Thermochemical conversion of Biomass

Combustion

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Biomass & Photosynthesis

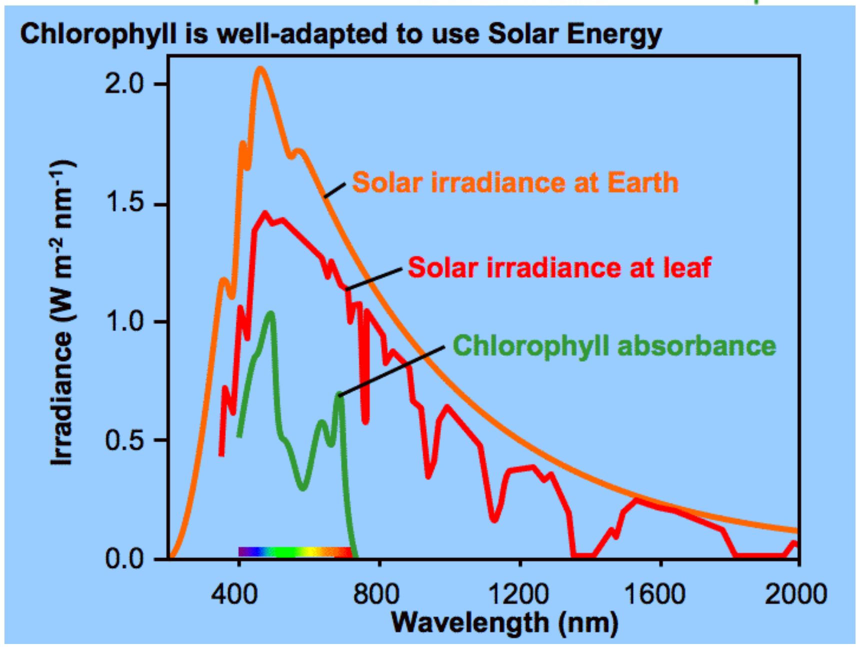
Ingredients | *Product*

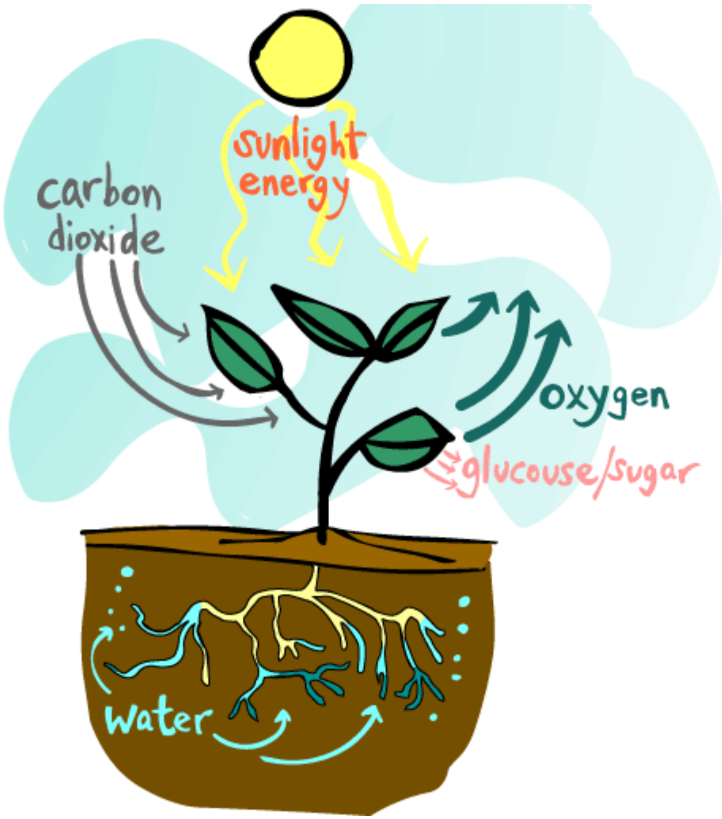
Sunlight +

$H_2O + CO_2 + \text{Nutrients} \rightarrow \text{“}CH_2O\text{”} + O_2$

Sun 2 LHV efficiency = 1 - 2%

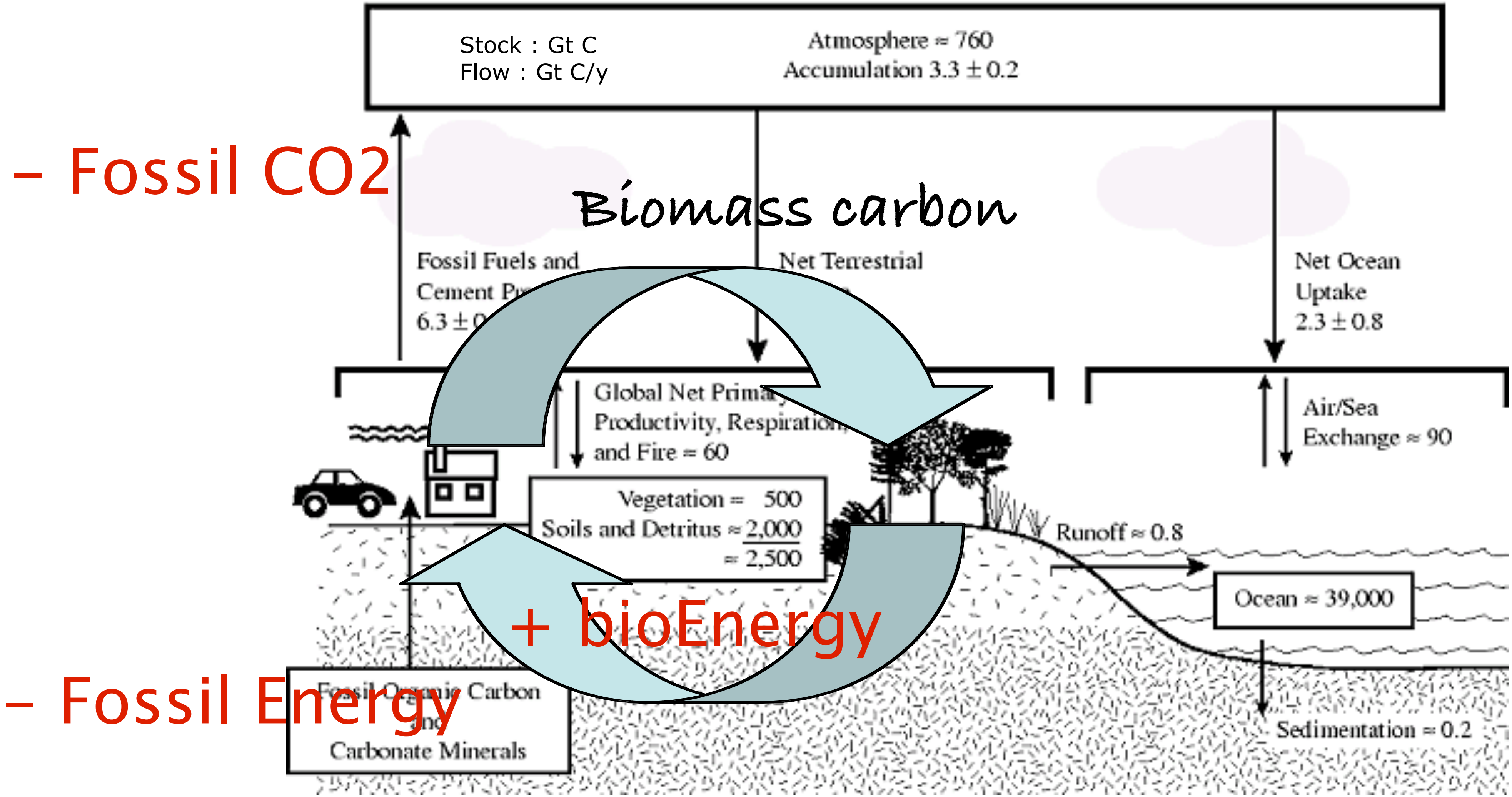
Water	Carbon dioxide	Nitrate NO_3 Phosphate PO_4 Iron Silica *among others*	“Organic matter”	Oxygen





