Master of Science in *Energy Engineering*
Renewables and Environmental Sustainability

http://beep.metid.polimi.it/

POLITECNICO DI MILANO

School of Industrial and Information Engineering
Academic Year 2017-18

Lecture notes for:
Bioenergy and Waste-to-Energy Technologies

Introduction to Bioenergy

Prof. Federico Viganò – Department of Energy

Lecture outline

- *Definition of Biomass*
- *Origins of biomass*
- *Energy consideration on biomass production*
- *Which biomass is relevant to energy purposes?*
- *The current and future contribution of biomass in meeting the energy needs*
- *Sources of biomass*
- *Concerns about energy exploitation of biomass*
- *Energy conversion routes for biomass*
- *Final remarks*

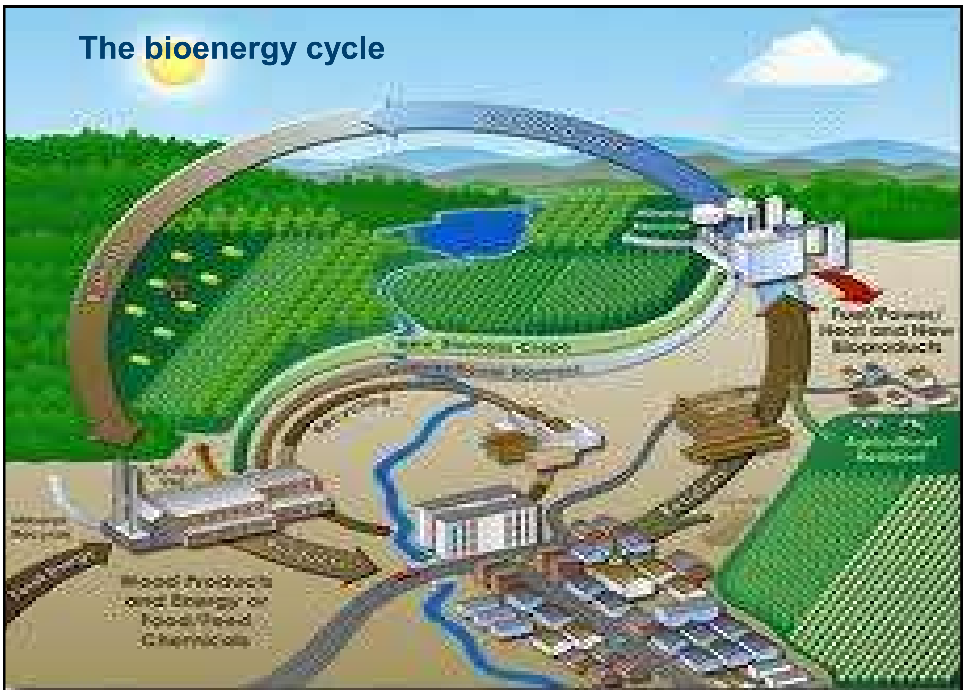
Definition of Biomass

Biomass is a biological material derived from living, or recently living organisms

Biomass is considered a renewable energy source when the utilization rate is equal to or lower than the capacity of production (biological capacity of renewal)

The energy exploitation of renewable biomass is a CO_2-neutral (or almost neutral) process

The bioenergy cycle



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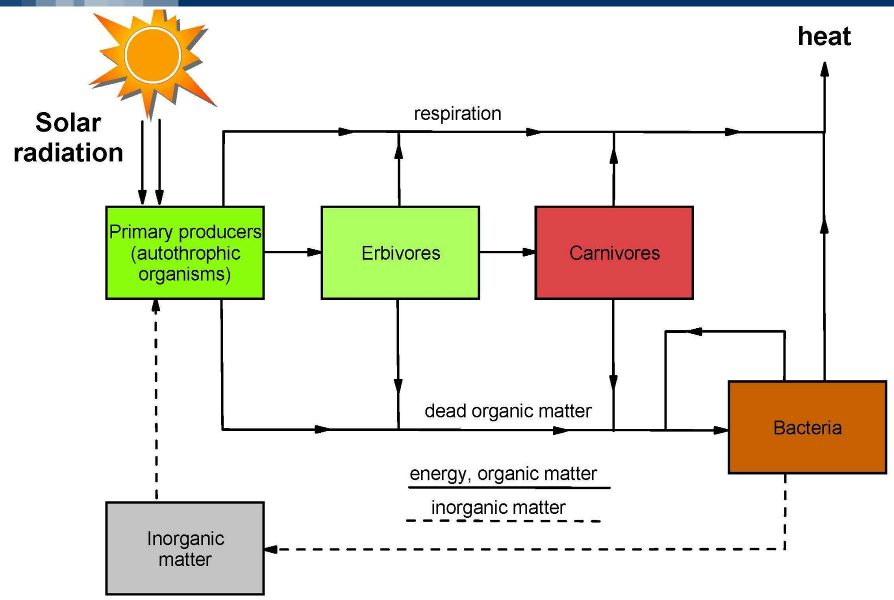
Where does Biomass come from?



Lecture outline

Chlorophyllian photosynthesis

The fundamental reaction is the fixation of CO_2 to form the group CH_2O, from which the carbohydrate:

$$n \cdot CO_2(g) + n \cdot H_2O(l) \xrightarrow{\text{light + chlorophyll}} (CH_2O)_n + n \cdot O_2(g)$$

Chemical energy accumulation: 470 kJ / mol of CO_2

To promote the reaction, 8 photons in the visible field are required (mean λ of 575 nm).
The energy associated with these 8 photons is ~ 1665 kJ

Energy efficiency of photosynthesis ~ 470/1665 = 28.2 %

Efficiency of biomass production

Photons in the visible field (λ in between 400 & 700 nm), which promote photosynthesis, account for about 43% of the overall solar radiation at the ground level.

The fraction of the incident radiation that is adsorbed by the surfaces capable of promoting photosynthesis can reach a maximum of about 80%.

Part of this radiation is used in processes different from photosynthesis (e.g. transpiration). The available fraction for photosynthesis is never higher than 75%.

In conclusion:
Chemical energy accumulated in biomass / sunlight at ground = Max $(0.282 \cdot 0.43 \cdot 0.80 \cdot 0.75) \sim$ Max 7.3 %

Biomass productivity: some examples

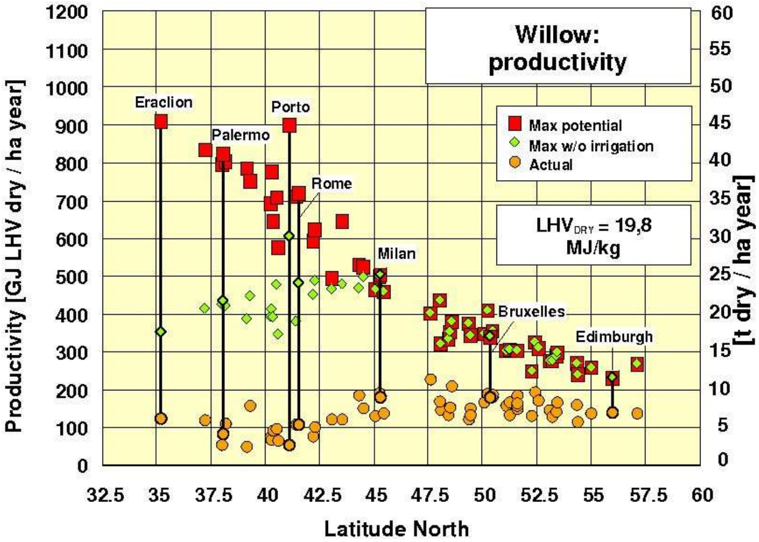
Willow
(Salix)

Wheat
(Triticum)

Eucalyptus

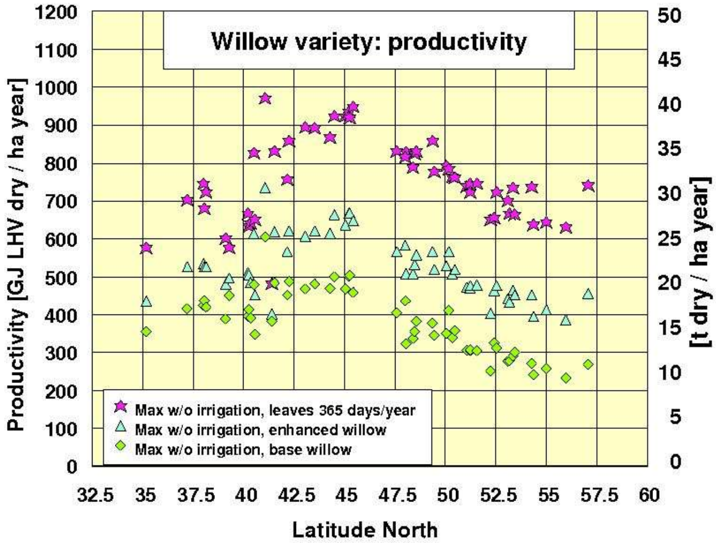
Productivity: Willow

Values estimated by Nonhebel (1997) for 58 European areas



Productivity: Willow

Potential productivity enhancements (Nonhebel, 1997)



Productivity: wheat

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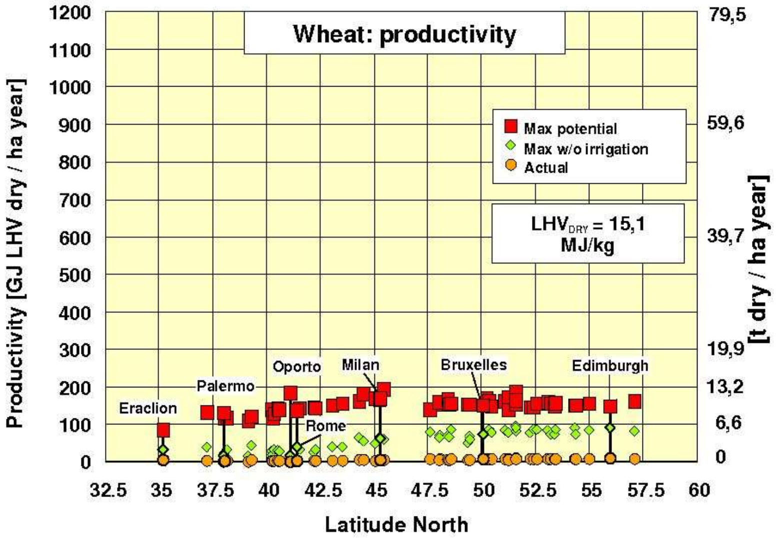
Values estimated by Nonhebel (1997) for 58 European areas



