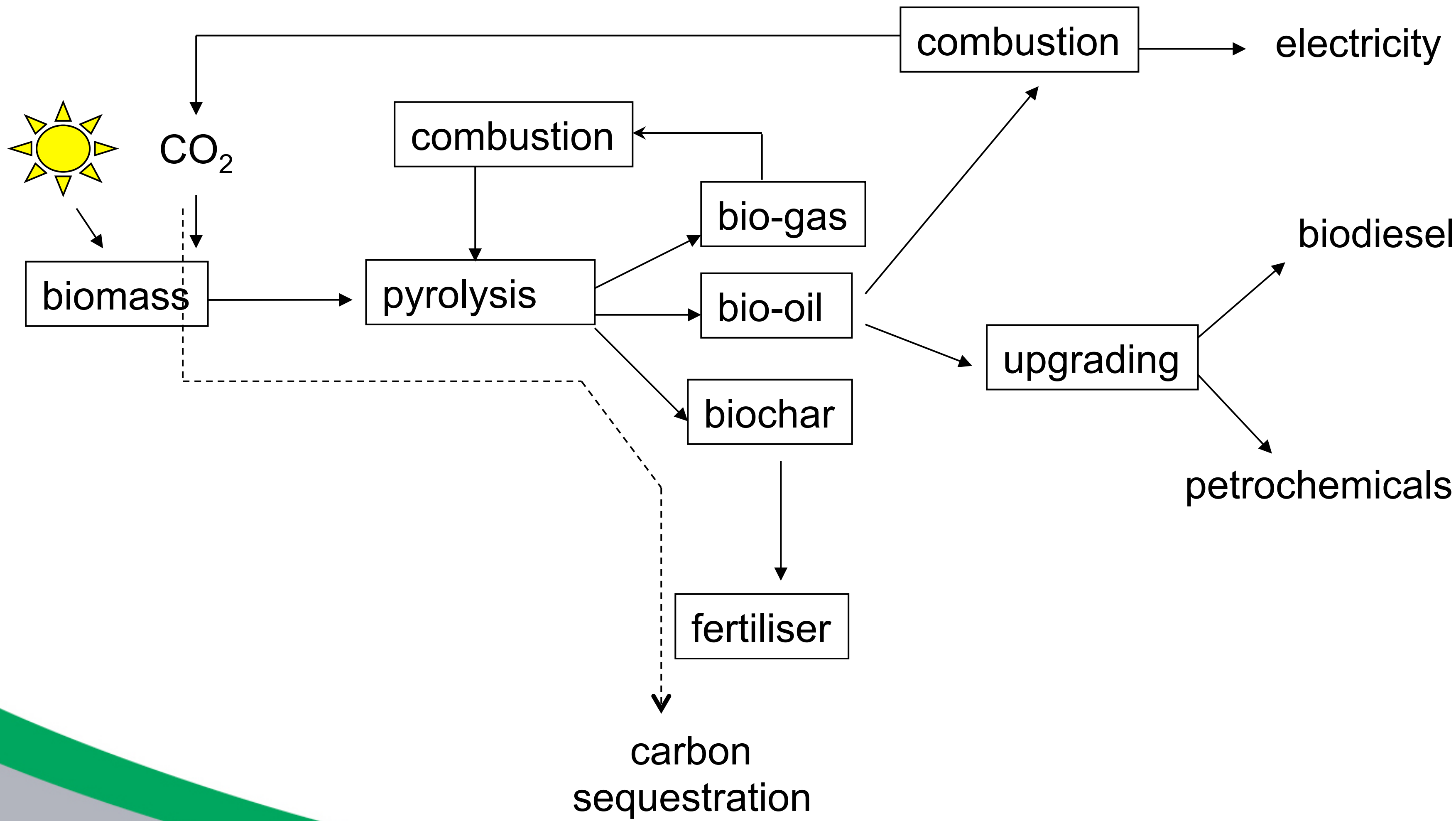
Biodiesel production



Ethanol production

Source: FAPRI (Food and agricultural policy research Institute), 2013

Biomass pyrolysis



Agricultural use of the biochar – Terra Preta Soils

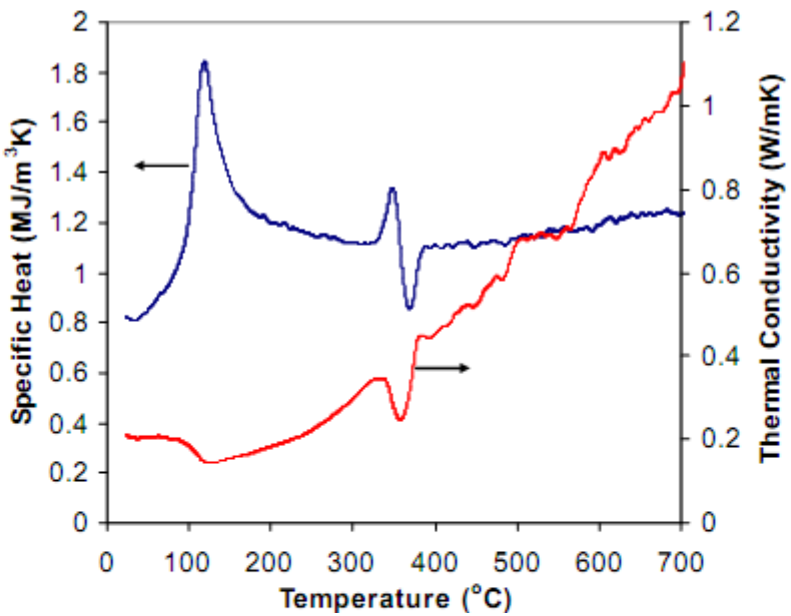
Source: Glacer, http://www.carbon-terra.eu/en/biochar/application/Terra_Preta

