

Forest Biomass and Bioenergy: Opportunities and Constraints in the Northeastern United States

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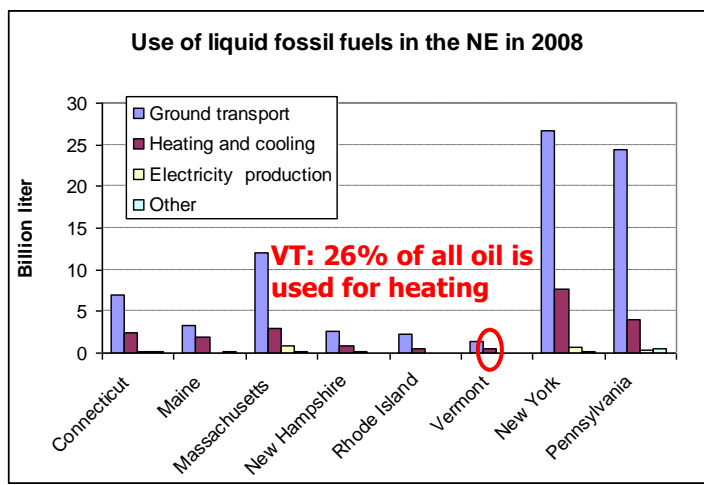
^a) Carbon Dynamics Lab, University of Vermont
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^b) Cary Institute of Ecosystem Studies

^c) Environmental Defense Fund (EDF)



How much oil can be replaced by using woody biomass?



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Goal of the study and data used

Produce a regional assessment for the Northeast of:

The potential forest-based biomass energy supply (USDA FS Forest Inventory Assessment – FIA), and

The degree to which that energy could supplant current fossil fuel based energy consumption within the Northeast (Energy Information Administration datasets).

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What is the Condition of Northern Forests?

- A common assumption:
“Northeastern forests are **even-aged** and **mature**, dating from a period of intensive harvests over 100 years ago”
 - *A corollary: Their rates of growth (and carbon sequestration) are declining as they mature*

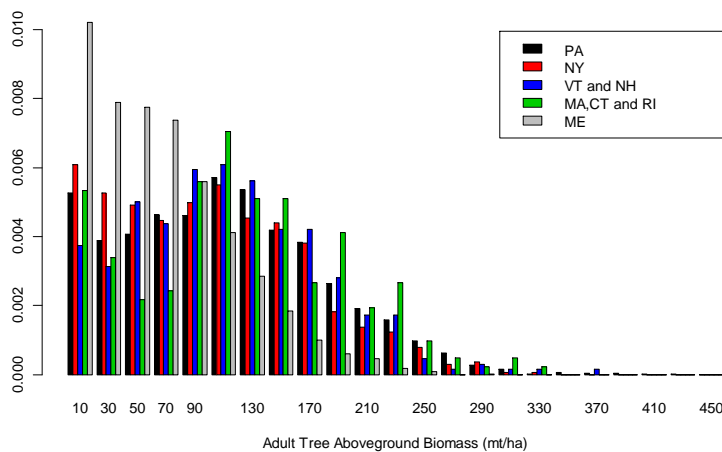
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But, this is a very common sight from the air...



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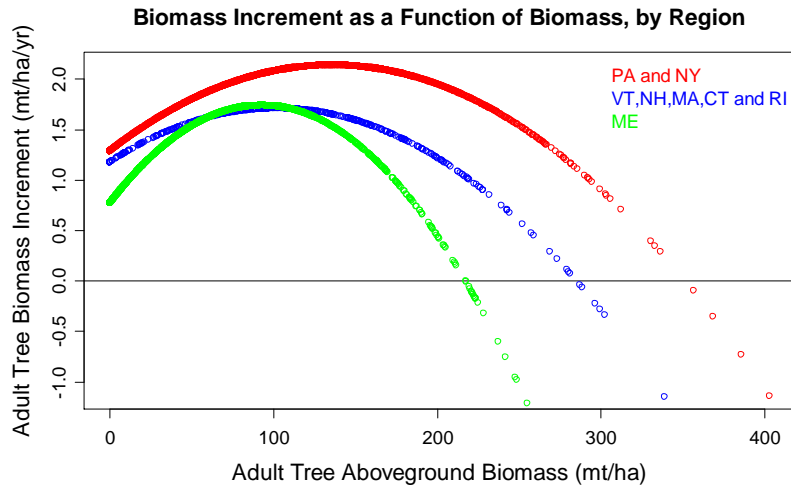
Current Frequency Distribution of Aboveground Tree Biomass, by Region



Data from the most recent full-state FIA census cycle (typically 2003-2007)

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Have our forests “matured”, and stopped growing?