Productivity: Eucalyptus

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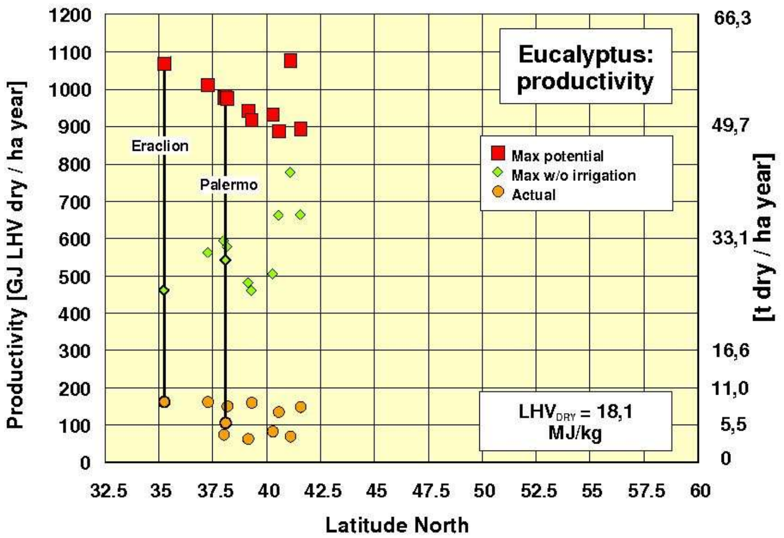
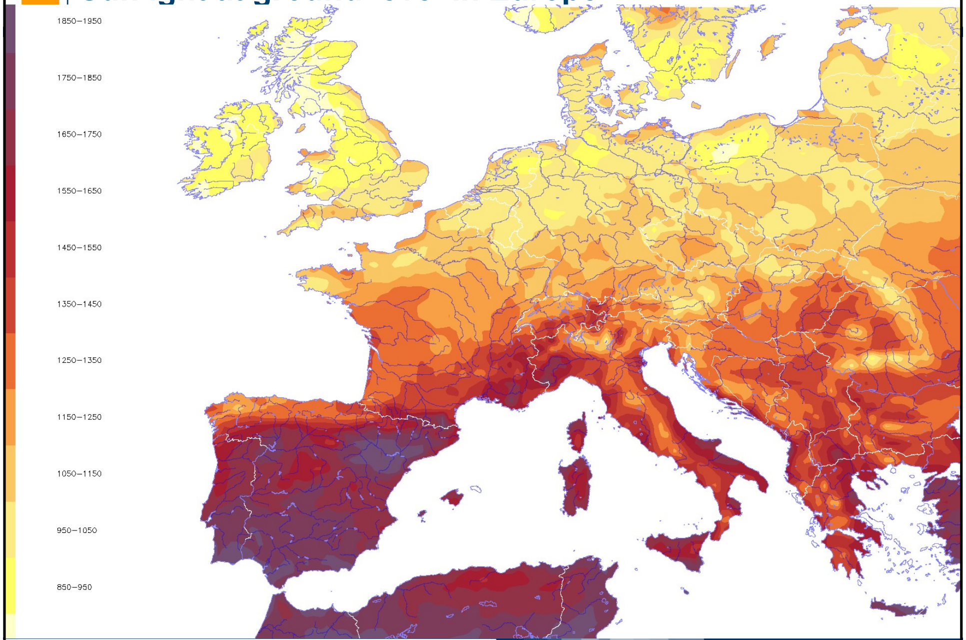
Values estimated by Nonhebel (1997) for 11 European areas



Sunlight at ground level in Europe

15



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Sunlight in the 58 European areas considered by Nonhebel (1997)

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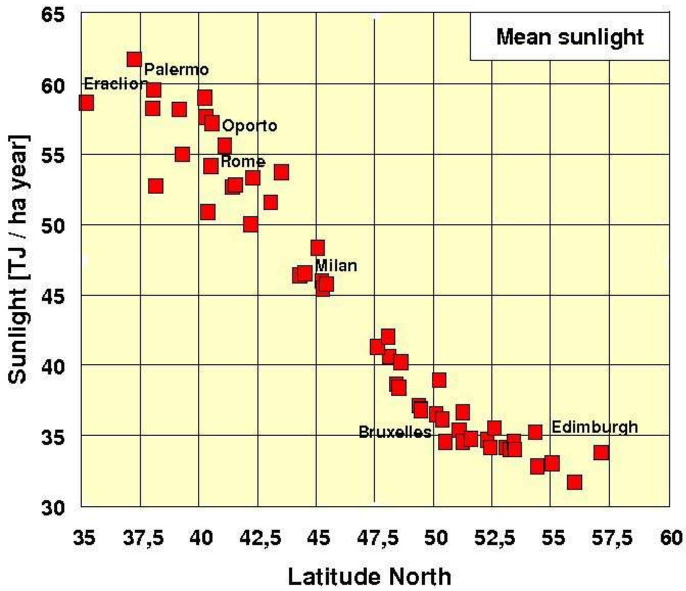

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Yield: Willow

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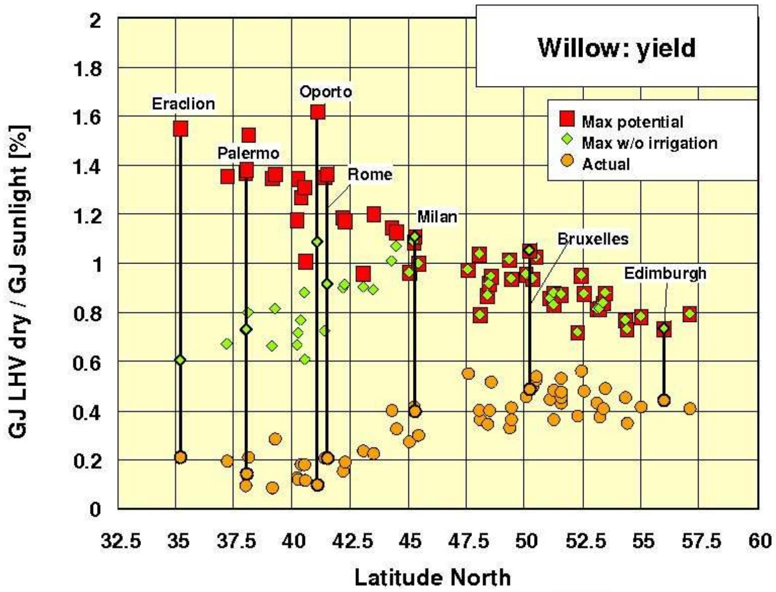

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Yield: wheat

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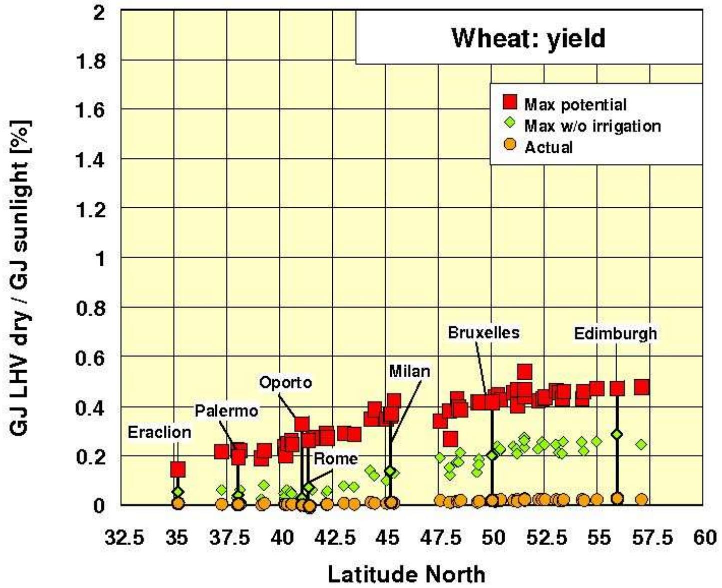

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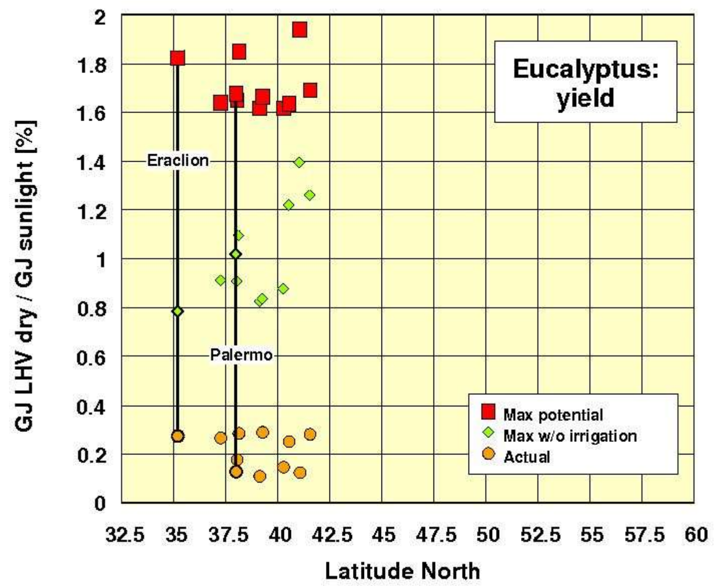
Yield: Eucalyptus



Energy accumulation in biomass

PRODUCTION:

Carbon fixed every year ~ 53 Gt

Corresponding Volatile Dry Matter (VDM) in biomass ~ 106 Gt

Corresponding energy (assuming LHV_{VDM} = 15 MJ/kg) ~ $1.6 \cdot 10^{15}$ MJ/year ~ 38 Gtoe/year

RESERVES:

Carbon ~ 825 Gt

Volatile Dry Matter (VDM) ~ 1650 Gt

Corresponding energy ~ 590 Gtoe

Energy coming from the Sun

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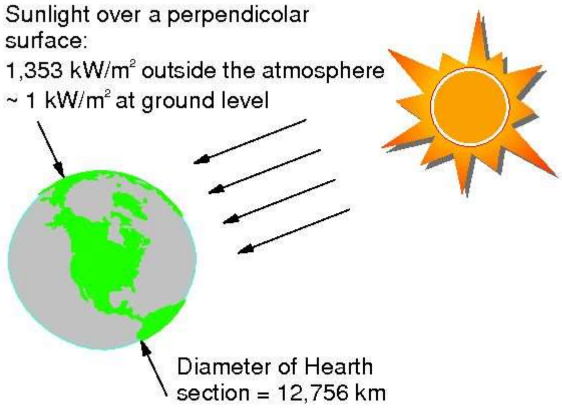

Available solar energy at ground level:

$$1\ \frac{kW}{m^2}\cdot\pi\cdot\left(6{,}378\cdot10^6\ m\right)^2\cdot\frac{8760\,h}{year}\cdot\frac{3600\,s}{h}=4{,}03\cdot10^{18}\ \frac{MJ}{year}$$

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Mean energy efficiency for the production of biomass over lands above sea level

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Biomass production ~ 1.6·10^{15} MJ/year

Sunlight over lands above sea level ~ 1150·10^{15} MJ/year

MEAN ENERGY CONVERSION EFFICIENCY FROM SOLAR TO CHEMICAL ENERGY ~ 0.14 %

Then, assuming to generate electricity with a mean net efficiency of 20%, the mean overall energy efficiency from solar energy to electricity would be 0.028%

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Energy balance for energy crops (Poplar - Nonhebel, 1997)

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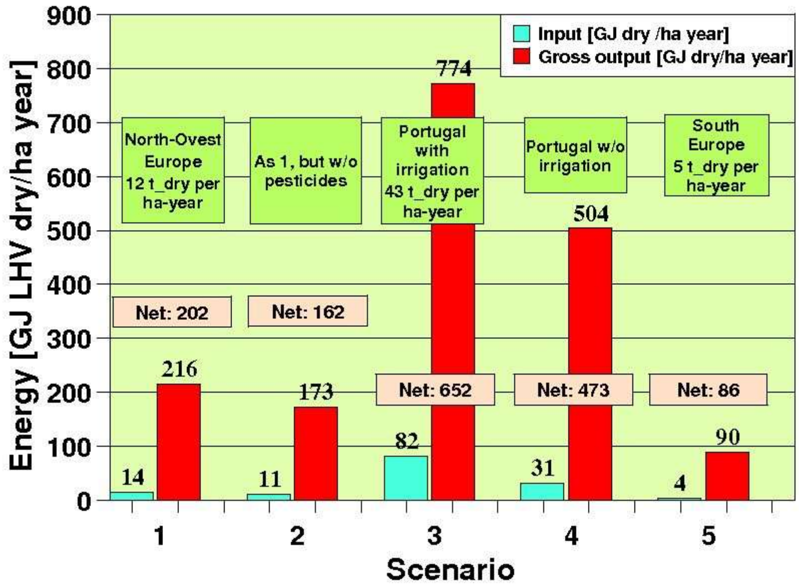
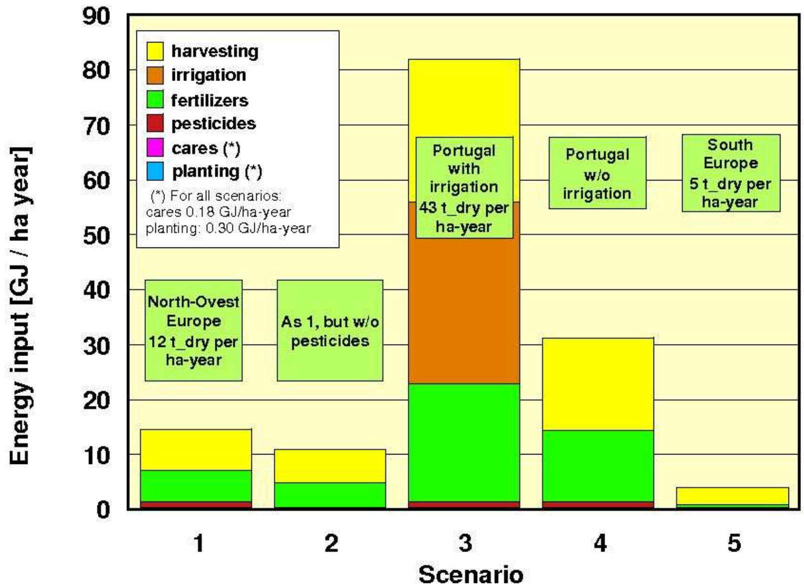


Energy balance for energy crops (Poplar - Nonhebel, 1997)

24



Energy considerations on biomass production

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1) **Energy efficiency for the conversion from solar to chemical energy varies a lot with the crop variety, growth conditions, geographic location**
2) **The mean energy efficiency achieved by biomass on lands above the sea level is about 0.14%**
3) **The intensive cultivation of the most adapt species can lead to energy efficiencies as high as 2%**
4) **Intensive cultivation implies a reduction of the ratio (energy out)/(energy in), which, however, can reach values of 8-10**

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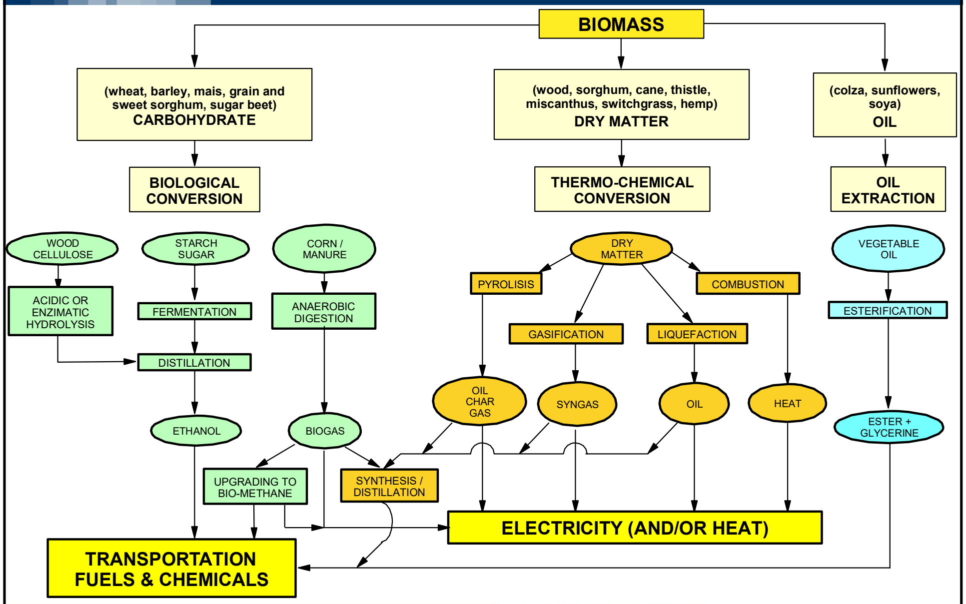
Which biomass is relevant to energy purposes?



Woody feedstock

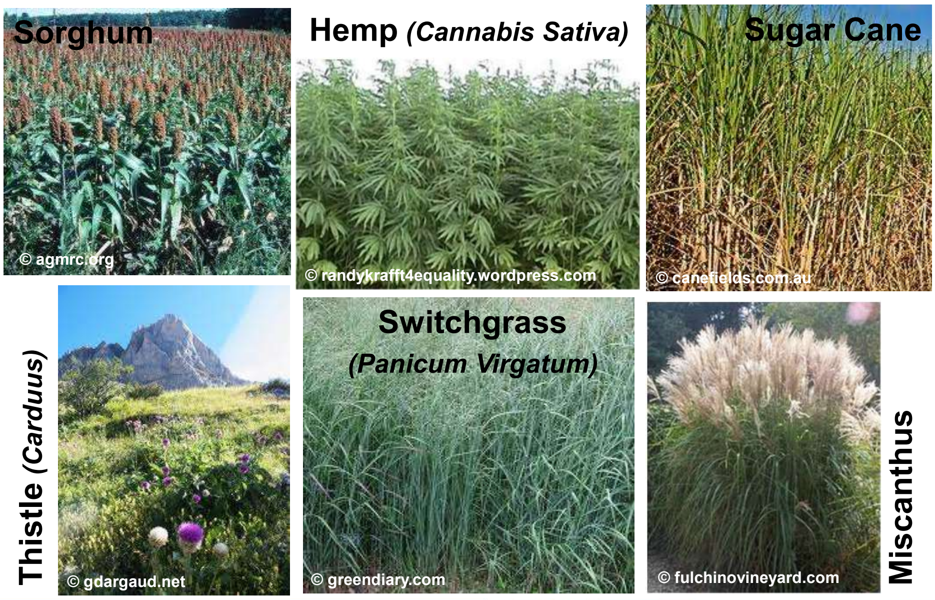
Wood logs

Wood chips

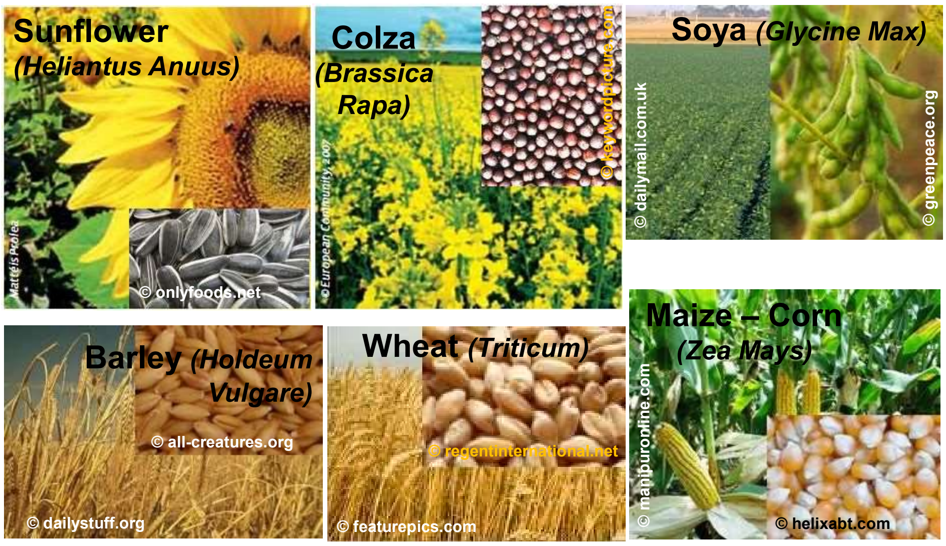
Wood bark residues

Wood pellet

Herbaceous feedstock



Seed feedstock



Other biomass feedstock

And many others:

- manure;
- poultry litter;
- sewage sludge;
- algae;
- etc.