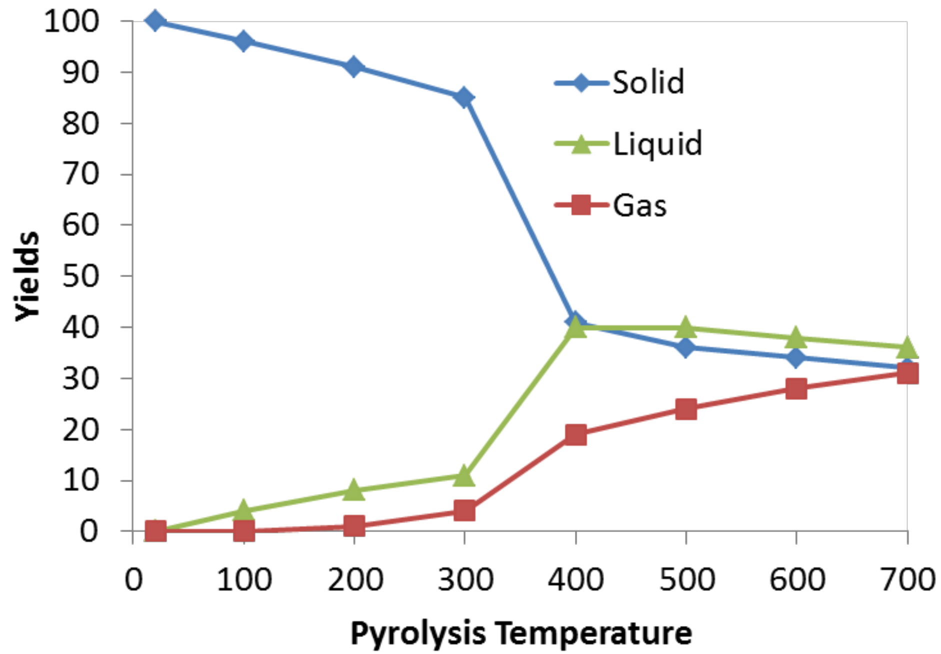
Terra Preta or “dark earth” are carbon-rich soils discovered in the Amazon region

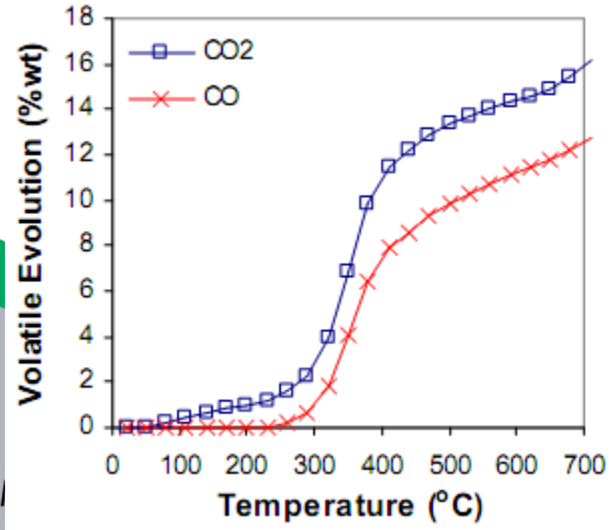
Biochar is now used to produce Terra Preta type of fertile soils as it improves:

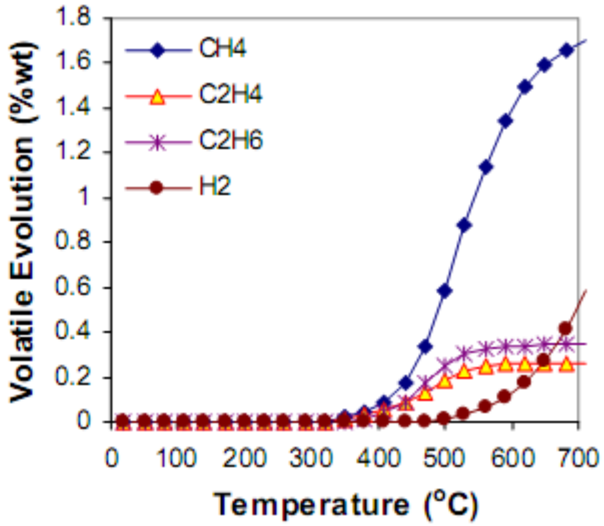
- Water holding capacity
- Soil aeration
- Improves microbial activity
- Stimulates nutrient dynamics
- Stops nutrient leaching
- Carbon mitigation