Silvicultural Systems in the Northern Forest

- **Perception:** clearcutting is still the dominant forestry
- **Reality:** clearcutting is uncommon except in certain forest types (conifers). Partial harvests are the norm, but there is regional variation in the **frequency** and **intensity** of harvests...
- **Analysis:** use FIA data to characterize the regional forest “harvest regime”

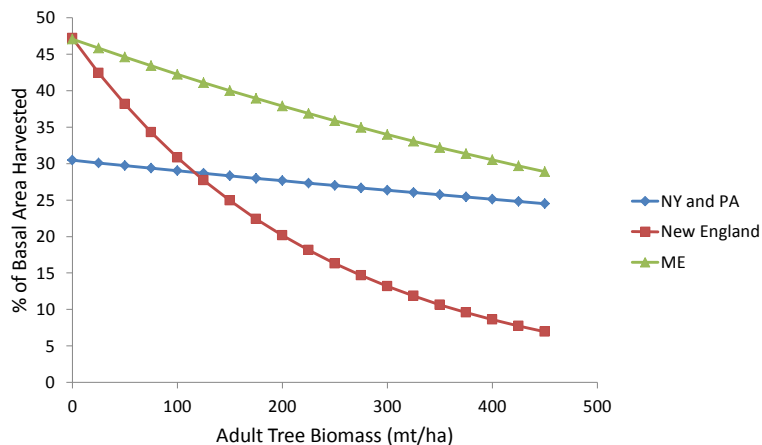
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A Statistical Model for the Aggregate Regional Harvest Regime

- FIA data record whether trees are “removed” (harvested)...
- So, fit a two-part statistical model to the plot data:
 - First: Estimate the probability that a plot is not logged (removal = 0)
 - Second: Estimate the fraction of basal area removed if a plot is logged
- Independent variable (for both parts): adult tree biomass

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Estimated Fraction of Tree Basal Area Removed (if a stand is harvested)



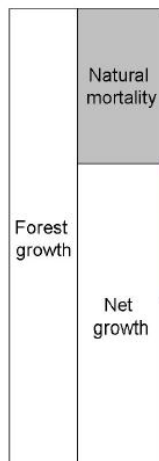
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Table 2. Average annual net volume growth of aboveground biomass, mortality, and removals, by state, over the period 2004-2008 from FIA program population estimates in units of tree volume (m³/yr). "Difference as a % of total volume" is the difference between net growth and removals, as a percent of total volume of trees, and indicates the estimated annual % increase (or decrease) in total tree volume, given these rates of net growth and removal.

STATE	NET GROWTH m ³ /yr	MORTALITY m ³ /yr	REMOVALS m ³ /yr	GROWTH - REMOVALS m ³ /yr	DIFFERENCE AS % OF TOTAL VOLUME	REMOVALS AS A % OF NET GROWTH
Connecticut	1,985,171	1,206,620	1,972,099	13,072	0.01%	99%
Maine	16,585,125	9,944,035	17,381,728	-796,611	-0.11%	105%
Massachusetts	3,548,842	2,345,552	1,028,608	2,520,258	1.15%	29%
New Hampshire	5,744,156	3,508,445	2,490,233	3,253,953	1.08%	43%
New York	20,015,035	14,447,706	9,788,476	10,226,655	0.91%	49%
Pennsylvania	24,207,723	9,216,975	12,742,610	11,465,221	1.14%	53%
Rhode Island	475,929	193,091	80,258	395,675	1.78%	17%
Vermont	5,107,525	2,897,275	3,412,785	1,694,756	0.59%	67%
Total	77,669,505	43,759,699	48,896,797	28,772,980	0.76%	63%

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Legal, physical, economic and social constraints to additional biomass harvests



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Table 4. Biomass availability by scenario and state in metric tons (dry) per year. If constraints on forestland availability are factored into the calculations, current harvest rates in both Connecticut and Maine already exceed net growth, so no additional harvests were factored into Scenarios B and C for those two states.

State	Scenario A- Diverting Biomass from Paper to Energy	Scenario B - Biomass from New Harvests		Scenario C Combined	
		Low	High	Low	High
Connecticut					
Maine					
Massachusetts					
New Hampshire					
New York					
Pennsylvania					
Rhode Island					
Vermont					
Total					

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Fossil fuel replacement scenarios

- 10% co-firing with coal for electricity
- Wood electricity, 25% efficiency
- Wood electricity, 40% efficiency
- Combined Heat and Power (CHP), 40% efficiency for electricity and usable heat
- Wood chips for commercial and industrial heat
- Pellets for residential heat
- FT diesel for transport
- Cellulosic ethanol for transport

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Results Scenario B Low

Biomass can be used in many different energy sectors and with different efficiencies. Using the conservative estimate of 4.2 million metric tons of forest biomass supply for energy, the Northeast could either:

- Replace 6% of its coal consumption (used for electricity); **or**
- Provide 4 to 6% of its total electricity mix from biomass, with an additional 14% replacement potential of the liquid fossil fuels used in the commercial and industrial heating sector if Combined Heat and Power (CHP) technology is used; **or**
- Replace 28% of the liquid fossil fuels used in the commercial and industrial heating sector; **or**
- Replace 16% of the liquid fossil fuels used in the residential heating sector; **or**
- Replace 5 or 2% of its current highway diesel or gasoline consumption, **if** future liquid transport biofuels become commercially available.