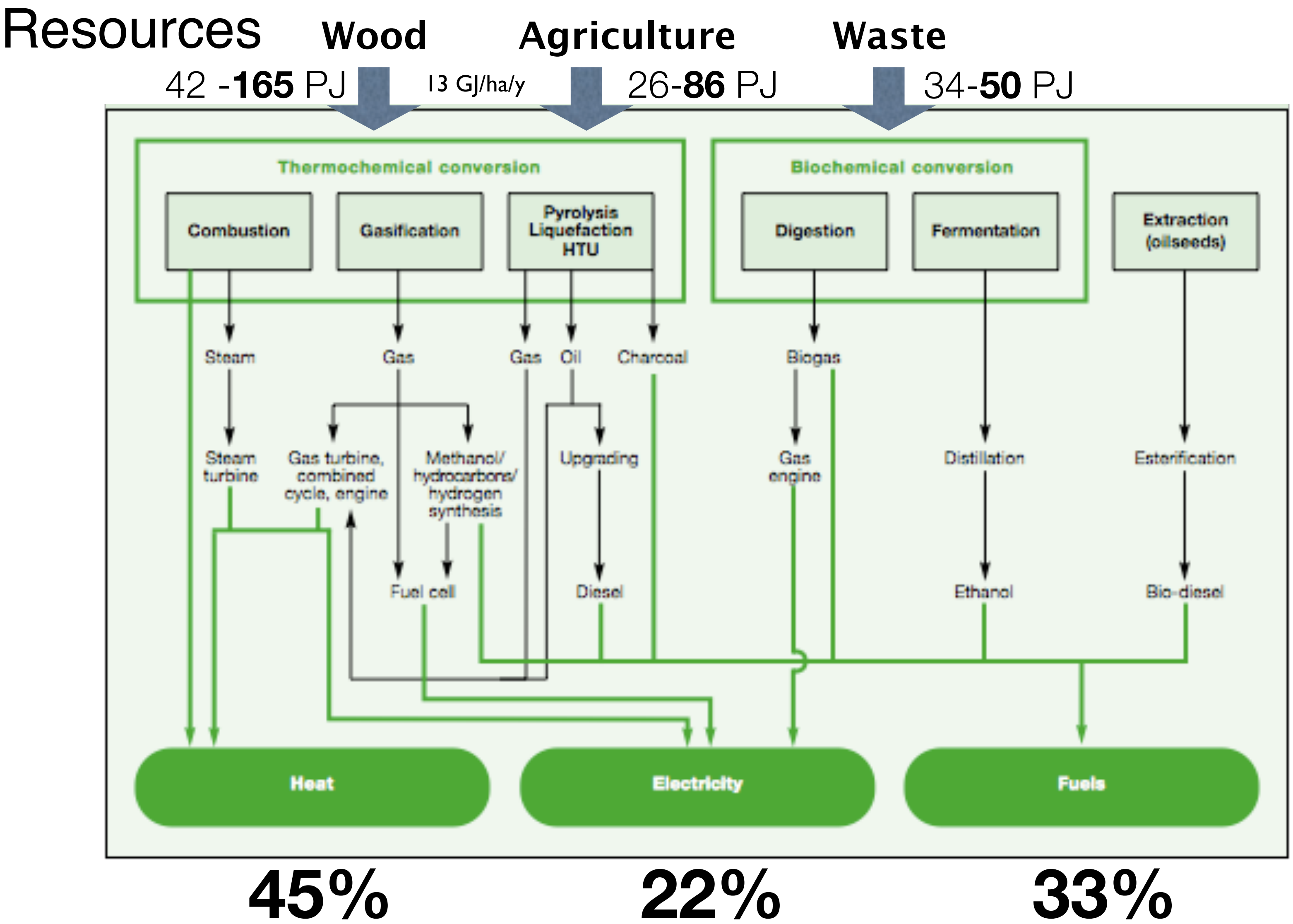
Source: http://www.sheppardsoftware.com

Biogenic CO2 cycle



Biomass conversion routes and production potential in Switzerland

sustainable -**Technical** in PJ/year



Figures for Switzerland (sustainable potential : total = 82-301 PJ)

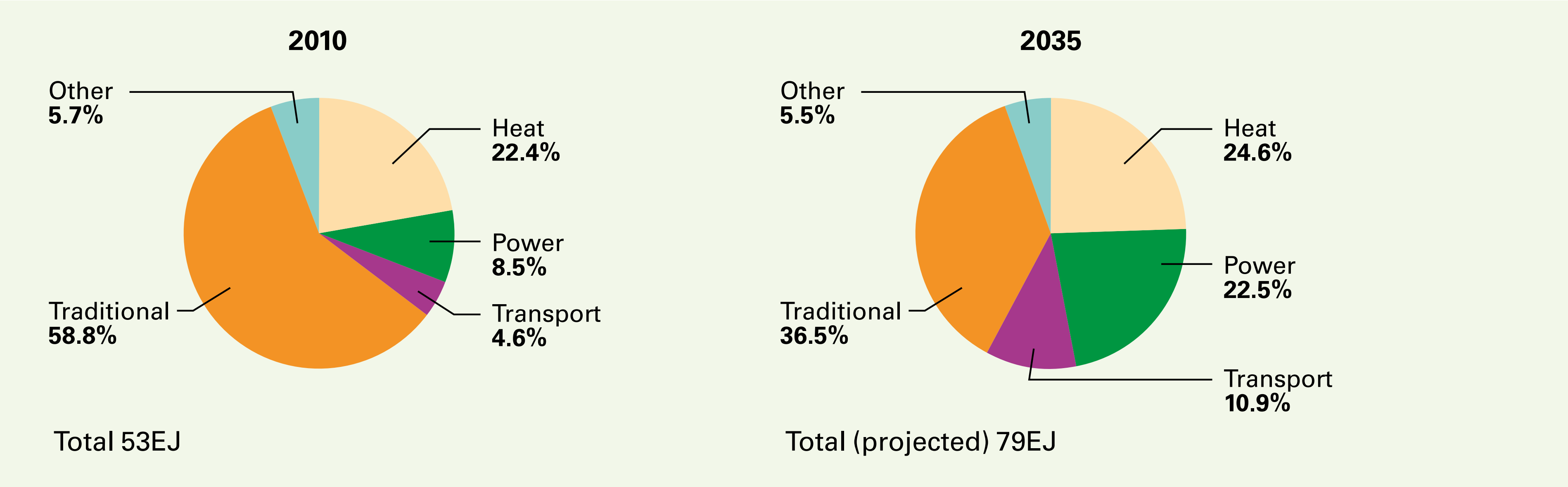
Source : world energy assessment : UNDP 2000

Bioenergy in Switzerland: assessing the domestic sustainable biomass potential
B Steubing, R Zah, P Waeger, C Ludwig
Renewable and Sustainable Energy Reviews 14 (8), 2256-2265