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Primary energy (in 2015) - Mtoe

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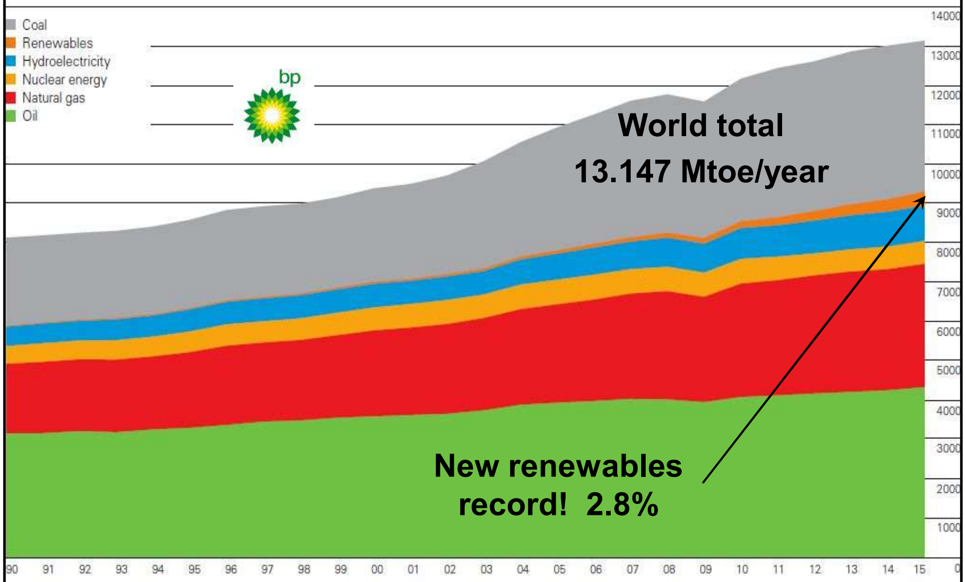

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Primary energy by region (in 2015), %

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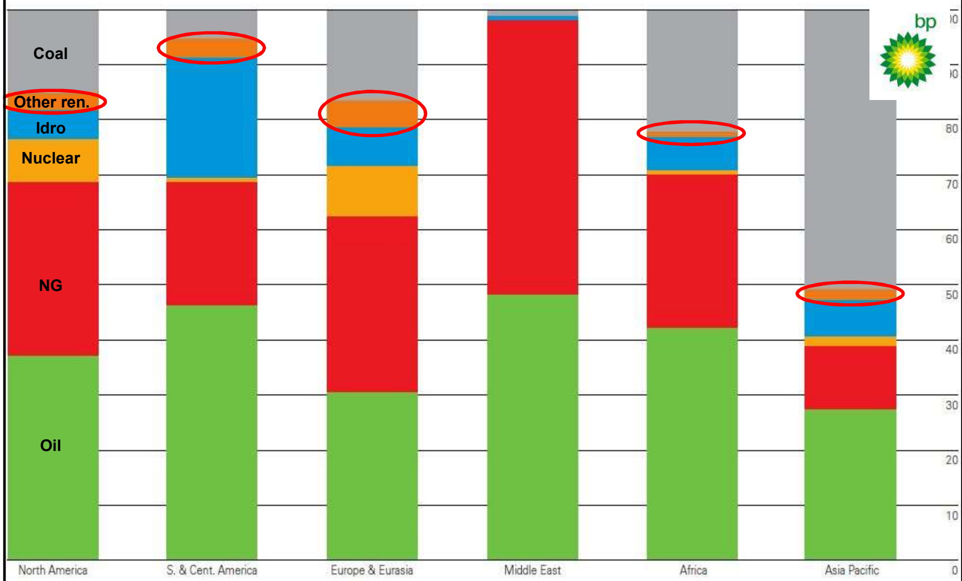

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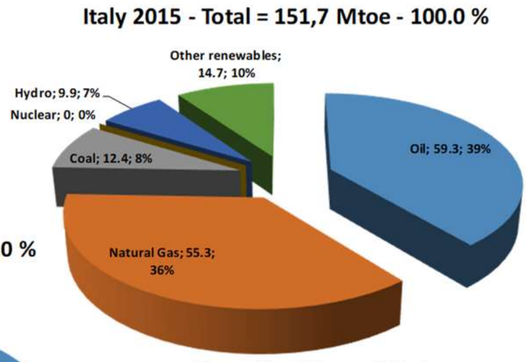
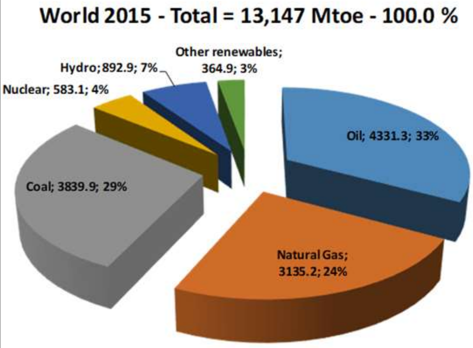
Primary energy in the World & in Italy in 2015





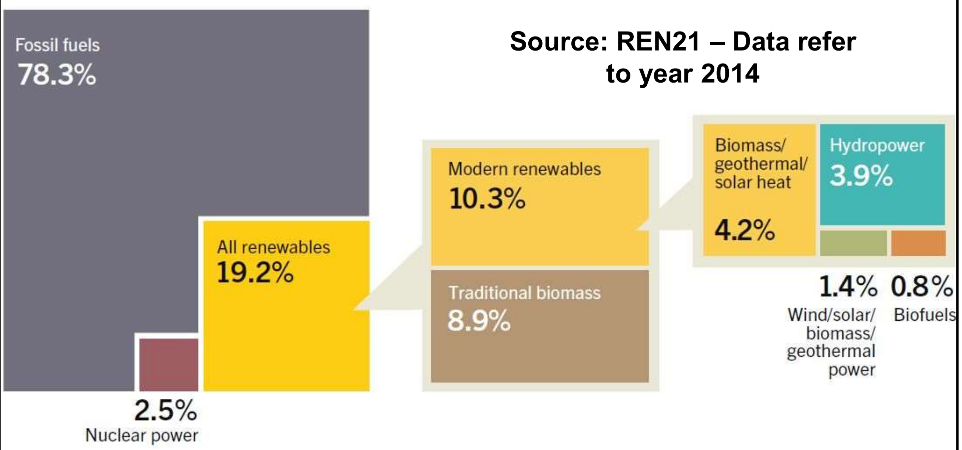
Peculiarities of Italy
(1.15% of World in 2015):

- no nuclear
- little coal
- large import

Renewable share of global final energy consumption

Please notice the differences between:
“Global final energy consumption” and “Primary energy consumption”

Source: REN21 – Data refer to year 2014



There are differences also in conversion factors

Primary energy equivalent for renewables

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- The methodology to calculate the total primary energy demand that correspond to a given amount of final energy (such as electricity and heat) is not straightforward, in particular for renewable energy sources.
- Normally, when possible, the *physical energy content* methodology is used:
  - For coal, oil, gas, biomass and waste, the Lower Heating Value (LHV) of these fuels is considered.
  - This approach is correct when the energy conversion route is based on combustion, but it is quite unsatisfactory when a biological process is involved (for example in anaerobic digestion, HHV would be a much better reference).
- For other renewables, IEA adopts its own conventions, i.e. 33% efficiency for nuclear energy, 100% for hydro, wind and solar photovoltaics, 10% for geothermal electricity, 50% for geothermal heat, and 40% for solar concentrating solar power.

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Traditional vs. Modern biomass

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Modern renewables encompass all renewable energy sources other than traditional biomass, which is in turn defined as biomass consumption in the residential sector in developing countries and refers to the use of wood, charcoal, agricultural residues and animal dung for cooking and heating. All other biomass use is defined as modern.

Commonly energy statistics do not account for traditional biomass, due to the difficulties in gathering reliable data. Only in recent year the IEA World Energy Outlook estimates this contribution as result of a specific focus on energy poverty.