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Table 5. Energy use (in Tera Joule), by state and for the region as a whole, in 2007, and the potential fraction of that energy use that could come from forest biomass given the estimates of sustainable biomass harvests (for energy) under 4 of the scenarios presented in Table 4. The calculations assume that the biomass is used in a combined heat and power plant with an 80% overall efficiency (40% in electricity generation, and 40% in usable heat), and thus represent a best-case scenario.

STATE	2007 Total Energy Use (TJ)	Scenario B - Biomass from New Harvests		Scenario C - Biomass from New Harvests and All Existing Pulp Harvests	
		LOW	HIGH	LOW	HIGH
Connecticut	918,589	0.3%	0.3%	1.5%	1.5%
Maine	480,658	8.4%	8.4%	40.0%	40.0%
Massachusetts	1,597,903	0.5%	0.8%	0.9%	1.2%
New Hampshire	331,481	6.6%	9.8%	13.6%	16.7%
New York	4,268,847	0.7%	1.2%	2.3%	2.8%
Pennsylvania	4,226,541	1.5%	2.5%	4.2%	5.2%
Rhode Island	229,568	0.4%	0.7%	0.6%	0.9%
Vermont	171,016	5.1%	10.1%	22.9%	28.0%
TOTAL	12,224,602	1.4%	2.2%	4.7%	5.5%

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Results Scenario B Low

- Maine could replace up to 42% or 49% of its current use of liquid fossil fuels in the **commercial/industrial OR residential heating sector**, respectively
- New Hampshire could replace 84% of its current use of liquid fossil fuels in the **industrial and commercial heating sector** with local forest biomass if all biomass would be directed into that sector only.
- Neither Connecticut nor Rhode Island will be able to substitute > 10% of any of their fossil fuel sectors (transport fuels, heating applications, electricity production) with forest-based biomass energy.

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How much oil can be replaced in Vermont by using woody biomass (Scenario B Low)?

Heating oil in VT:

- **12,168,000 barrel/year (EIA 2008)**
- **\$92/barrel (mean 2008)**
- **>\$ 1.1 billion leaving the state annually**
- **Most realistic biomass availability from additional harvests and residue collection: ~200,000 dry tons/yr**
- **VT policy goal 25x25: double biomass share in energy portfolio (McNeil alone consumes 300,000 dry tons/yr)**
- **Forest biomass could replace max. 13% of currently used heating oil (25% of residential OR 58% industrial & commercial)**

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Discussion!



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Download the full study at:
http://www.ecostudies.org/press_2011-02-17.html

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Regional variation in average biomass and biomass increment

State	Number of Plots	Mean Aboveground Biomass (mt/ha)	Mean Biomass Increment (mt/ha/yr)	Coefficient of Variation
Pennsylvania	1944	115.0	2.08	3.5%
New York	559	103.2	1.23	9.5%
Southern New England	191	121.3	1.07	20.2%
Vermont	134	115.1	1.64	12.7%
New Hampshire	143	117.8	1.83	10.3%
Maine	2589	67.92	1.35	3.0%

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Factors limiting the available resource base

- **Legal restrictions**
 - Only ~ 6% of forestland in the 9-state region is legally reserved
 - Some additional limits due to buffer limitations along water bodies, and limits on logging at high elevations
- **Physical site restrictions**
 - ~ 4% of FIA plots are in "hydric" conditions (wetlands)
 - ~ 5% of FIA plots are on steep slopes
- **Access limitations**
 - ~ 8% of FIA plots are > 1 mile from the nearest improved road
- **Parcel size limitations**
 - Common assumption that small parcels are rarely logged, but this is not borne out by surveys of family forest owners
- **Landowner interests**
 - **The real wild card:** what factors determine whether a private (or public) landowner is willing to consider a harvest on their property