Paper Sludge Pyrolysis



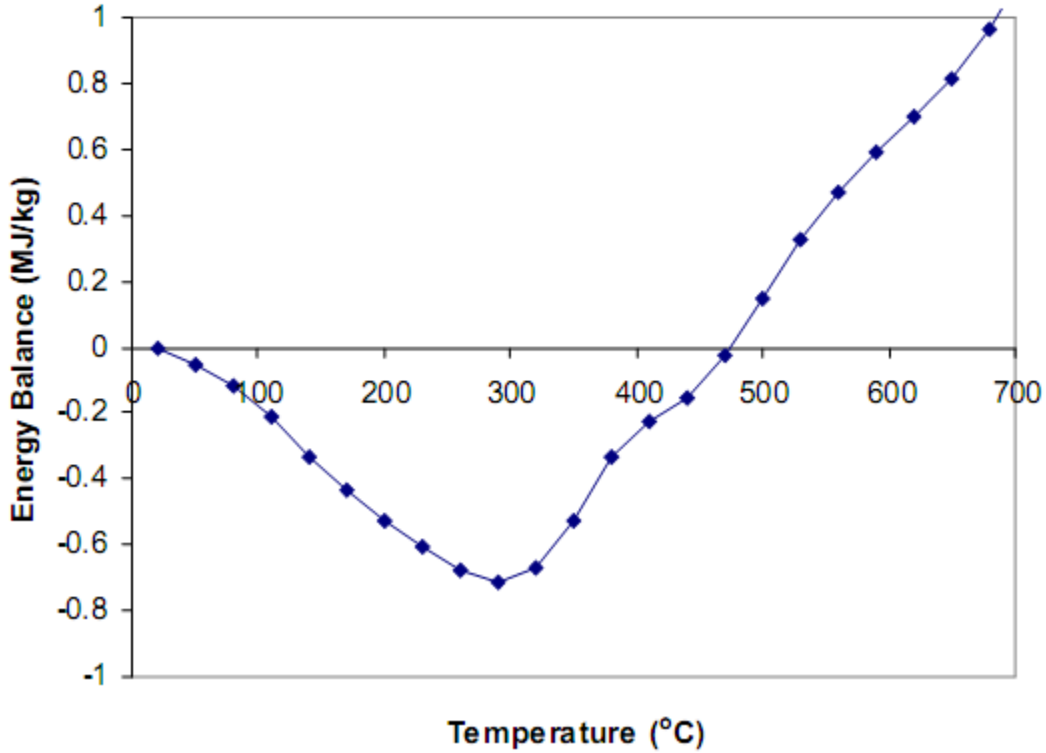






Strezov & Evans, *Waste Management*, 29, 1644-1648, 2009

Energy Balance for Paper Sludge Pyrolysis



For a dried paper sludge sample, the energy balance, becomes positive under stoichiometric and no-heat loss conditions at temperatures above 500 °C.

Strezov & Evans, *Waste Management*, 29, 1644-1648, 2009

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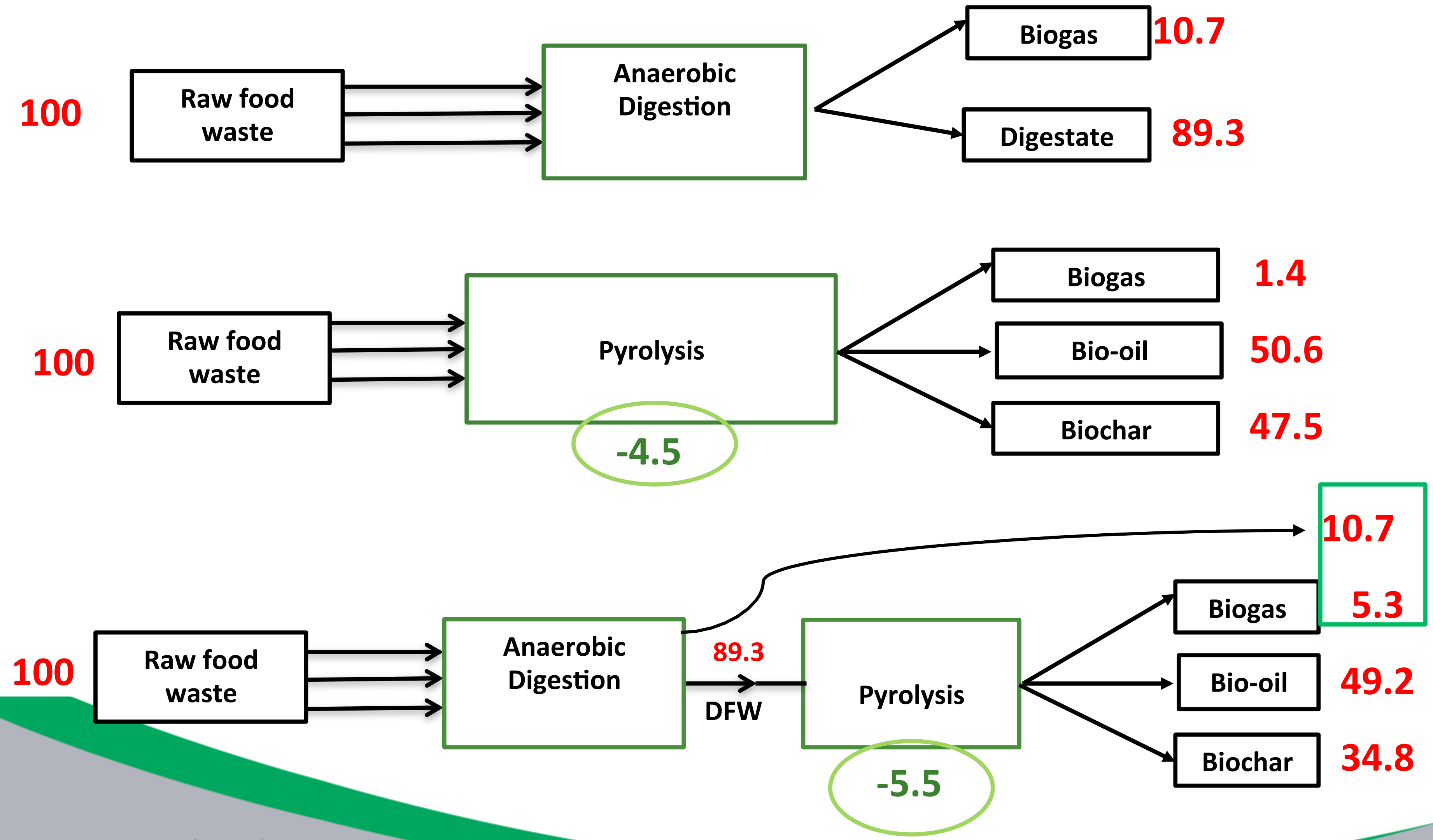
Food Waste Processing