Bioenergy usage : projections

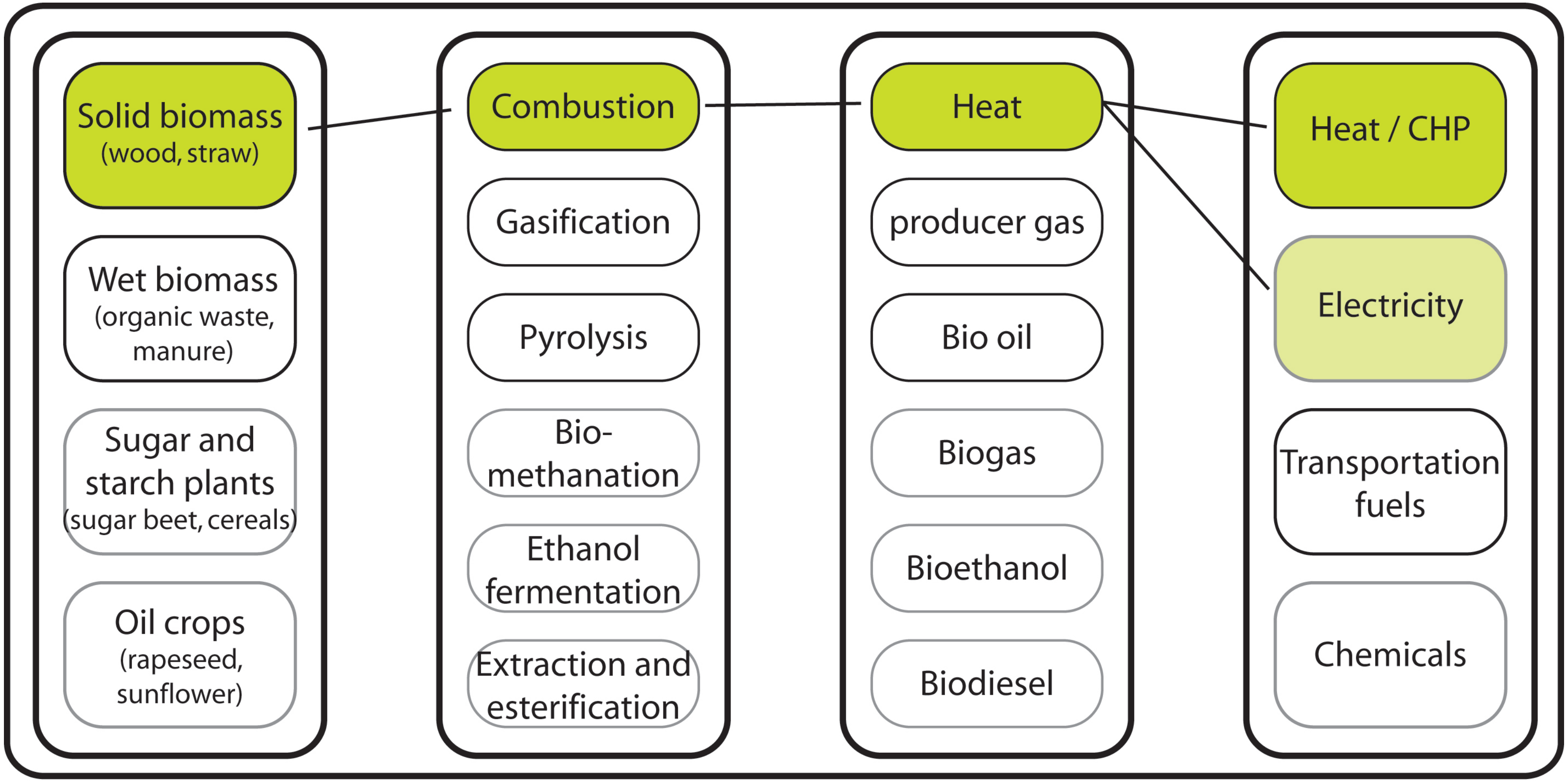
Figure 1.5

Use of bioenergy by sector in 2010 and 2035 (projected by the IEA for conditions where new policies are implemented). Use is estimated to rise from 53EJ in 2010 to 79EJ in 2035. The proportion used for heat by traditional methods (heating and cooking) is projected to fall considerably; the proportion used for heat via modern methods of production remains almost unchanged; while proportions used for power and transport by modern methods make significant increases[2].



Davis, S.C., Hay, W. & Pierce, J. (2014),
Biomass in the energy industry: an introduction.

Biomass conversion
Combustion



adapted from Chemical Engineering 10 (2006)

Heating value of biomass

- Higher heating value (20 MJ/kg$_{dry}$)
  - Boie formula

$$HHV = 35.17c_C + 116.26c_H - 11.10c_O + 10.47C_S + 6.28c_N$$

  - concentrations in (%mass)
- Lower heating value (17 MJ/kg$_{dry}$)

$$LHV_{dry} = HHV - \frac{\tilde{m}_{H2O}}{2}c_H * \Delta h_{vap} \qquad \Delta h_{vap} = 2441[kJ/kg]$$

- Humidity (2.5 MJ/kg$_{steam}$)

$$LHV_{wet} = HHV - (\frac{\tilde{m}_{H2O}}{2}c_H + \frac{\phi}{1-\phi}) * \Delta h_{vap}$$

$$\phi \quad in \quad \%mass$$

Typical heating value

substance name	ID in [4]	humidity[1] %wt	C	H	O	N	S	ash	HHV MJ/kg$_{dry}$	LHV$_{dry}$ MJ/kg$_{dry}$
			composition %wt							
municipal solid waste	1518	39	31.0	1.0	21.6	1.1	0.8	44.5	9.7	9.3
wet sewage sludge	2810	73	27.0	3.8	17.2	3.2	0.9	47.8	12.3	10.7
freshwater biomass	2319	84	54.6	6.7	23.4	6.7	0.4	8.2	24.9	23.3
fruit/vegetable waste	**2811**	**7**	**46.5**	**6.1**	**38.5**	**0.7**	**0.5**	**7.7**	**19.2**	**17.8**
cattle manure	**1885**	**13**	**13.0**	**1.5**	**10.1**	**1.5**	**0.3**	**73.6**	**5.3**	**4.1**
pig manure	**1366**	**92**	**35.4**	**4.5**	**21.5**	**2.8**		**35.8**	**15.2**	**13.7**
poultry manure	1872	4	35.9	5.0	27.4	3.6	0.8	27.4	15.7	14.2
sugarbeet	417	77	44.5	5.9	42.8	1.8	0.1	4.8	17.9	16.5
bagasse	894	10	48.6	5.9	42.8	0.2		2.4	19.2	17.9
grass	568	40	48.0	5.5	41.1	0.5	0.1	4.8	18.7	17.5
vine shoots	1253		46.9	5.9	44.2	0.8		2.2	18.4	17.1
straw	**2129**	**14**	**47.7**	**5.9**	**41.0**	**0.7**	**0.2**	**4.5**	**19.1**	**17.7**
wood	own data	50	50.7	5.7	42.7	0.2		0.7	19.8	18.5
lignin	2000	75	62.1	5.9	31.1	0.2	0.1	0.6	25.3	24.0
rapeseed	2156	5	58.7	8.6	23.5	3.7		5.5	28.3	26.3

[4] Phyllis, database for biomass and waste. Energy research center of the Netherlands, http://ecn.nl/phyllis.

Compared with other fuels

	HHV [MJ/kg]	LHV [MJ/kg]
Hydrogen	141.8	121
Methane	55.5	50
Gasoline	47.3	44.4
Paraffin	46	41.5
Kerosene	46.2	43
Diesel	44.8	43.4
Coal (Anthracite)	27	
Coal (Lignite)	15	
Wood (MAF)	21.7	

Wiki

Energy Densities of Various Fuels

Fuel	Particle Density	Bulk Density	Energy Density
	kg/m^3	kg/m^3	GJ/m^3 bulk product
Crude oil		855	35.8
Coal	1350	700	21
Natural gas (80 bar)		57	2.9
Biomass	450	230	3.7
Bio-oil		1200	20
Gasoline		760	35
Methanol		784	19

Source: Higgman

Disadvantage in volume

	Proximate Analysis [% by wt dry basis]			Ultimate Analysis [% by wt dry basis]					HHV $[MJ/kg_{db}]$
	FC	VM	ASH	C	H	O	N	S	
Coal - 8 Anth	84.59	7.09	8.32	83.67	3.56	2.84	0.55	1.05	32.856
Woodchips	23.5	76.4	0.1	48.1	5.99	45.74	0.08	0	19.916
Eucalyptus	21.3	75.35	3.35	46.04	5.82	44.49	0.3	0	18.64
Wheat straw	23.5	63	13.5	45.5	5.1	34.1	1.8	–	17
Miscanthus	12.4	87.2	0.4	–	–	–	–	–	19.297

Parikh 2005

the presence of oxygen is reducing the heating value

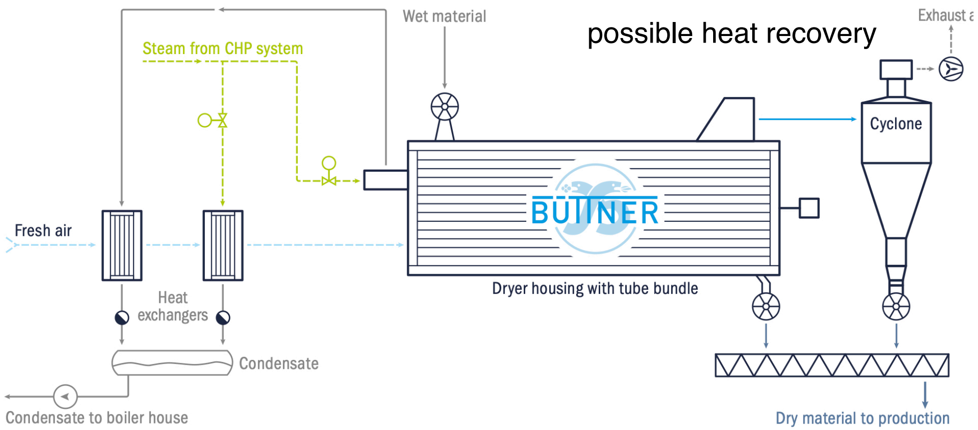
Life cycle emissions compared with other resources

Supply chain needs to be considered !