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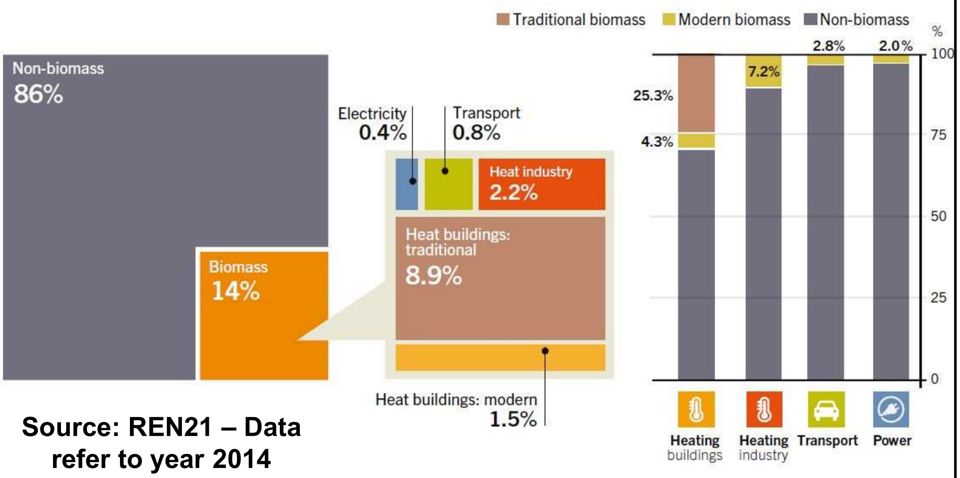
India – traditional biomass for cooking & heating

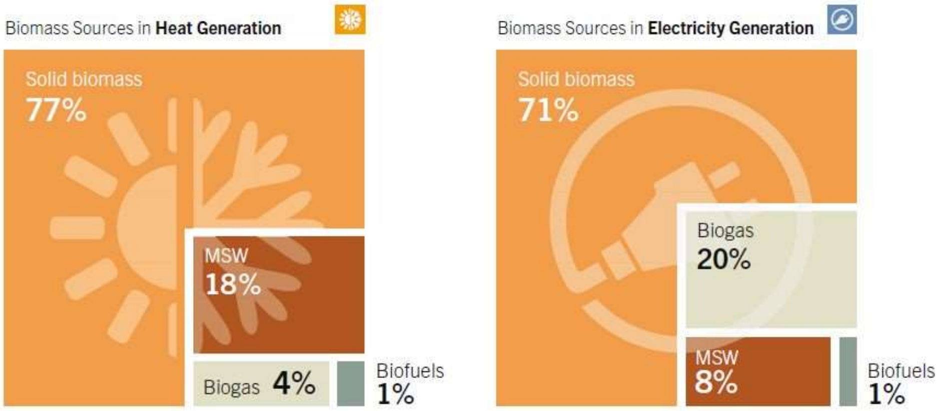
Bioenergy shares and breakdown by sector

Data refer to global final energy consumption



Source: REN21 – Data refer to year 2014

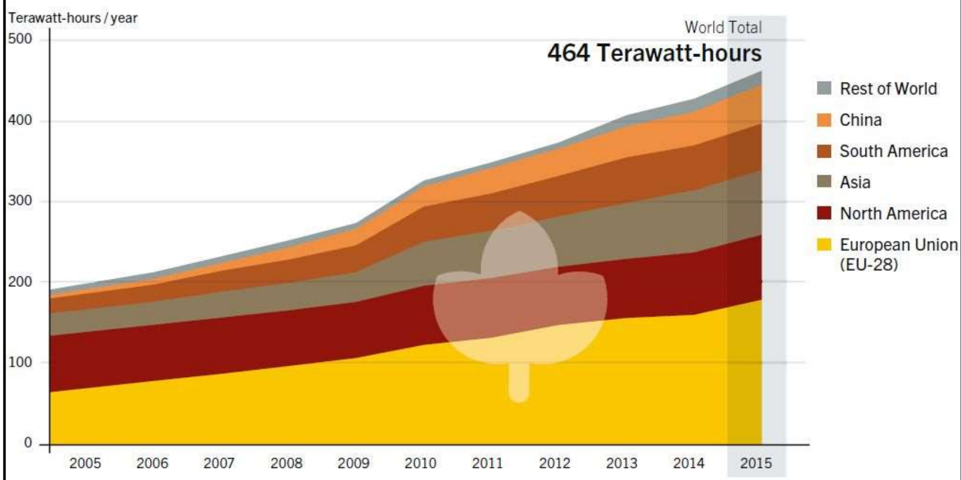
Bioenergy shares in global heat and power sectors



MSW (Municipal Solid Waste) refer to the biogenic quota only (typically ~50% of the energy content)

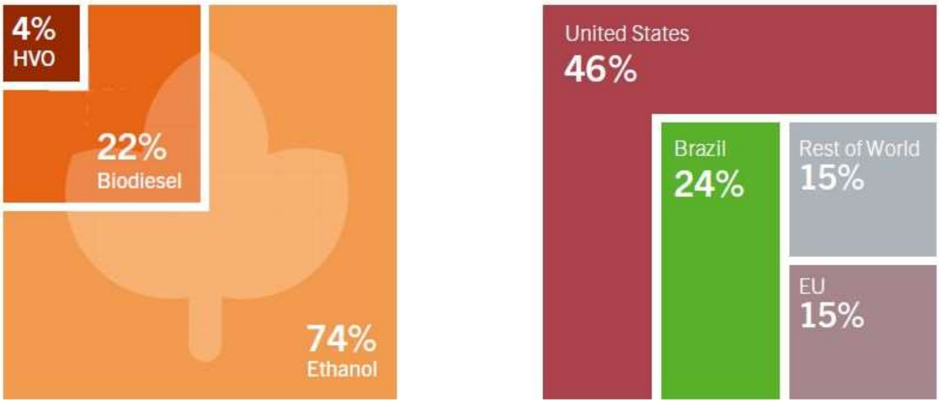
Source: REN21 – Data refer to year 2015

Biopower Global Generation in 2005-2015



Source: REN21

Biofuels global generation and shares in 2015



HVO = Hydrogenated Vegetable Oils

Source: REN21

Current situation for bioenergy (& renewables …)

- Despite the impressive growth of renewable energy in recent years, most of the world's energy needs are still met by fossil fuels and most of the increase in energy demand since 2000 has been also met by fossil fuels.
- On a global scale, 19% of electricity came from renewables in 2008 (mainly hydropower), a share that has changed very little since 2000 (despite more than 900 TWh/year of new hydropower), while the shares of coal and gas have increased by 2 and 3.6 percentage points, respectively.
- In transportation, oil use is about fifty times greater than that of biofuels.
- The use of fossil fuels for heat is ten times higher than the use of modern renewables.

Current situation for bioenergy (& renewables …)

Collectively, renewables secured their position as the second-largest source of electricity in 2014, behind coal. Compared to 2013, renewables accounted for 85% of the increase in total generation. Supportive policies led to the installation of a record-high 130 GW of renewables capacity in 2014. Over the last decade, 318 GW of hydropower were built, more than any other form of renewables, followed by wind power (304 GW) and solar PV (173 GW). During that time, hydropower output in China increased by two-thirds more than gas-fired generation in the United States.

Outlook for bioenergy (& renewables …)

- The renewables resource base is very large and can amply meet a large portion of energy demand. However, most renewables are not cost competitive under present market conditions and rely on various forms of incentives.
- The existence of government programmes to make renewables attractive to investors and create market for them is **<u>the most important factor</u>** affecting the expansion of renewable energy.
- Such incentives already exist in many countries and are reflected in the significant rate of increase in the use of renewable energy.
- Often in combination with financial incentives, a number of countries have imposed a requirement on suppliers to raise the share of renewables in electricity production or in transport fuels.
- The use of carbon markets as a means to promote renewables is limited at present, applying, on a large-scale, only in the European Union (EU).
- The Clean Development Mechanism (CDM) has contributed to the expansion of renewables in developing countries.
- Overall, however, it is direct government support, rather than pricing of CO_2, that drives the growth in renewables at present.

Global modern renewable energy supply and shares in total by scenario

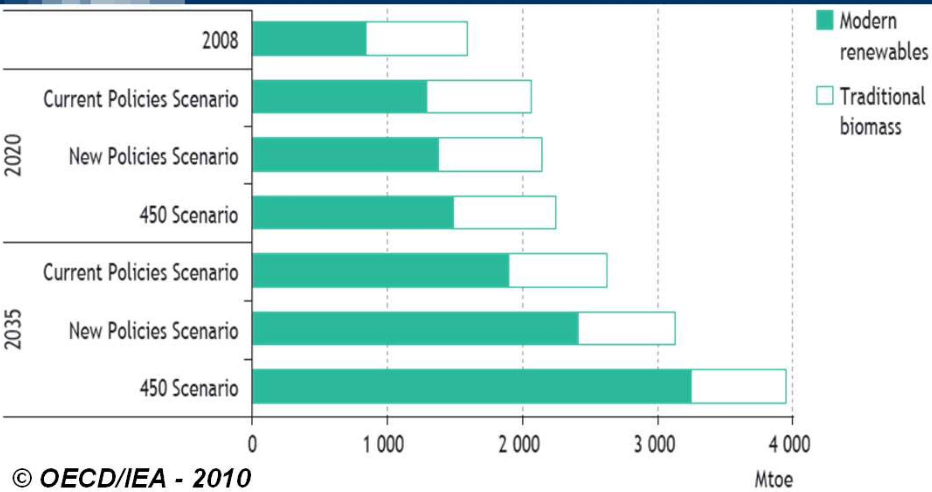
	2000	2008	2035 New Policies Scenario	2035 Current Policies Scenario	2035 450 Scenario
Electricity (TWh)	2 876	3 774	11 174	8 873	14 508
Share in total electricity generation	19%	19%	32%	23%	45%
Heat (Mtoe)	266	312	660	540	790
Share in total demand for heat	10%	10%	16%	12%	21%
Biofuels (Mtoe)	10	45	204	163	386
Share in total transport	1%	2%	6%	5%	14%

New Policies Scenario: *actions are taken to limit the temperature increase to 2°C.*
450 Scenario: *actions are taken to limit atmospheric CO_2 concentration to 450 ppm.*

World electricity generation by source and scenario (TWh)