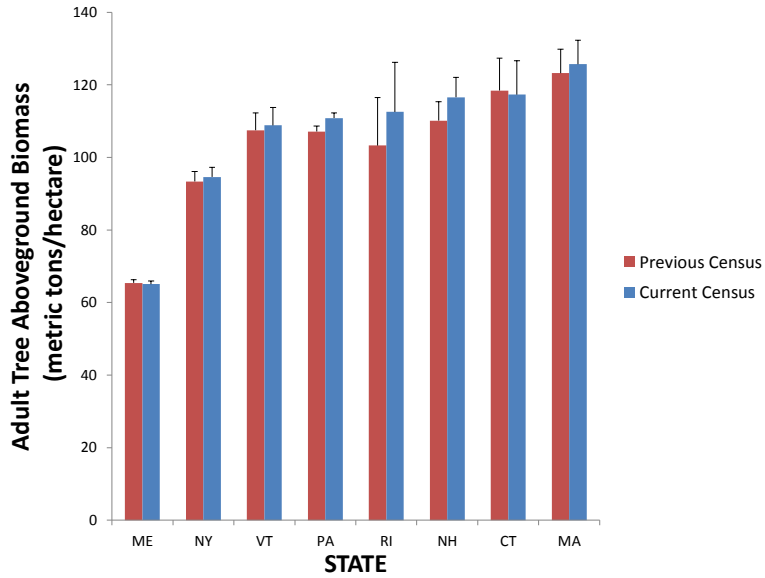
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What is the Potential Biomass Yield from the Northern Forest?

- **Perception:** current harvest levels are far below sustainable yield – there is a large, unused resource out there...
- **Reality:** There is certainly a lot of live tree biomass on the landscape (**stock**), but a significant fraction of annual **yield** (particularly from "available" forestland) is already being harvested
- **Uncertainty:** How much of an increase over current harvests is sustainable?

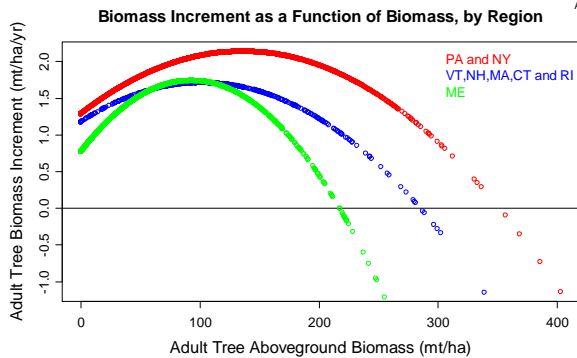
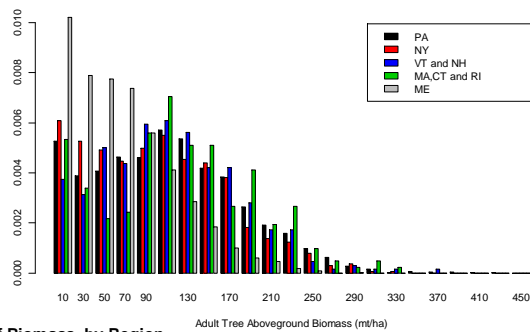
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Average adult tree aboveground biomass (per hectare), by state



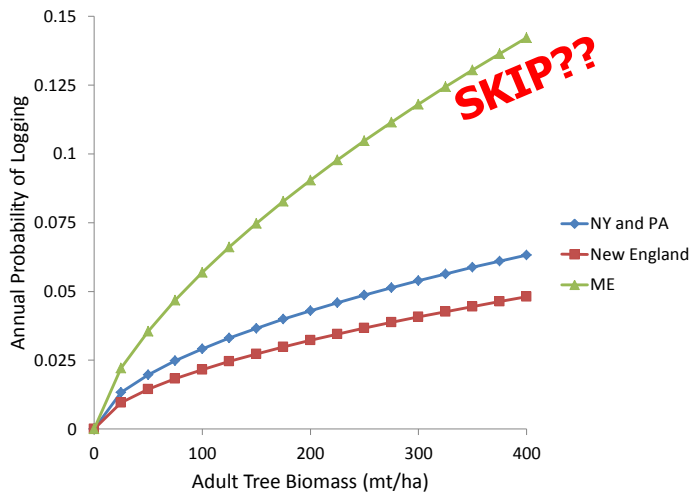
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The difference between “sustainable yield” and steady-state forest biomass...



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Estimated annual probability that a stand will be logged



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How much oil can be replaced by using woody biomass?

Heating oil in VT:

- 12,168,000 barrel/year (EIA 2009)
- \$92/barrel (mean price 2008)
- >\$ 1.1 billion leaving the state annually

Use more woody biomass from forests to:

- Heat homes?
- Satisfy industrial heating demands?
- Produce electricity?
- Hope for the development of future liquid fuels from wood?