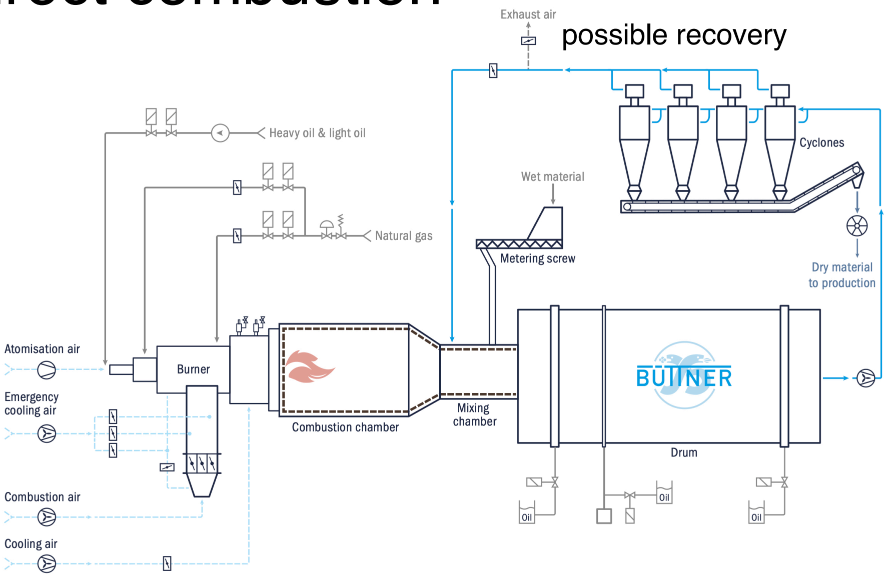
		Natural gas	Wood	Gasoline	Diesel
	kg/m3	700	240	800	800
LHV	MJ/kg	50	17.8	44.4	43.4
	GJ/m3	0.0359	5.3-9.6	35.5	34.7
CO_2	g CO_2/MJ	49.3	0	67	72
supply eq CO_2	g CO_2/MJ	11.6	1.6 - 2.9	16.7	13.4
	g CO_2/MJ	60.9	1.6-2.9	83.7	85.4
		19%	-	20%	16%
Cost	cts/kWh	10	3 - 7.5	18.6	19.2
industry	cts/kWh	3.4			

Biomass drying

Indirectly heated dryer



Direct combustion



Equilibrium humidity of wood

$$\begin{aligned}\Phi_{wood} &= 2.865 \cdot 10^{-2} \varphi_{air}^{1/2} \\ &\quad + (2.307 \cdot 10^{-1} - 1.273 \cdot 10^{-3}(T - 273))\varphi_{air} \\ &\quad - 2.519 \cdot 10^{-1} \varphi_{air}^{2} \\ &\quad + (2.199 \cdot 10^{-1} + 8.630 \cdot 10^{-4}(T - 273))\varphi_{air}^{3} \end{aligned} \tag{2.7}$$

In this equation, Φ_{wood} terms the wood humidity in $\text{kg}_{H2O}\ \text{kg}_{tot}^{-1}$, φ_{air} the relative humidity of air in % and T the air temperature in K.

Relative humidity calculated by the partial pressure of saturation

$$P^{sat}[atm] = 0.001315 \cdot 10^{\left(8.07131 - \frac{1730.63}{233.426 + T[^{o}C]}\right)}$$

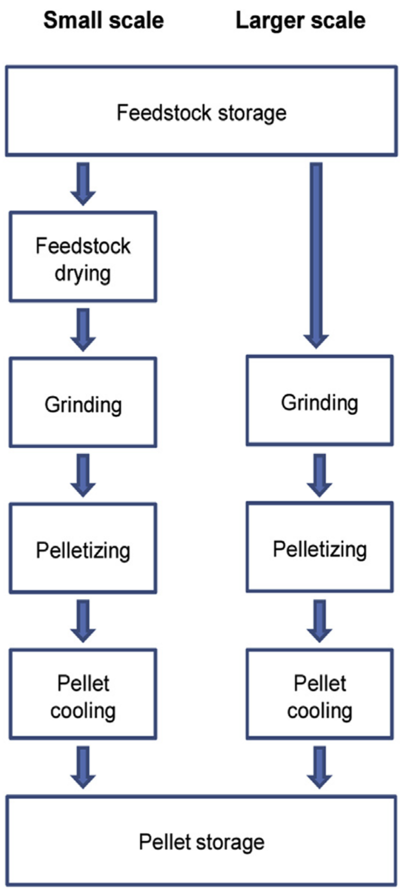
Mass transfer modelled by partial pressure driving force

$$\frac{\dot{m}_{H2O,vap}}{\dot{m}_{air}} = U_p \Delta p_{lm} \qquad \text{with} \qquad \Delta p_{lm} = \frac{\Delta p_1 - \Delta p_2}{\ln(\Delta p_1 / \Delta p_2)}$$

$$U_p = 11.0 \quad 10^{-3} [bar^{-1}]$$

Pellet production

- Consumes around 9% of the Heating Value
- Pellets are dried and uniform in sizes => easier to process and to transport