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Source: Opatokun et al., Energy (in print)

Industrial-Scale Pyrolysis Facilities

Company	Process	Description	Location	Capacity	Feed	Primary Product	References
Kior	Fast pyrolysis	Catalytic pyrolysis (reactor type unknown)	Columbus, OH	500 t/day (dry)	Pine woody biomass	Oil	Kior Inc. 2013
Mitsubishi Heavy Industries/ Mie Chuo Kaihatsu	Slow pyrolysis	Indirect heating rotary kiln	Mie Prefecture, Japan	100 t/day	Woodchips	Gas	Koga et al. 2007; JSIM 2001; Machida et al. 2004
Ensyn	Fast pyrolysis	Circulating fluidised bed	Rhinelander, Wisconsin Renfrew, Canada	40 t/day (dry) 100 t/day (dry)	Hardwood wastes Wood residues	Oil	Ringer et al. 2006; Ensyn 2013; Bridgwater 2012

Selection of Pilot/Demonstration-Scale Pyrolysis Plants in Operation

Company	Process	Description	Location	Capacity	Feed	Primary Product	References
Pytec	Fast pyrolysis	Ablative pyrolysis	North Germany	6 t/day (demo)	Wood	Oil	Butler et al. 2011 Bridgwater 2012 Pytec 2013
University of Science and Technology of China	Fast pyrolysis	Fluidised bed	Hefei, China	120 kg/h (pilot), 15 t/day (demo)	Wood and agricultural waste	Oil	Zhu 2006 Wu et al. 2010
Kansai Corporation	Carbonisation	Heated kiln	Kyoto, Japan	12 t/day (demo)	Rice husk, greenwaste (pruned branches)	Char	Kansai Corporation 2013
Lurgi/ Forschungszentrum Karlsruhe	Fast pyrolysis (followed by gasification of liquid and charcoal product)	Twin screw fluidised bed	Karlsruhe, Germany	20 kg/h (pilot), 12 t/day (demo)	Straw, agricultural waste	Oil	Henrich 2007 Butler et al. 2011 Meier et al. 2013
BTG	Fast pyrolysis	Rotating cone	Netherlands	250 kg/h (dry)	Wood	Oil	Butler et al. 2011 Bridgwater 2012 BTG 2013
Pacific Pyrolysis	Slow pyrolysis	Heated kiln	New South Wales, Australia	300 kg/h (pilot)	Various	Char	Pacific Pyrolysis 2013
Chaotech	Slow/ carbonisation	Heated kiln	Queensland, Australia	100 kg/h (pilot)	Sawdust	Char	Chaotech Pty Ltd. 2013
Agri-therm	Fast pyrolysis	Fluidised bed	Mobile plants	5 t/day mobile plant	Agricultural wastes	Oil	Agri-therm 2013
ABRI-Tech	Fast pyrolysis	Auger	Ottawa, Canada	500 kg/h mobile plant	Wood waste	Oil	Meier et al. 2013

Source: Strezov and Evans, Biomass Processing Technologies, 2014

Typical Properties of Bio-Oil, and Light and Heavy Fuel Oils

Analysis	Pyrolysis Liquids	Light Fuel Oil	Heavy Fuel Oil
Water, wt %	20–30	0.025	0.1
Solids, wt %	<0.5	0	0.2–1
Ash, wt %	<0.2	0.01	0.03
Carbon, wt %	32–48	86	85.6
Hydrogen, wt %	7–8.5	13.6	10.3
Nitrogen, wt %	<0.4	0.2	0.6
Oxygen, wt %	44–60	0	0.6
Sulphur, wt %	<0.05	<0.18	2.5
Vanadium, ppm	0.5	<0.05	100
Sodium, ppm	38	<0.01	20
Calcium, ppm	100	Not analysed	1
Potassium, ppm	220	<0.02	1
Chloride, ppm	80	Not analysed	3
Stability	Unstable	Stable	Stable
Viscosity, cSt	15–35 at 40°C	3–7.5 at 40°C	351 at 50°C
Density (at 15°C), kg/dm^3	1.1–1.3	0.89	0.94–0.96
Flash point, °C	40–110	60	100
Pour point, °C	−10 to −35	−15	21
Conradson carbon residue, wt %	14–23	9	12.2
LHV, MJ/kg	13–18	40.3	40.7
pH	2–3	Neutral	Not analysed
Distillability	Not distillable	160°C–400°C	

Source: Chiaramonti, D. et al., *Renewable and Sustainable Energy Reviews* 11, 1056–1086, 2007.