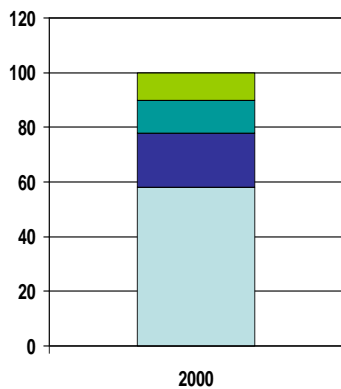
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World Biomass Use

- In 2000, about 16% of the world’s terrestrial net primary production (NPP) was harvested for use as one of the six Fs (Krausmann et al. 2008)
 - 65% was used by societies
 - 35% ended up being “unused”
 - 12% aboveground material that was killed but not used (e.g. residues from agriculture and forestry)
 - 10% belowground material that was killed but not used
 - 13% destroyed in human induced fires

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World Biomass Use



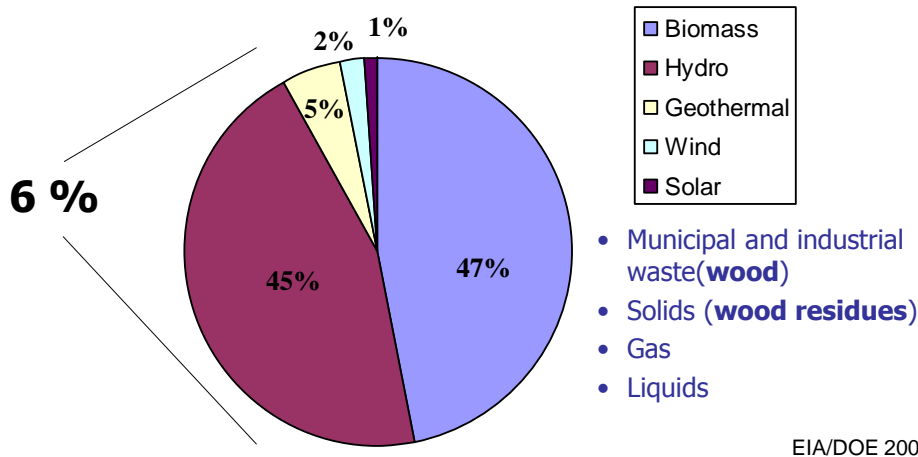
Biomass is the source of five F’s:

- Feed
- Fiber
- Food
- Fuel
- Fertilizer

Source: (Krausman et al. 2008)

Bioenergy in the US

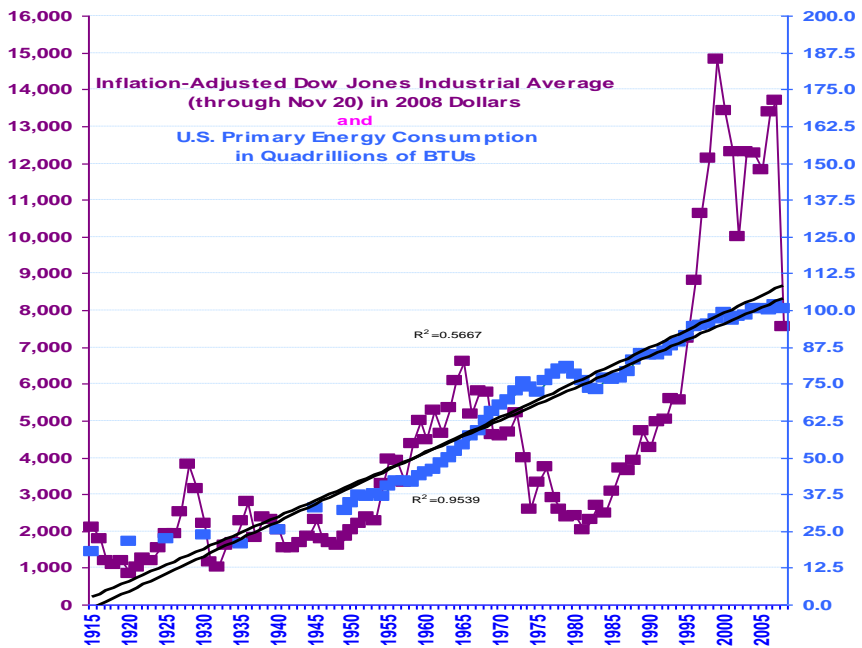
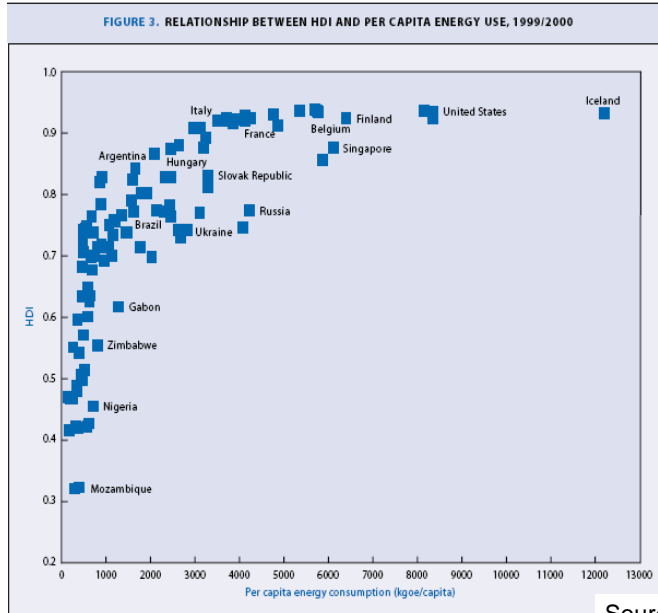
Example: How much of energy used in the US comes from renewables?