in EU : Biomass = 60% of the total cost

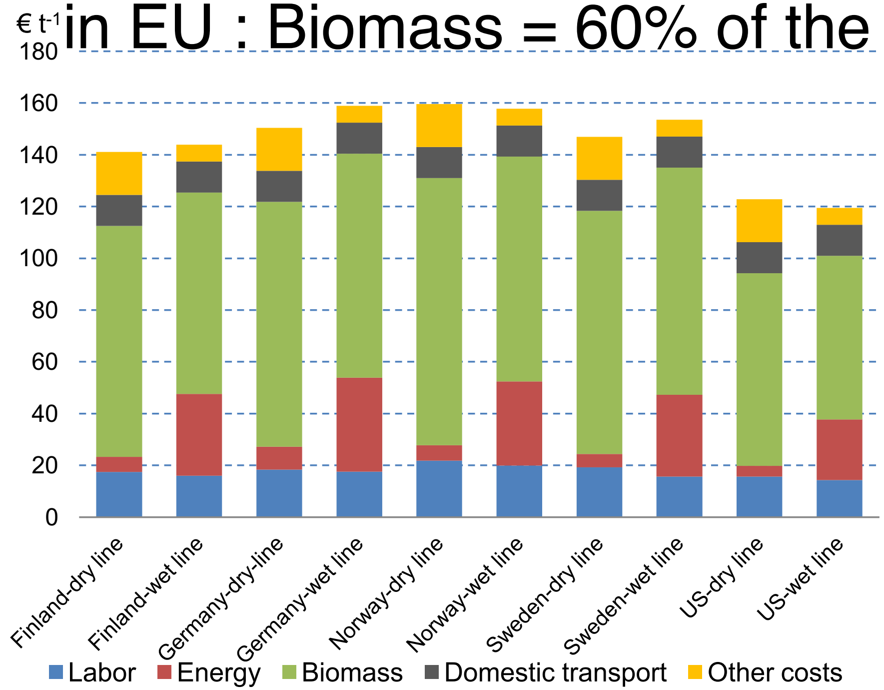
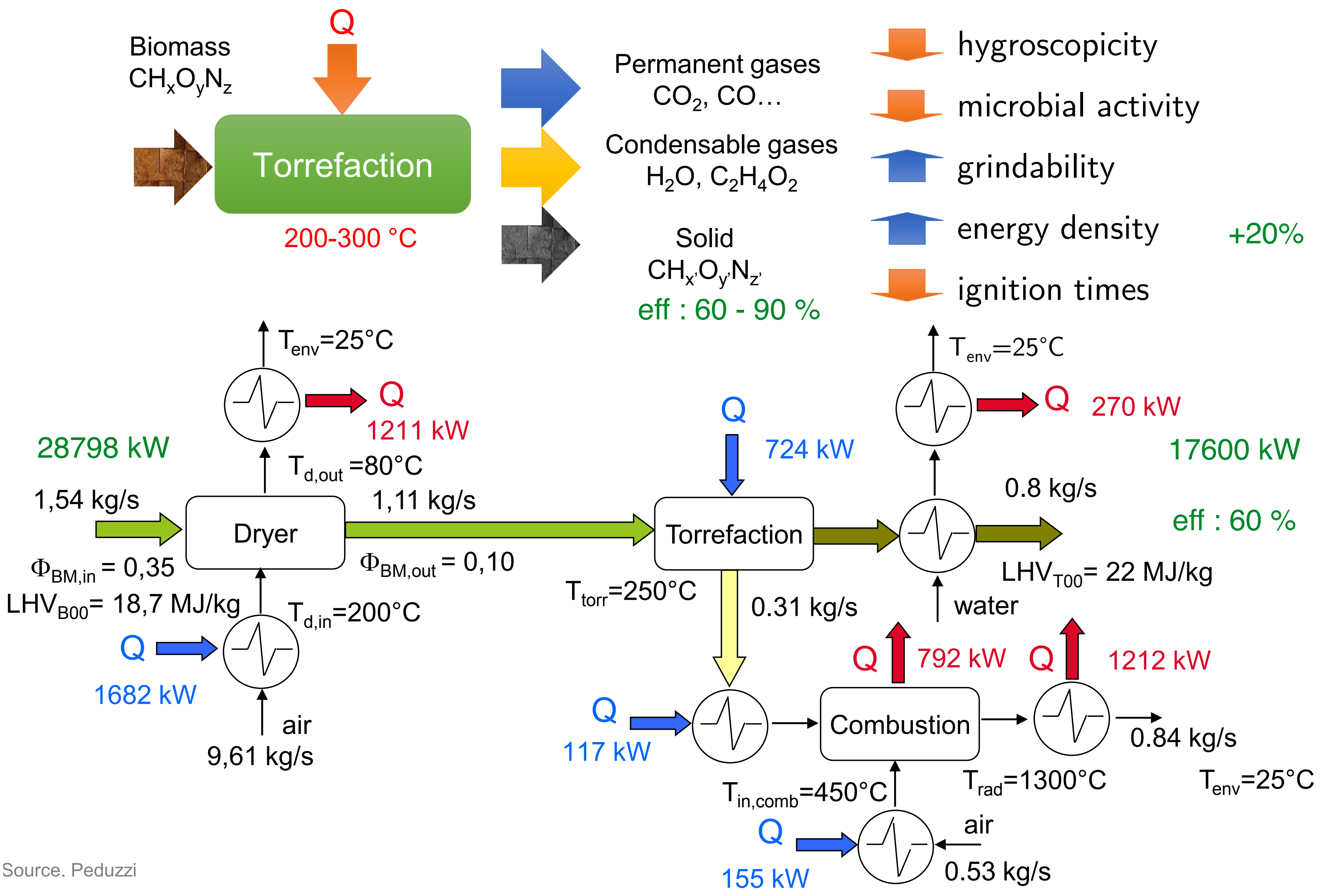


Fig. 2 – Cost structure of pellet production per country and technology, € t^{-1}. Biomass costs are delivered pellet mill gate, domestic transport is costs for transport of pellets from mill gate to customer or harbor.

biomass and bioenergy 57 (2013) 68e77

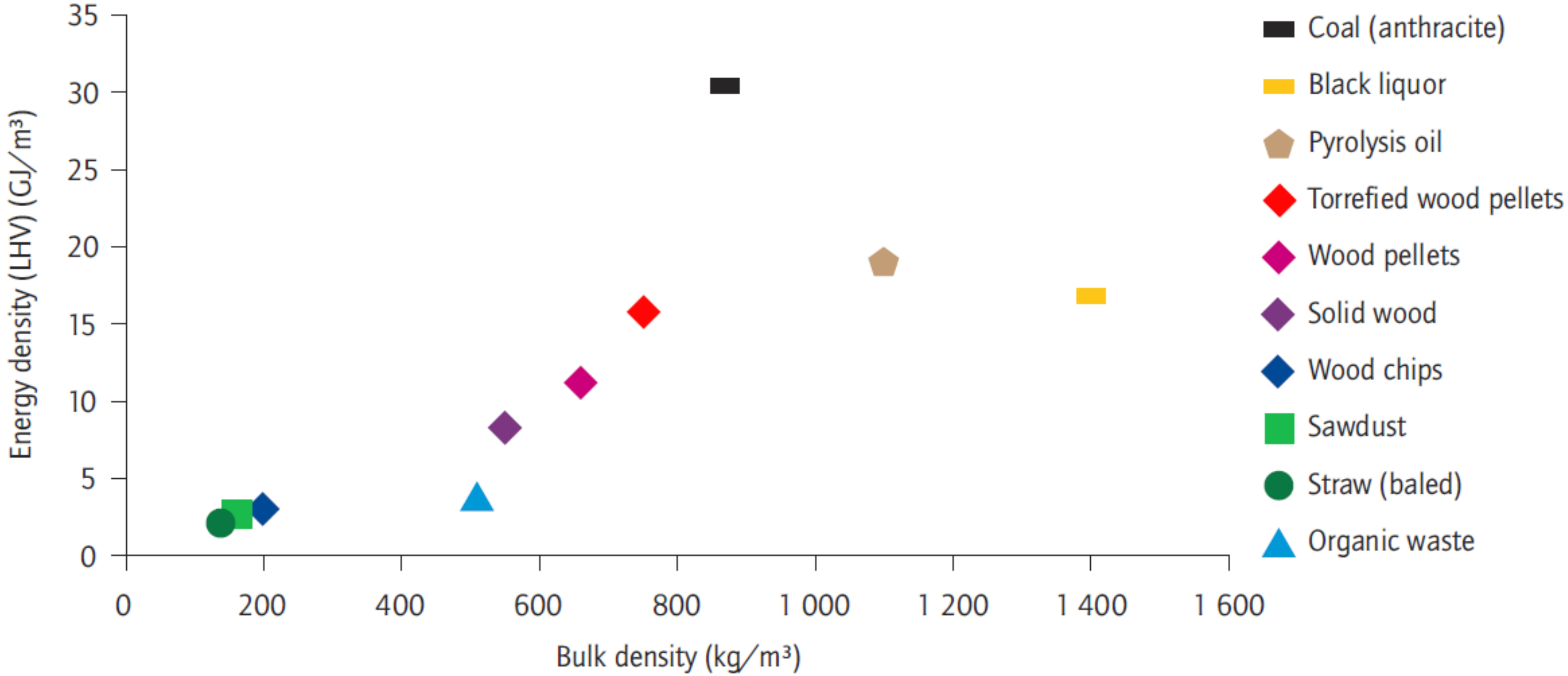
Torrefaction : Increase the energy density/reduce the humidity



Source. Peduzzi

Energy density

Figure 5: Comparison of bulk density and energy density of different biomass feedstocks



Source: IEA analysis based on DENA, 2011; FNR, 2011a; IEA Bioenergy, 2011; Kankkunen and Miikkulainen, 2003. For detailed data see Table 6 in Appendix I.