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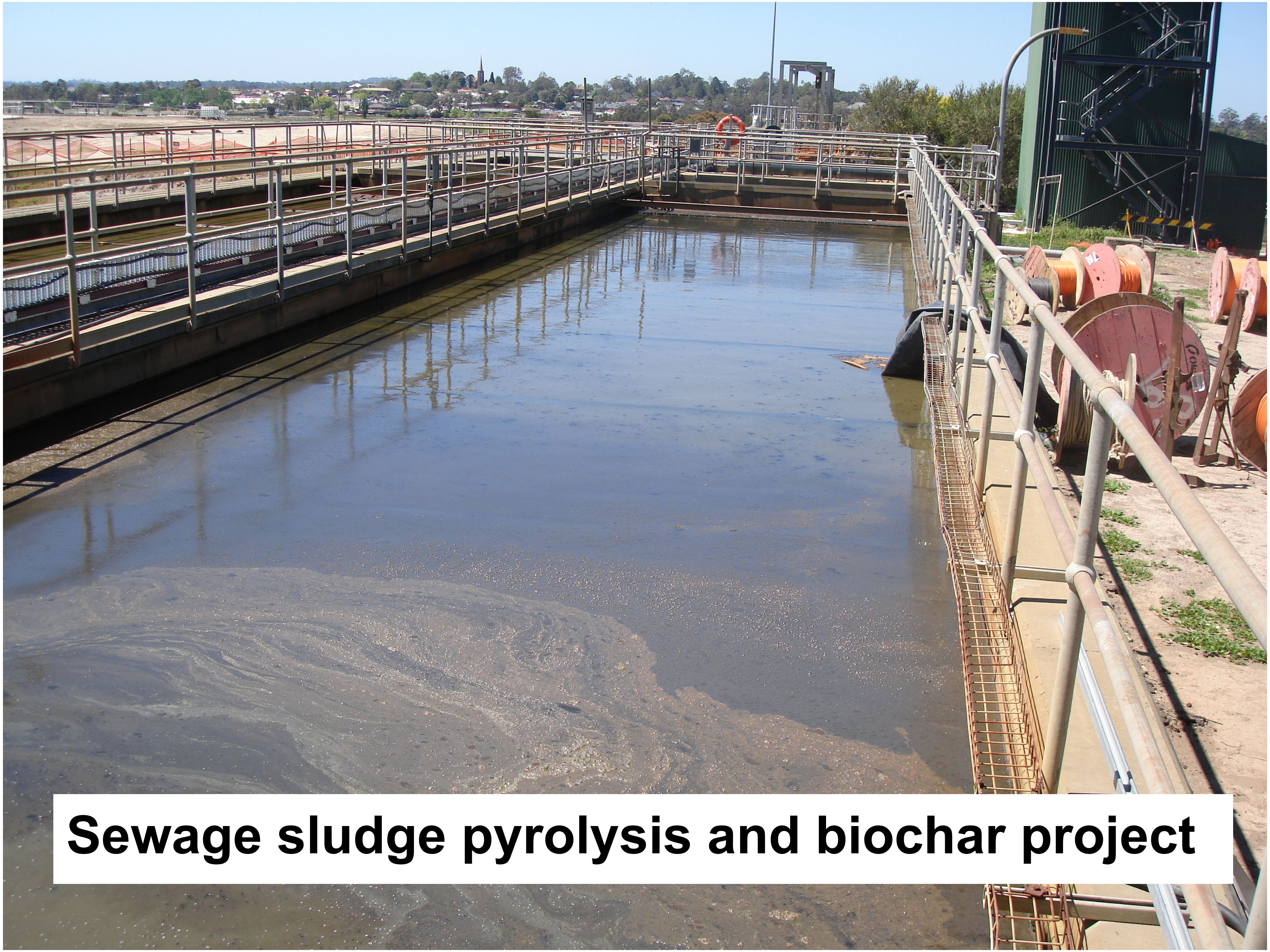


Sewage sludge pyrolysis and biochar project

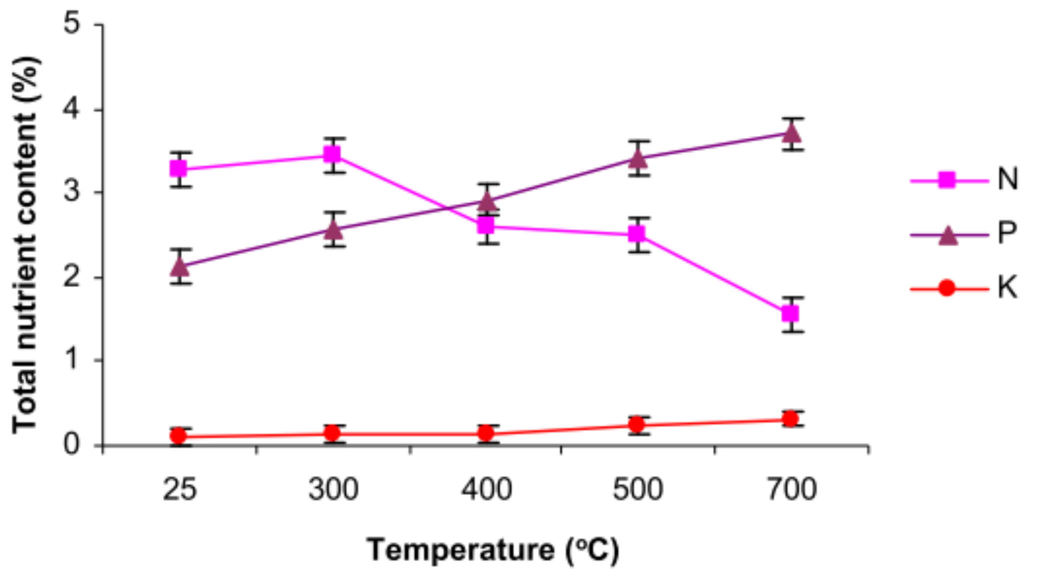
Sewage sludge pyrolysis

Comparison of the volatiles, liquids and char of different sample at 550 °C.

	B (commercial origin)	C (domestic origin)	M (industrial origin)
Gas (wt%)	5.7	5.6	4.2
Liquid (wt%)	42.7	30.4	51.1
Char (wt%)	51.6	64.0	44.7
Heat of combustion of bio-gas at 550 °C (kJ/kg)	825	660	370
Energy required to heat sample to 550 °C (kJ/kg)	730	1180	708