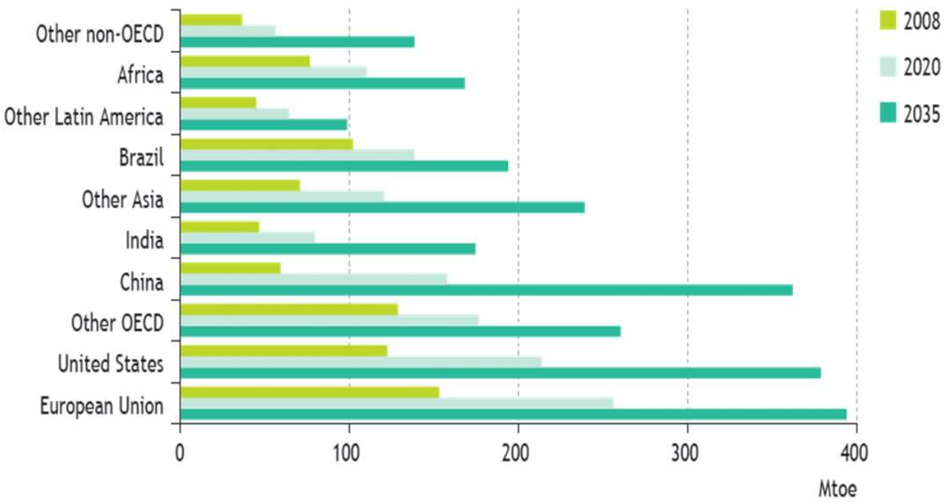
	2000	2013	New Policies 2020	New Policies 2040	Current Policies 2020	Current Policies 2040	450 Scenario 2020	450 Scenario 2040
Total	15 431	23 318	27 222	39 444	27 988	43 120	26 206	33 910
Fossil fuels	9 966	15 735	16 805	21 409	17 772	27 659	15 604	9 851
Coal	6 001	9 612	10 171	11 868	10 918	16 534	9 185	4 107
Gas	2 752	5 079	5 798	9 008	6 006	10 534	5 658	5 465
Oil	1 212	1 044	836	533	849	590	760	279
Nuclear	2 591	2 478	3 186	4 606	3 174	3 974	3 218	6 243
Hydro	2 620	3 789	4 456	6 180	4 423	5 902	4 464	6 836
Other renewables	255	1 316	2 774	7 249	2 619	5 586	2 921	10 980
Fossil fuels	65%	67%	62%	54%	63%	64%	60%	29%
Coal	39%	41%	37%	30%	39%	38%	35%	12%
Gas	18%	22%	21%	23%	21%	24%	22%	16%
Oil	8%	4%	3%	1%	3%	1%	3%	1%
Nuclear	17%	11%	12%	12%	11%	9%	12%	18%
Hydro	17%	16%	16%	16%	16%	14%	17%	20%
Other renewables	2%	6%	10%	18%	9%	13%	11%	32%

World primary renewable energy supply by scenario



- The use of traditional biomass rises slightly to 2020 and then declines by 2035 in all three scenarios, although at different rates by region. Consequently, the share of traditional biomass in all renewables diminishes over time

Modern renewables primary energy demand by region in the New Policies Scenario



- Shares of renewable energy by sector and region in the New Policies Scenario

	Electricity		Heat		Biofuels			
					Road transport		Aviation	
	2008	2035	2008	2035	2008	2035	2008	2035
OECD	17%	33%	11%	23%	3%	12%	0%	3%
Europe	21%	44%	12%	25%	3%	12%	0%	0%
United States	9%	25%	10%	25%	4%	15%	0%	4%
Japan	10%	19%	3%	7%	0%	1%	0%	4%
Australia/ New Zealand	15%	31%	18%	41%	0%	2%	0%	0%
Non-OECD	21%	31%	9%	12%	2%	6%	0%	0%
China	17%	27%	1%	5%	1%	4%	0%	0%
India	16%	26%	24%	19%	0%	6%	n.a.	n.a.
Other Asia	16%	31%	11%	15%	1%	4%	0%	0%
Brazil	84%	75%	47%	50%	21%	41%	0%	3%
Other Latin America	52%	65%	13%	15%	0%	5%	0%	0%
Russia	16%	28%	5%	5%	0%	2%	0%	0%
Middle East	1%	16%	1%	3%	0%	0%	0%	0%
Africa	16%	39%	31%	37%	0%	2%	0%	0%
World	19%	32%	10%	16%	3%	8%	0%	1%
European Union	*17%*	*41%*	*13%*	*26%*	*3%*	*14%*	*0%*	*0%*

Note: Electricity = share of renewables in total electricity generation; heat = share of renewables for heat in total demand for heat; biofuels = share of biofuels used in road transport in total road transport and share of biofuels used in aviation in total aviation fuel.

Remarks on the expansion of biomass use

- Total primary biomass use — both traditional and modern — in the New Policies Scenario increases from 1,225 Mtoe in 2008 to nearly 2,000 Mtoe in 2035.
- Over 60% of total biomass used in 2008 was traditional biomass, which was consumed in developing countries (essentially in India and sub-Saharan Africa), mainly for cooking and space heating.
- This share drops to 37% by 2035, both because people who rely on it switch to modern fuels and technologies), and because demand for modern biomass increases substantially as a result of government policies.
- Global modern primary biomass consumption nearly triples between 2008 and 2035. The pattern of use changes over time (see next graph).
- The main application of modern biomass today is in industry, where it is mainly used in the production of process steam, while the power sector is the second-largest user.
- Over the period 2008-2035, most of the increase in biomass comes from the electricity sector and transportation. By 2035, power generation becomes the largest biomass-consuming sector, ahead of industry.
- The share of biofuels in modern biomass use grows from 10% in 2008 to 16% in 2035.

World modern biomass primary demand by sector in the New Policies Scenario

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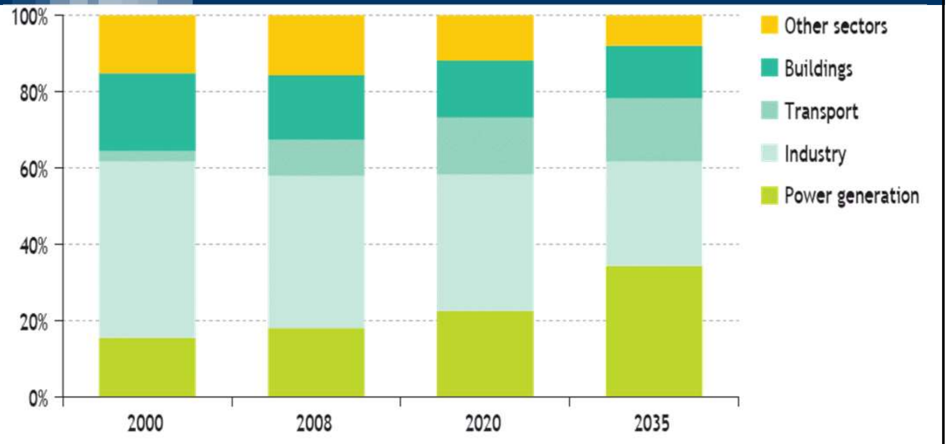

Note: Power generation includes biomass used in combined heat and power plants to produce electricity and heat, and in heat only plants.

© OECD/IEA - 2010

Bioenergy potentials on a global scale (17 studies)

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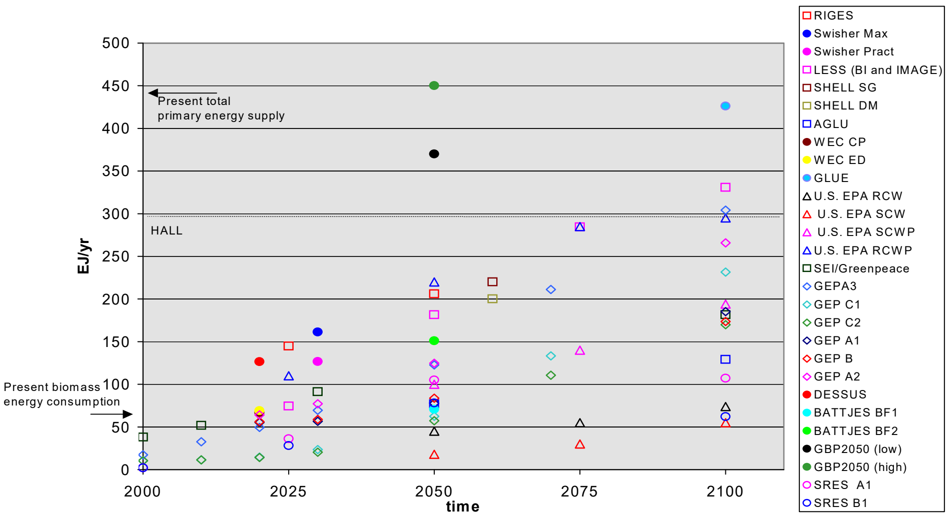
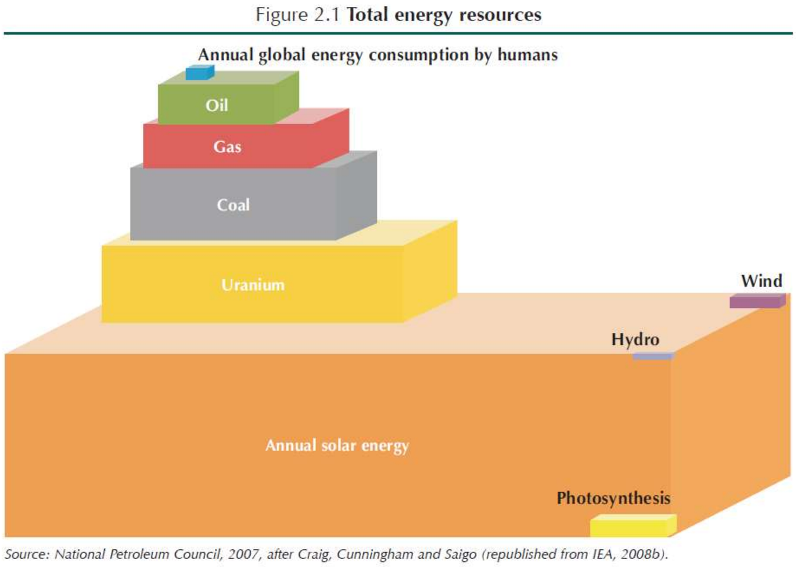
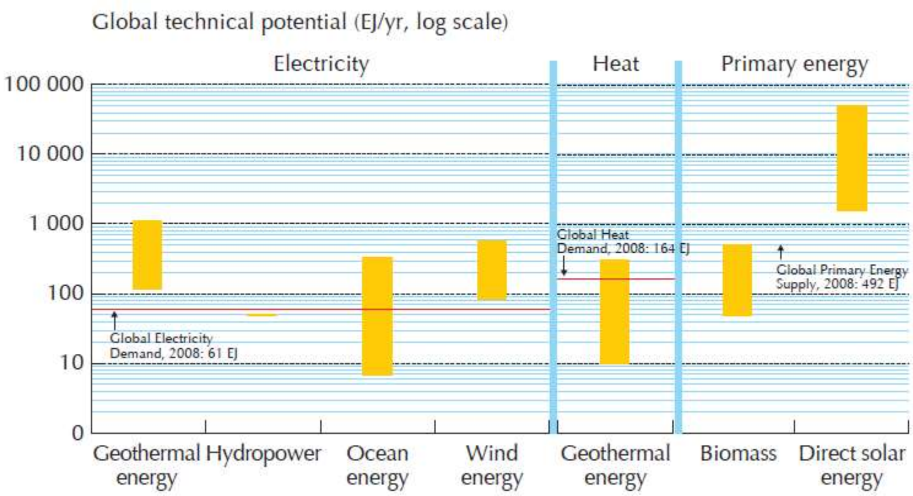