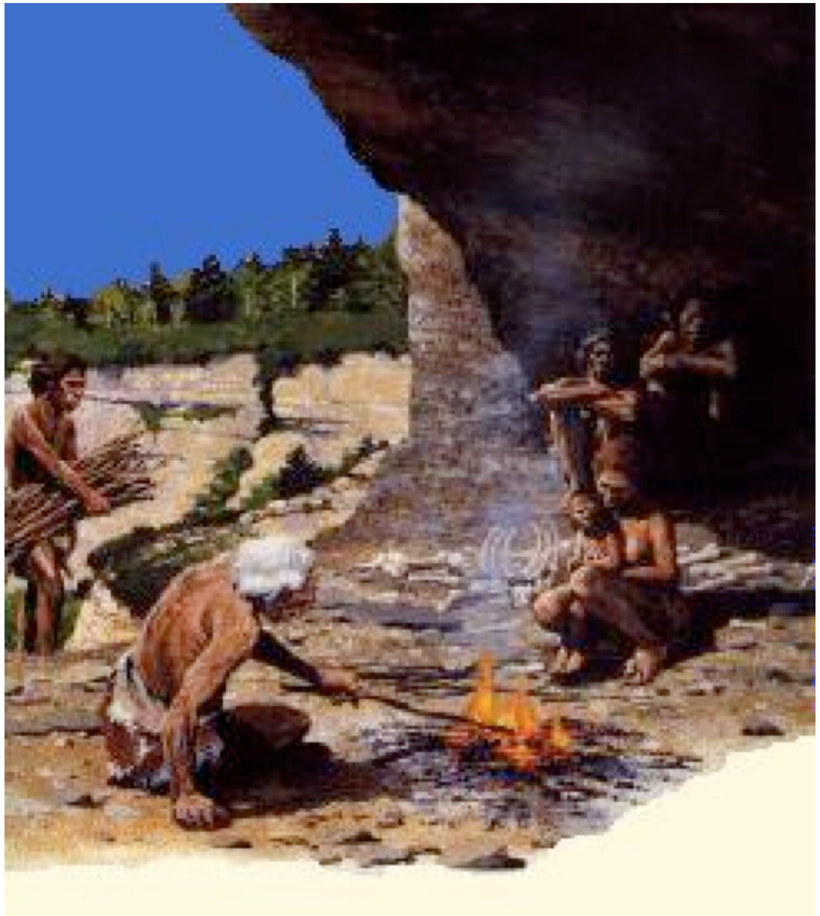
Source: IEA Technology Roadmape Bioenergy for Heat and Power, 2012.

Combustion

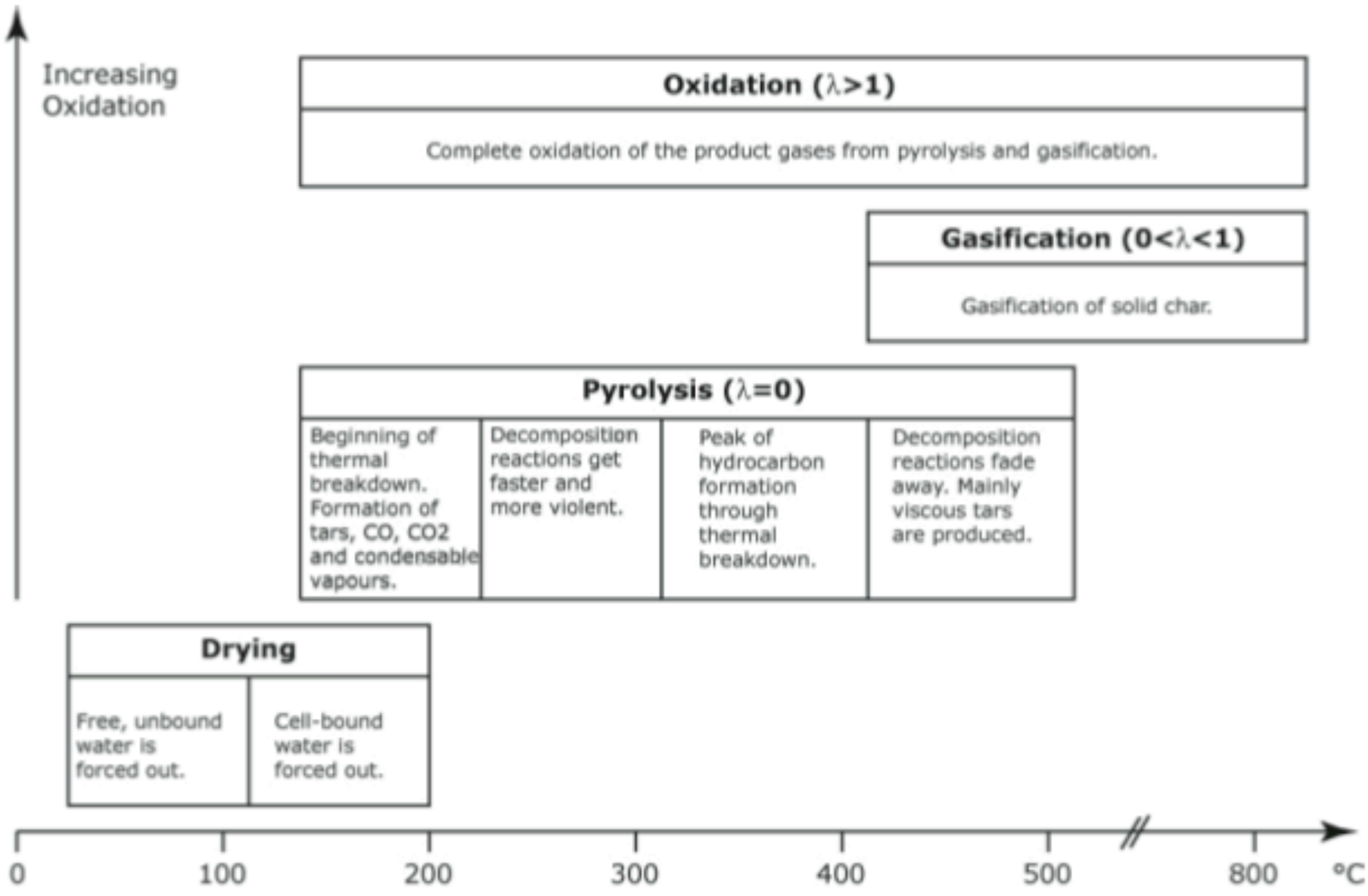
Known since more than 400.000 years

1er law efficiency : 92% (LHV)
2nd law efficiency : 16% (T = 60°C)