What is energy?

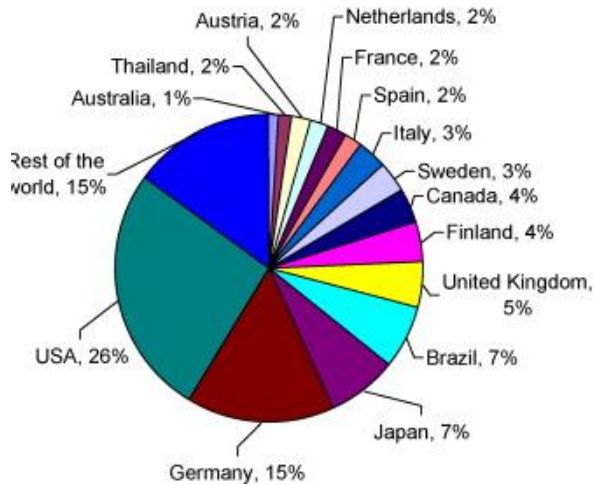
- Energy is the capacity of a physical system to perform work
- Heat, mechanic (kinetic), light
- Calorie, Joule, kWh, Newton meter, BTU, Barrel of Oil Equivalent (BOE)
- 'Energy' in this lecture is used to describe primary energy sources to humanity excluding food

Energy and standard of living



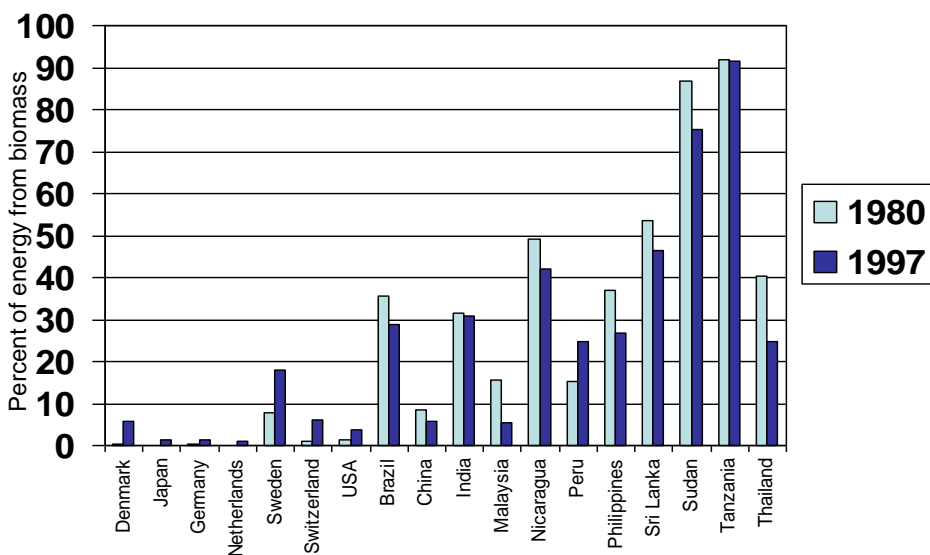
Source: Charles Hall SUNY_ESF

Global distribution of biomass energy use in 2008



Source: Evans et al. 2010

Global Bioenergy Consumption



© (Rosillo-Calle 2007)

What is biomass?

- Clean Development Mechanism has a definition of renewable biomass that is longer than a page
- What is bioenergy? 'Modern' bioenergy?
- What types of bioenergy exist?
- What kind of biomass is common for bioenergy?

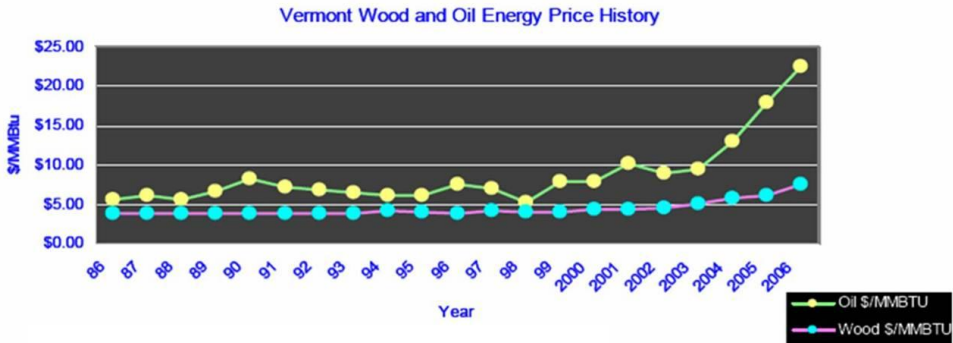
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Why a focus on wood in this lecture?