Source: A. Faaij – Utrecht University

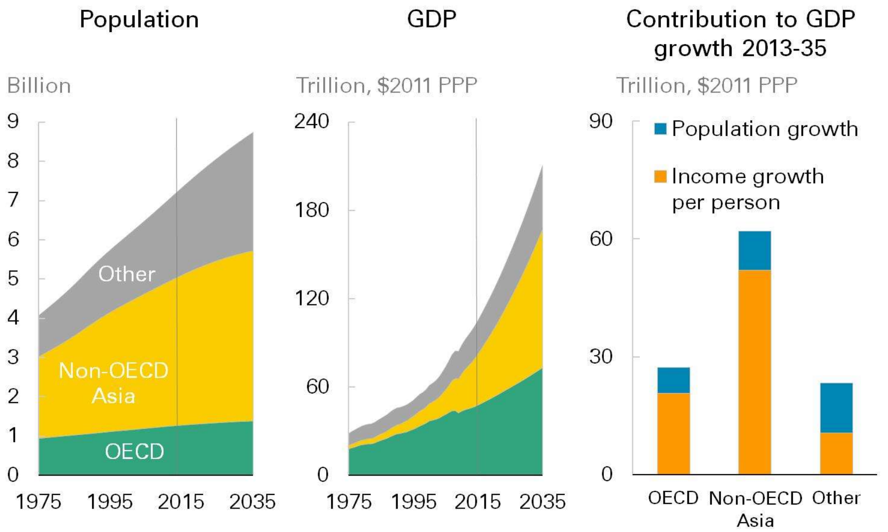
Potentials of various energy sources



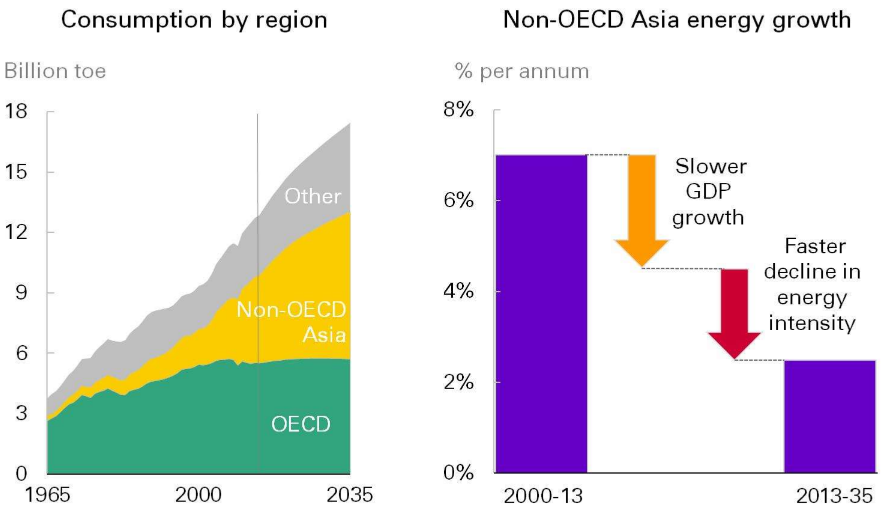
Potentials of renewable energy sources



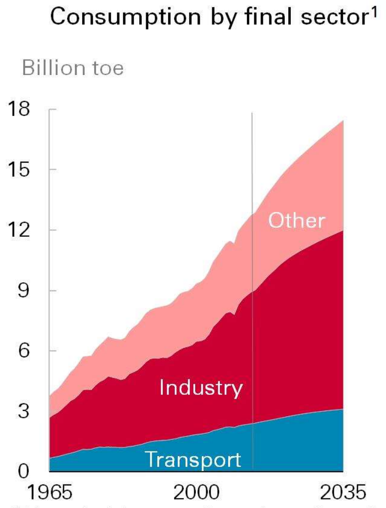
Global population and increases in income per person...

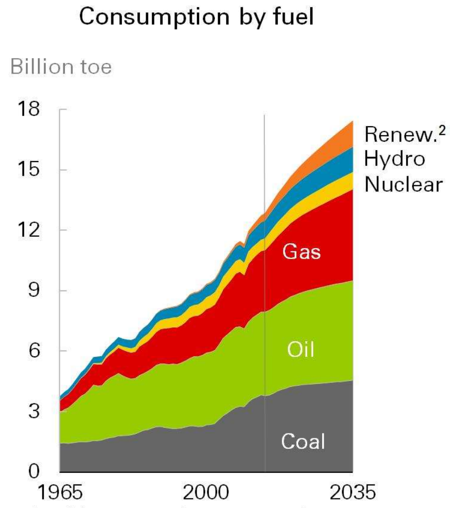


Primary energy consumption growth slows...



The slowdown in demand growth from industry...

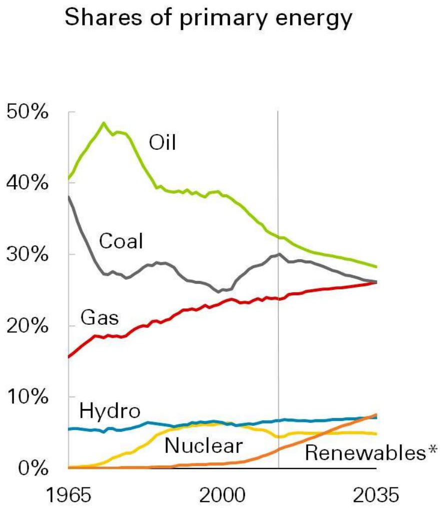




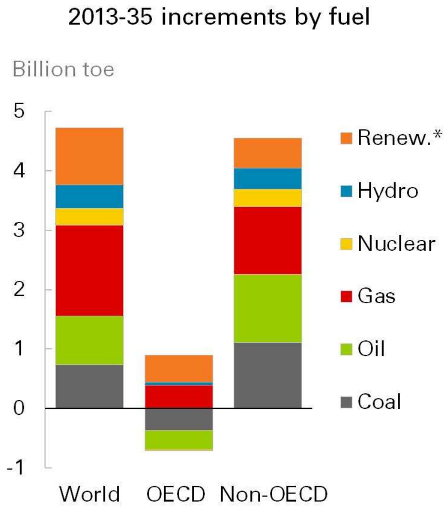
[1]Primary fuels in power allocated according to final sector electricity consumption
[2]Includes biofuels

Energy Outlook 2035 12 © BP p.l.c. 2015

Fossil fuels continue to provide most of the world's energy...



*Includes biofuels



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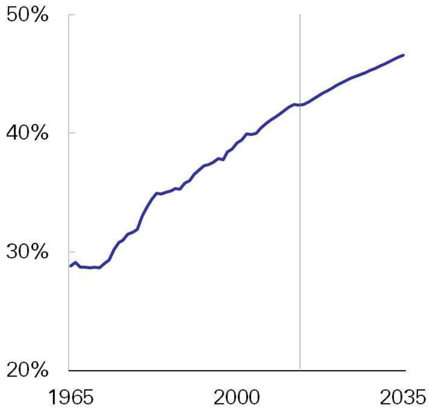
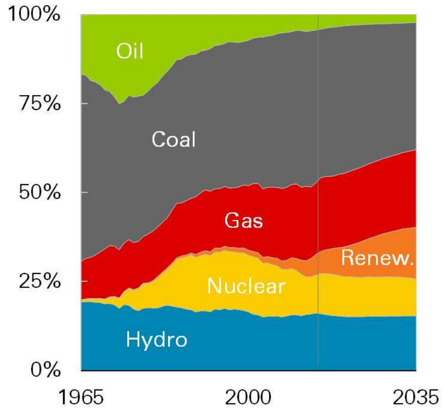
The power sector takes an increasing share of energy...

Inputs to power as a share of total primary energy



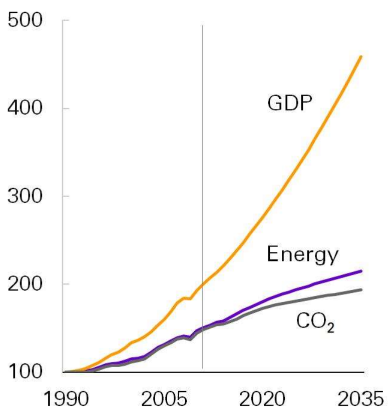
Primary inputs to power



Energy efficiency restrains the growth of emissions...