Applications today
Domestic heating
District heating
Heat networks



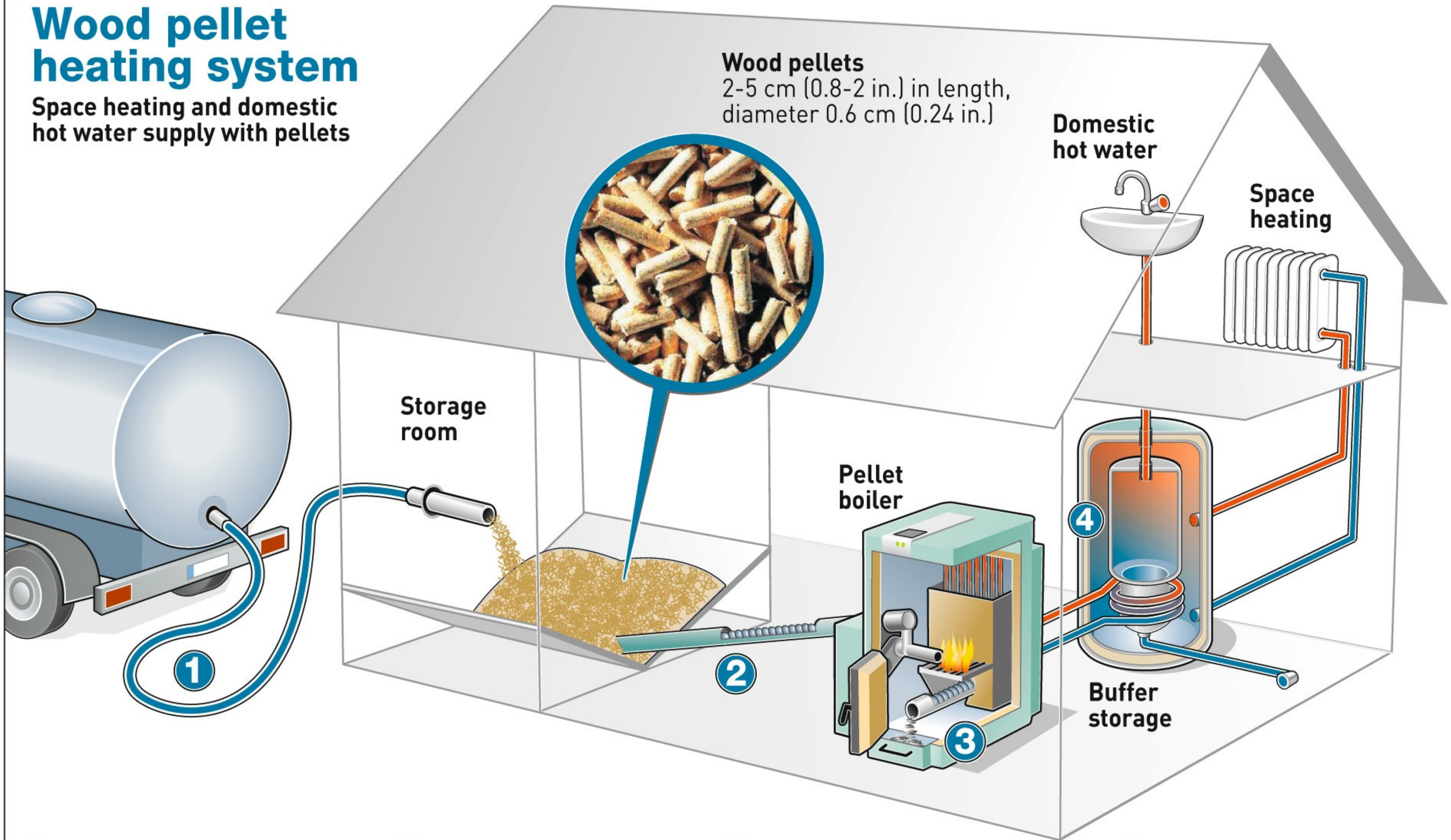
Oxidation and temperature



Biomass Combustion – Domestic Heating

Wood pellet heating system

Space heating and domestic hot water supply with pellets



1. Once or twice a year the pellets are delivered by a silo tanker. A loaded storage room of 4.5 m² is enough to keep a single-family house warm for one year.
2. The pellets are carried from the storage room to the boiler by a fully automatic pellet feed.
3. After the burning process all that's left is ash – with a weight of only 0.5 per cent of the original pellet. The ash can be disposed of with the domestic waste.
4. If the pellet boiler is interconnected with a buffer storage, emissions can be reduced and efficiency increased.

www.unendlich-viel-energie.de

Renewable Energies Agency

http://www.unendlich-viel-energie.de/

The boiler

http://www.Hoval.ch

Wood Boilers emissions

Table 3
CO_2, CO, TOC, particles and NO_x emissions

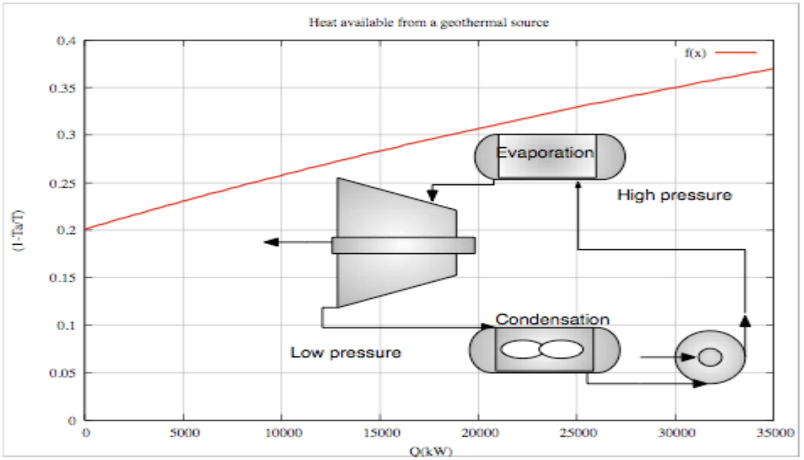
	Case	CO_2 (%)	CO	TOC	CH_4	NMVOC	PAH	Particles	Particles (1/MJ)	NO_x
Old-type wood boilers	a	8.4	4100	660	—	—	—	87	—	65
	b	4.7	5200	1300	—	—	—	350	—	72
	c	6.8	4800	1100	610	270	14	89	17×10^{13}	71
	d	8.3	5900	1500	670	430	13	103	3.9×10^{13}	67
	e	6.9	16400	4800	4800	2000	64	2200	200×10^{13}	28
	f	5.6	8200	3000	—	—	15	—	2.8×10^{13}	64
Modern wood boilers	g	12.2	707	14	1	1.9	0.21	27	4.5×10^{13}	125
	h	11.5	507	33	0.8	1.3	0.14	25	2.4×10^{13}	111
	i	5.1	3781	690	73	43	3.0	89	8.5×10^{13}	101
	j	10.3	1300	89	14	14	1.1	32	3.6×10^{13}	72
	k	9.1	770	63	9.2	7.8	0.44	23	6.4×10^{13}	81
	l	10.2	880	28	4.3	3.9	0.33	18	2.0×10^{13}	60
Pellet burners and boilers	m	9.5	36	4	0.76	1.2	0.32	22	1.4×10^{13}	68
	n	6.0	350	78	2.7	3.3	0.26	—	1.7×10^{13}	71
	o	4.8	290	31	—	—	0.12	28	1.3×10^{13}	68
	p	3.7	960	250	14	23	0.27	65	7.4×10^{13}	66
	q	13.0	120	3	<0.55	0.95	0.06	16	0.8×10^{13}	70
	r	9.1	990	60	5.3	20	8.5	64	1.6×10^{13}	64
	s	8.6	120	10	<0.84	1.7	0.55	15	0.8×10^{13}	67
	t	11.7	30	1	—	—	—	13	—	—
	u	6.8	380	2	—	—	—	12	0.1×10^{13}	62
	v	3.8	1100	92	—	—	—	51	0.2×10^{13}	62
	w	10.6	730	42	1.8	4.8	1.1	—	—	180
Oil	x	12.2	2	1	0.46	0.64	0.17	12	0.01×10^{13}	37
	y	10.6	9	32	0.52	0.38	0.006	6	0.1×10^{13}	41

Cogeneration : Organic Rankine Cycles (ORC)

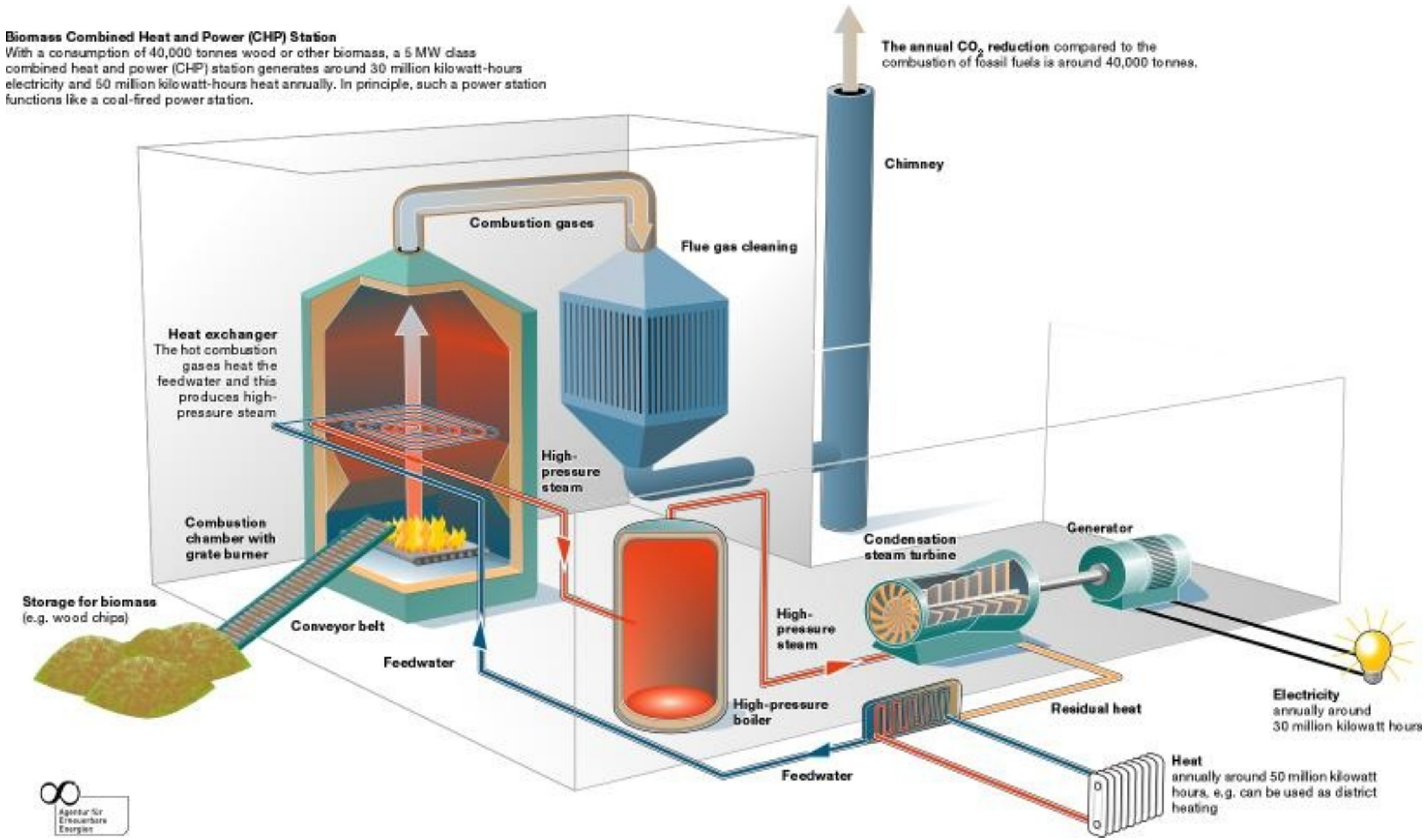
- Conversion of heat into electricity
  - T medium
  - Carnot eff : 50%
- Applications
  - Wood heating
  - Biogas engine
  - Geothermal energy