- Wood is the dominating bioenergy feedstock
- Consistency of feedstock
- Moisture content
- Low input resource (fertilizer, herbicide, labor, machinery, fuel)
- Price
- Flexible site demand –
 - can be grown on marginal and degraded land,
 - can be used to improve land over the long run,
 - Not necessarily competition with food production (can even enhance food production)
 - Agroforestry: less overall biomass output but more consistent

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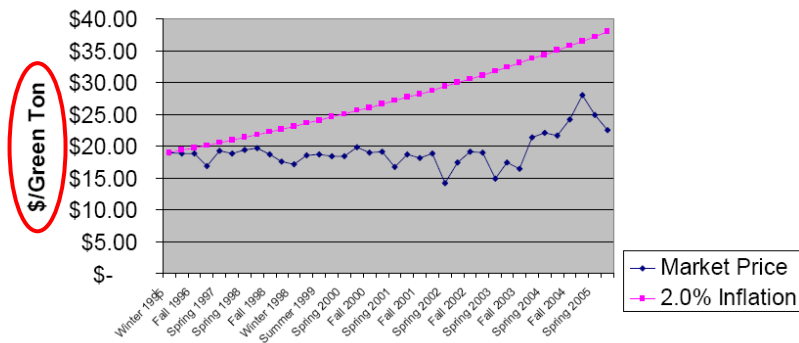
Biomass price development



Source: Paul Frederickson, VT Dept. of Forests, Parks & Rec.

Biomass price development

10 Year Mean Woodchip Prices for New Hampshire



Source: Paul Frederickson, VT Dept. of Forests, Parks & Rec.

Wood energy carriers – price ranges

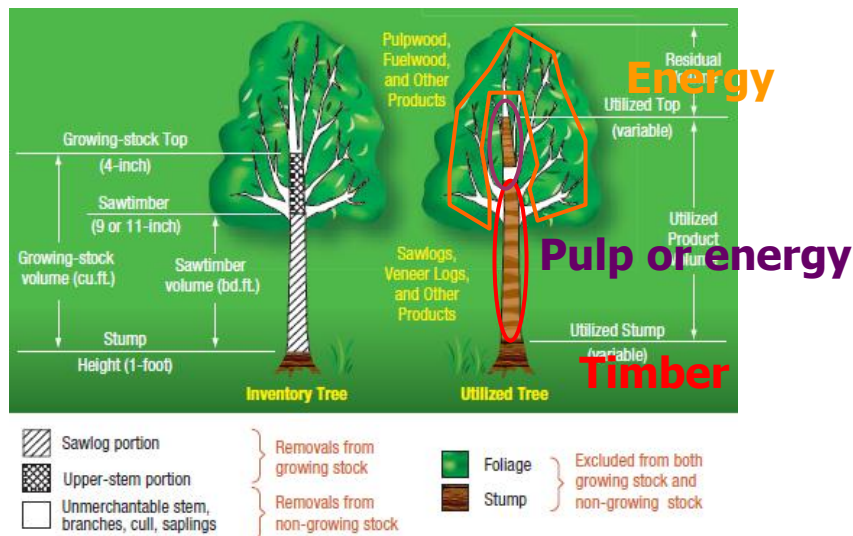
- Wood pellets: 150-300 \$/odt*
- Wood chips: 30-70 \$/odt
- Cord wood**: \$200/odt

* Oven-dried ton, 0% moisture

** Seasoned, delivered to Burlington VT

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And now the forest manager perspective...



- Logging residue includes the unmerchantable tops and small branches.

Source: Northeastern Forest Inventory & Analysis Program

Portion of cuts (in volume)

	Hardwoods	Softwoods
▪ Sawtimber	~30-40%	~60%
▪ Pulpwood	~40-50%	~30%
▪ Tops	~20%	~10%

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What other forest biomass COULD be used for bioenergy?

- Stumps
- Dead biomass
- Underbrush
- Limbs
- Twigs/tops

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Bundling of slash in Germany