Hossain et al, *Journal of Analytical and Applied Pyrolysis*, 85, 442-446, 2009

Hossain et al, *Journal of Environmental Management*, 92, 223-228, 2011



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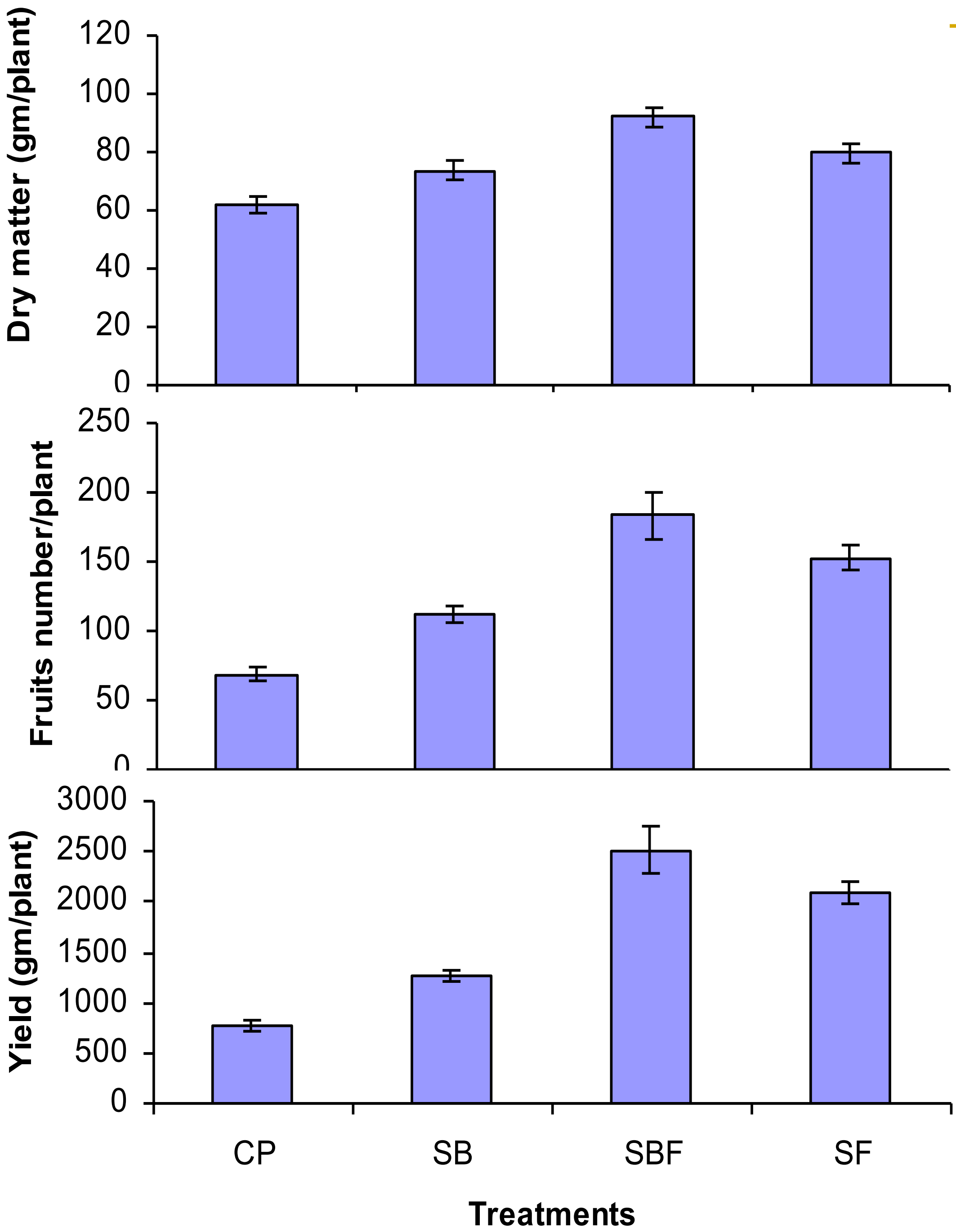
Tomato cultivation with sewage sludge biochar



Tomatoes grown in:

CP = soil only

SB = soil + 10% biochar

SBF = soil + biochar + fertiliser

SF = fertiliser

Hossain et al, *Chemosphere*, 78, 1167-1171, 2010

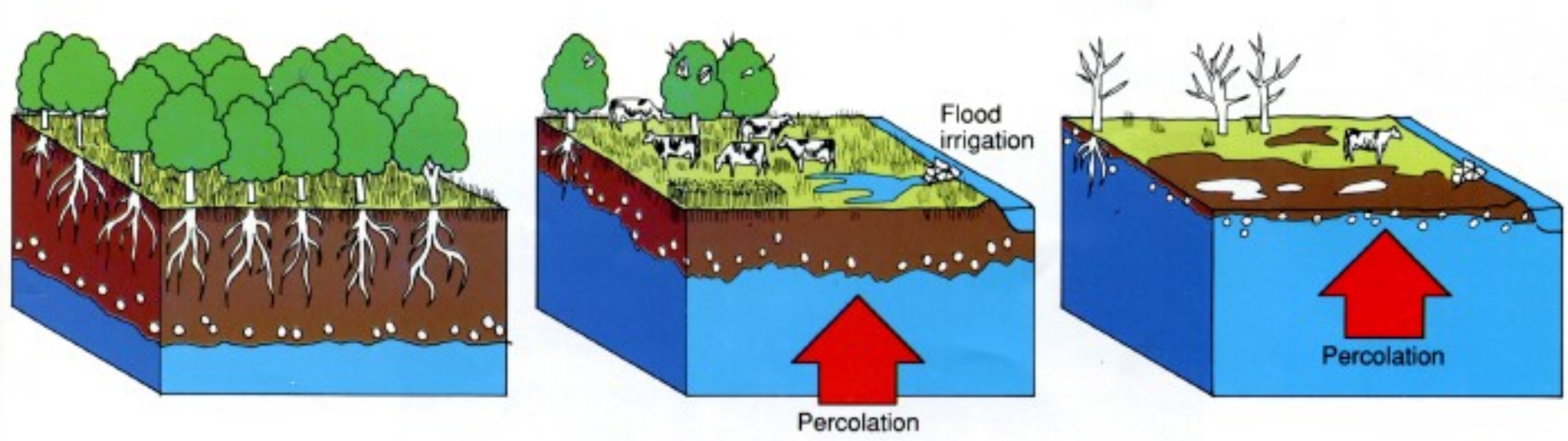
Concentration of metals and trace elements in wastewater sludge (WS) and sludge biochar and their bioaccumulation in fruits cultivated in soil amended with wastewater sludge (SS) and biochar (SB) comparing to Australian food standard limitations for heavy metals in food (mg kg^{-1})