$$\dot{E} = \eta_{Carnot} \cdot \dot{m} \cdot LHV \cdot \left(1 - \frac{T_0}{\tilde{T}_{gases}}\right)$$

$$\tilde{T}_{gases} = \frac{T_{gases}^{add} - T_{gases}^{stack}}{ln(T_{gases}^{add}) - ln(T_{gases}^{stack})}$$

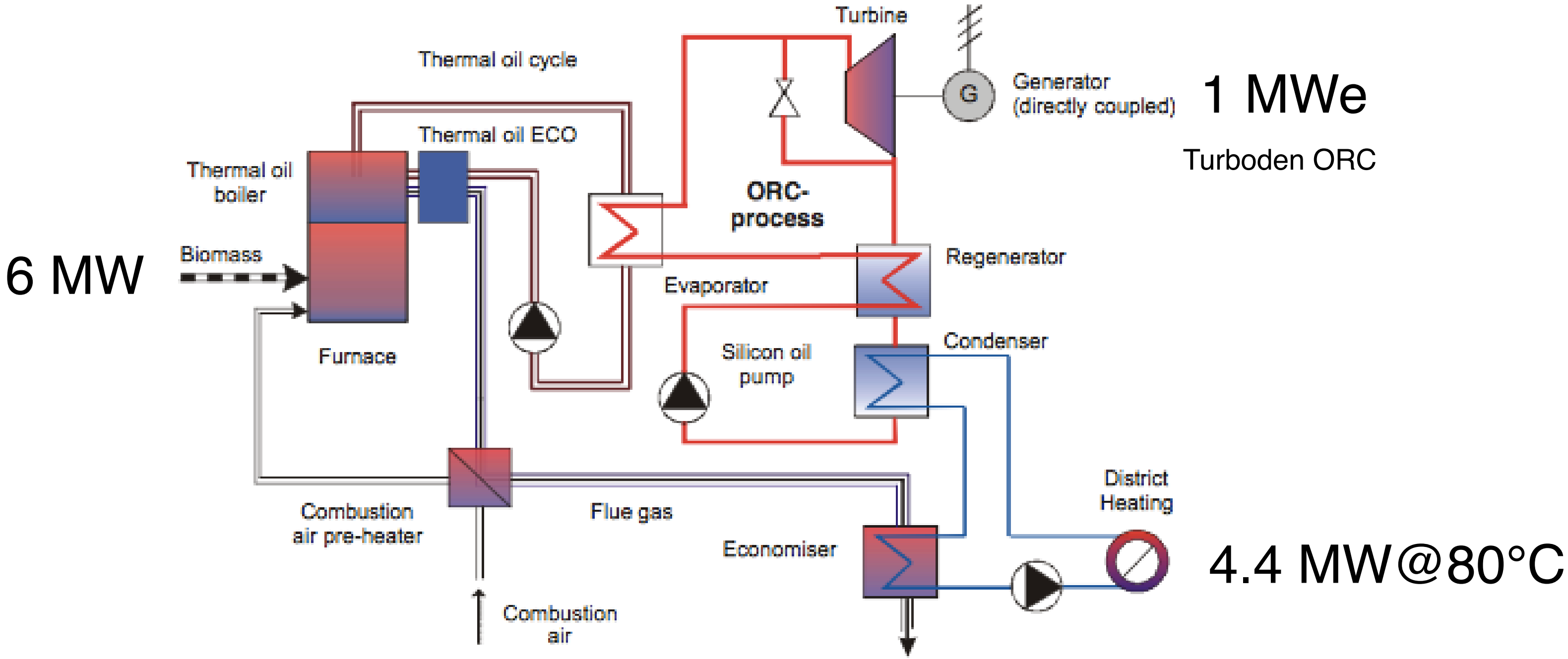


Biomass CHP – Steam Cycle



http://www.unendlich-viel-energie.de/

ORC Cycle with biomass



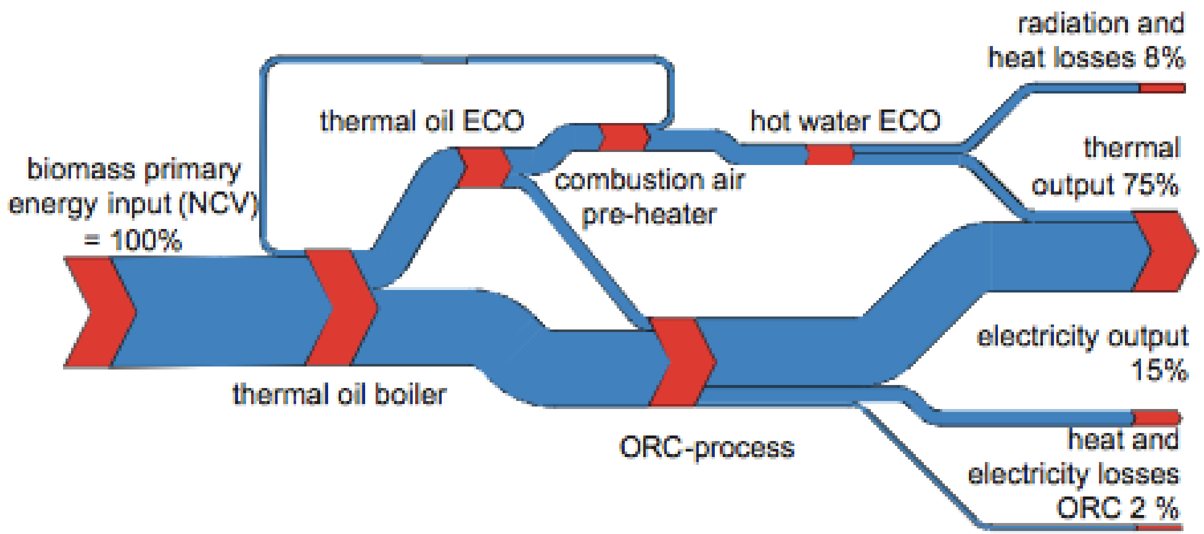


Figure 4. Energy balance of the biomass CHP plant in Lienz

International Nordic Bioenergy 2003 conference

Biomass and combustion

- By combustion biomass can be converted into heat
- Biomass drying to make it easier to burn
  - Dryers
  - Torrefaction
  - Pelletisation
- Biomass => particles and other emissions
- Biomass => ashes
- Combustion => CHP
  - Steam or Organic Rankine cycles
  - Typically used in district heating systems