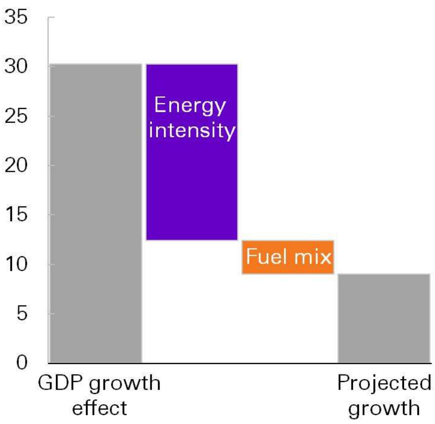
GDP, energy and emissions

Index: 1990 = 100



Emissions growth 2013 to 2035

Billion tonnes CO_2



Lecture outline

Sources of biomass

From agriculture From forestry From industry From zootechnics From organic fraction of MSW

Residues or by-products / diverted products

Always a residue

Energy crops

- … (Maize, wheat, …)
- … (Thistle, sugar cane, …)
- SRF: Short Rotation Forestry

Energy crops

Specialized crops featuring:

- high planting density;
- high level of mechanization;
- short harvesting intervals.

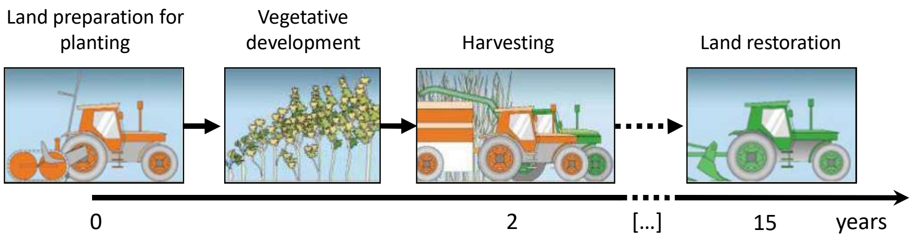
Species selection is based on the growing rapidity, adaptability and resistance:

Arboreal (poplar, false acacia, eucalyptus, …)

Annual herbaceous (sorghum, maize, …)

Multi-year herbaceous (hemp, miscanthus, …)

Scheme of the production process (15 year-long cycle):



Wood chipping

Chipping of wood from SRF

Lecture outline

- *Definition of Biomass*
- *Origins of biomass*
- *Energy consideration on biomass production*
- *Which biomass is relevant to energy purposes?*
- *The current and future contribution of biomass in meeting the energy needs*
- *Sources of biomass*
- *Concerns about energy exploitation of biomass*
- *Energy conversion routes for biomass*
- *Final remarks*

Global land surface and main land use categories

Land use category	(Gha)	Remarks
Agriculture	1.5	Includes grassland for intensive cattle farming
Pastures/grassland	3.5	More extensively managed
Forest	4.0	Includes natural – production forest
Inproductive	4.2	Includes (semi-)deserts, mountainous terrain and built-on areas.
Total	**13.2**	**Global land-surface (excludes large ice sheets).**

Source: A. Faaij – Utrecht University

Potential spread in the global demand for food (2050) 69

	Current situation	Vegetarian diet, low population growth	Average diet, average population growth	Protein rich diet, high population growth
Global population (billion)	5.9	7.7	9.4	11.3
Diet (dry kg $grain_{eq.}$/person/day)	2.6	1.3	2.3	4.2
Total demand for food (Gton $grain_{eq.}$/year)	5.650	3.670	8.240	17.310

Source: A. Faaij – Utrecht University

Potential global land surplus (in Gha) 70

for a world population of 9.4 billion people for different “average diets” and “agricultural systems” on a fixed land area of 5 Gha.

Global food production system	**Vegetarian diet**	**Average diet**	**Protein rich diet**
HEI	4.00	3.16	1.88
LEI	2.17	0.64	0.00

Source: A. Faaij – Utrecht University

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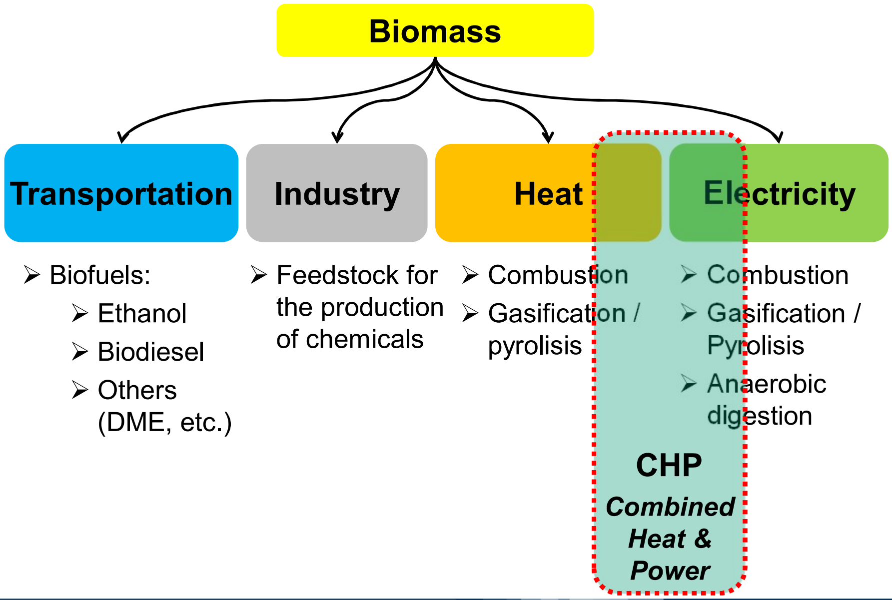
Energy conversion of biomass

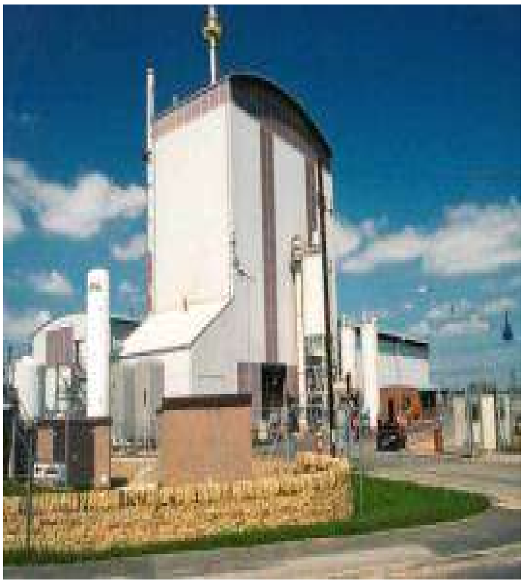


Energy conversion by biomass type

	Thermo-chemical conversion processes*	Anaerobic digestion	Fermentation	Acidic or enzimatic hydrolysis	Oil extraction	Other processes
"Dry" biomasses						
Wood	YES	NO	NO	YES	NO	NO
Herbaceous	YES	NO	NO	YES	NO	NO
Dried algae	YES	NO	NO	NO	NO	NO
"Wet" biomasses						
Manure	NO	YES	NO	NO	NO	NO
Green agricoltural residues	NO	YES	YES	NO	NO	NO
Silage	NO	YES	NO	NO	NO	NO
Algae	NO	YES	YES	NO	NO	YES
Sewage sludge	NO	YES	NO	NO	NO	NO
OFMSW	NO	YES	NO	NO	NO	NO
Seeds	NO	NO	YES	YES	YES	NO

** Combustion, Gasification, Pyrolysis*

Woodburning Electricity Generation (or CHP)



ARBRE (in the UK) is the first commercial wood-burning plant of its type in Europe.

It produces enough electricity for 33,000 people from clean and sustainable wood fuel sources.

The plant has a 10MW electricity generating capacity and 8MW is exported to the local grid.

The fuel for the plant is wood chips from forestry and short rotation coppice.

Coppice harvesting

First Renewables Ltd

Short rotation coppice harvesting for ARBRE wood-fuelled power station. As trees grow they store energy from the sun in their biomass. At ARBRE's power plant the energy stored in the biomass is converted to electricity.

Straw Burning Power Plant

Lorry leaving plant after delivering straw

- Elean Power station near Ely, Cambridgeshire (UK) generates 36MW of electricity and is the worlds largest such facility. It supplies 80,000 homes with electricity.

Biomass Plant in Fife (UK)

Plant burns poultry litter and produces 10MW of electricity and fertiliser

Fluidised bed boiler ensures efficient burning and low emissions

The largest biomass-fired power plant

http://www.eurobserv-er.org/pdf/baro194.pdf

Lecture outline

Limitations and constraints of biomass

1) **Agricultural production is oriented toward food crops**
2) **Energy crops can compete with other land use (production of foods, towns, infrastructures, etc.)**
3) **Possible high environmental, biological, landscape value of the involved ecosystem**
4) **Difficult accessibility of the areas for energy crops**
5) **Harvesting, handling and transportation more difficult and expensive than those of fossil fuels**
6) **Biomass requires more complex and expensive systems than those required by fossil fuels**
7) **Low efficiencies in the conversion to electricity or biofuels, mainly due to the small-scale of the plants**
8) **Hard to reach the same reliability than that of fossil fuel-fed plants**

Limitations and constraints of biomass

9) High O&M costs for biomass-fed plants
10) Environmental impact often problematic, except for greenhouse gas emissions, which are very limited
11) Large-scale diffusion of energy crops can require significant changes in society lifestyle
12) Social acceptance
13) Final product costs (electricity, heat, fuels) difficulty competitive with those obtained from fossil fuels, except in the presence of a significant incentive regime

Conclusions

1) Vegetable biomass represent a renewable resource that theoretically could meet the overall world energy demand
2) It is an almost CO_2 neutral source of energy, which can contribute significantly to the stabilization of CO_2 level in the atmosphere
3) In next years a significant increase in the use of biomass is expected, mainly due to government policies aimed at reducing greenhouse gas emissions
4) Beyond the valorization of particular residues, at present, biomass is economically competitive only when supported by an incentivizing regime
5) Energy exploitation of biomass encompass a wide portfolio of technological options
6) Several technological, environmental, economic and social problems are still unresolved, and must be faced in order to warrant a consistent energy exploitation of biomass