Elements	WS	Biochar	SS	SB	Aus food standards
Arsenic	5.9	8.8	0.04	0.02	1.0
Cadmium	2.6	4.7	0.06	0.04	0.05-2
Chromium	94	230	<0.05	<0.05	-
Copper	660	2100	7.5	6.2	10-70
Lead	85	160	<0.01	<0.01	1.5-2.5
Nickel	54	740	2.8	1.2	-
Selenium	3.8	7	<0.05	<0.05	1.0
Zinc	1200	3300	26	22	150
Antimony	4.7	8	<0.01	0.01	1.5
Silver	16	29	<0.01	<0.01	-
Beryllium	1	1	<0.01	<0.01	-
Cobalt	430	21	0.09	0.03	-
Tin	130	310	<0.05	<0.05	50
Strontium	150	390	2.3	3.1	-

Source: Hossain et al., Pedosphere (in print)


Western Australia Mallee Tree Project

Soil salinity



Before clearing
The system is in balance.
Most water is used where it falls.

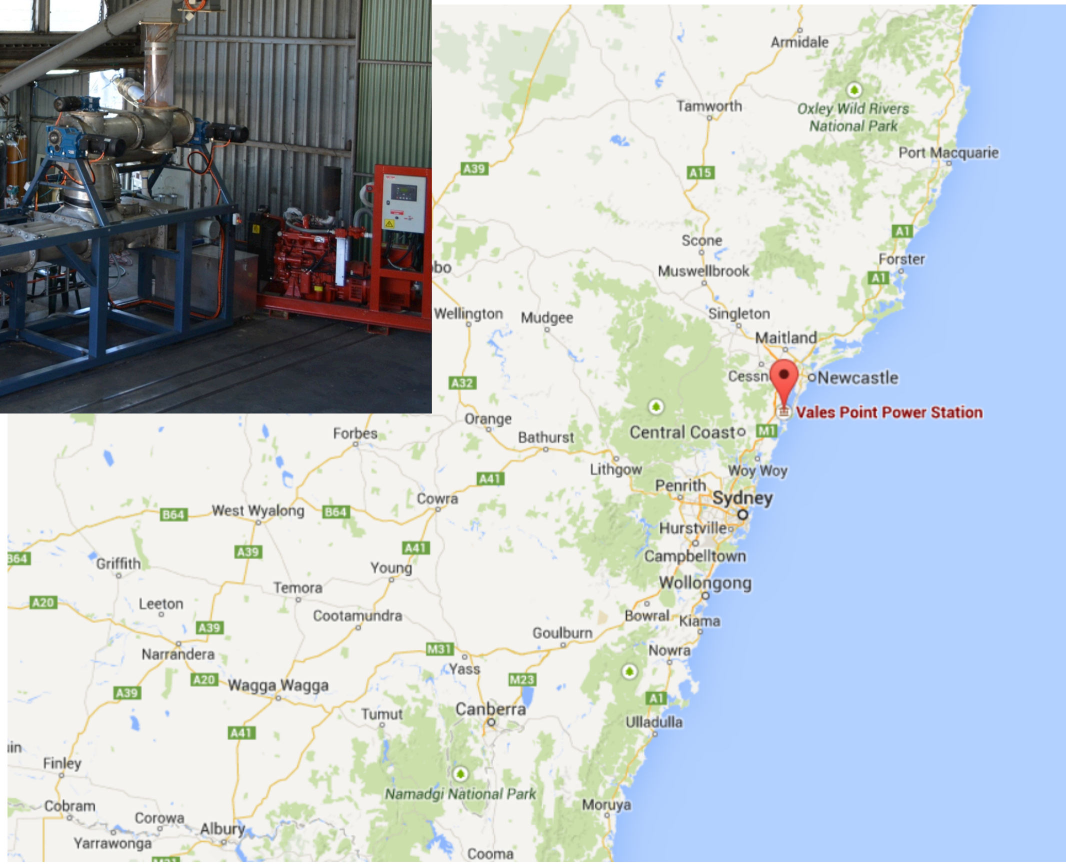
After clearing and irrigating
Evaporation and irrigation seepage concentrates saline groundwater at the surface.

Later
Protective plant cover is killed by the accumulation of salt at the surface.
The land is open to erosion.

Sources: http://vro.depi.vic.gov.au/dpi/vro/vrosite.nsf/pages/lwm_salinity_management_irrigation

Continuous Biomass Converter at Vales Point Power Station

Source: The Crucible Group Pty Ltd

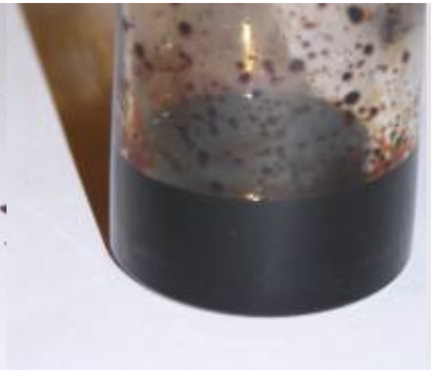


Algal biomass

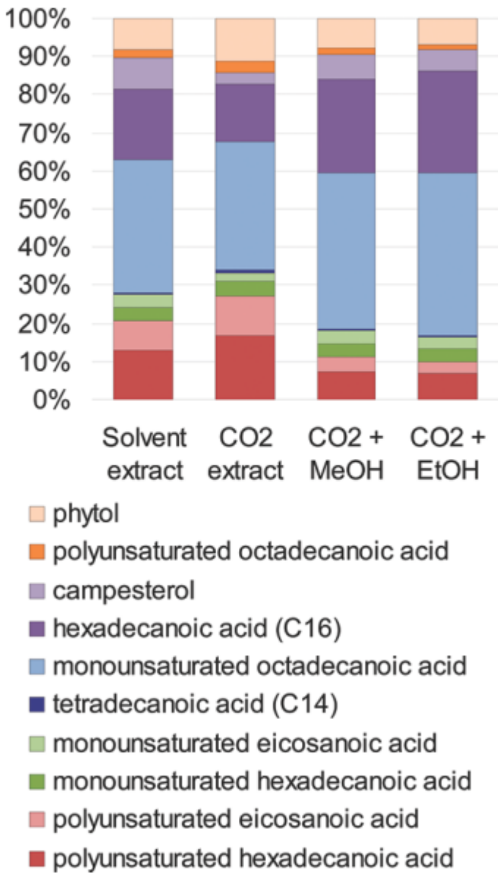
From: A. Ben-Amotz, Bio-Fuel and CO2 Capture by Algae, 2008

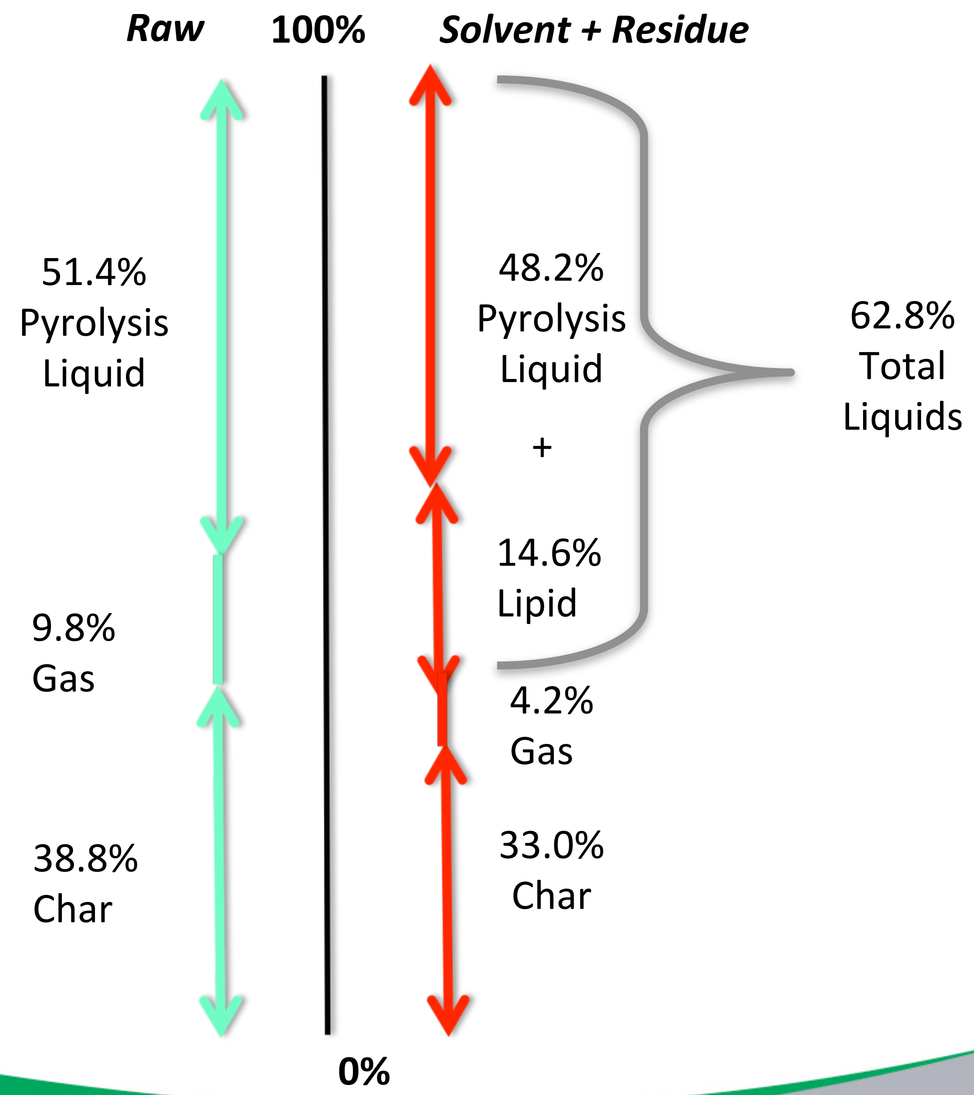
Bio-oil Extraction from Algae

Algae Biomass **Algae Bio-oil** **Algae Bio-char**


Processing of microalgae





Grierson et al, *Energy & Fuels*, 248-255, 2012

Conclusions

- Biomass will play one of the key roles in sustainable energy future
  - but, this is subject to how biomass is produced
- Standard classification of biomass properties and quality are needed
  - that will include physico-chemical properties, but also the biomass production route
- Some biomass technologies are already available, but the engineering systems needed for energy sustainability require further research

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- Mr Gary Leung, Macquarie University
- Dr Katrin Thommes, Macquarie University
- Ms Cara Mulligan, University of Newcastle
- Mr Suraj Opatoku, Macquarie University

Thank you!

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