Stump harvesting in Finland





Home » Applications

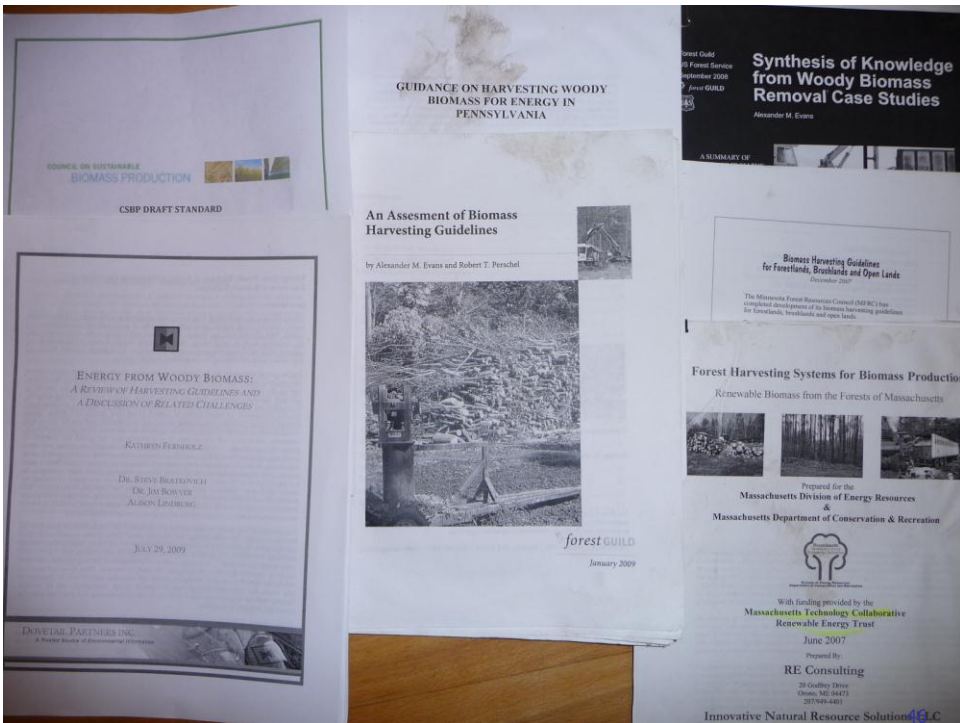
Applications

Bio-Mass Harvesting



Underbrush harvesting in pine plantations in Georgia

45



ADVANCE ON SUSTAINABLE BIOMASS PRODUCTION
 CSBP DRAFT STANDARD

ENERGY FROM WOODY BIOMASS:
 A REVIEW OF HARVESTING GUIDELINES AND
 A DISCUSSION OF RELATED CHALLENGES
 KATHYRN FERNANDEZ
 DR. STEVE BRADY, PH.D.
 THE JOE BONVIE
 ALISON LEWIS
 JULY 29, 2009
 DOWNTOWN PARTNERS INC.
 A Member of Environmental Connections

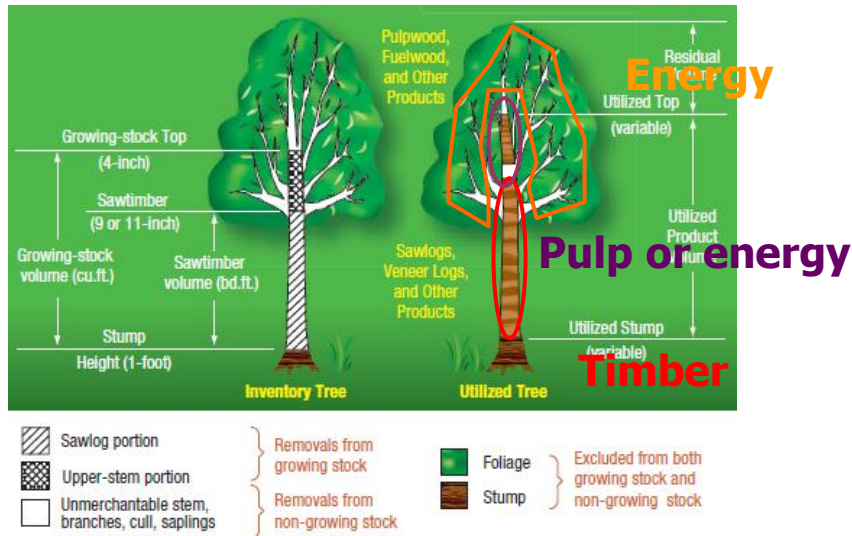
GUIDANCE ON HARVESTING WOODY BIOMASS FOR ENERGY IN PENNSYLVANIA
 An Assessment of Biomass Harvesting Guidelines
 by Alexander M. Evans and Robert T. Pertschel
 forest GUILD
 January 2009

forest Guild
 US Forest Service
 September 2009
 forest GUILD
 Synthesis of Knowledge from Woody Biomass Removal Case Studies
 Alexander M. Evans
 A SUMMARY OF

Biomass Harvesting Guidelines for Forestlands, Brushlands and Open Lands
 October 2007
 The Massachusetts Forest Management Council (MFMCC) has completed development of its biomass harvesting guidelines for forestlands, brushlands and open lands.

Forest Harvesting Systems for Biomass Production
 Renewable Biomass from the Forests of Massachusetts
 Prepared for the
 Massachusetts Division of Energy Resources
 &
 Massachusetts Department of Conservation & Recreation
 With funding provided by the
 Massachusetts Technology Collaborative
 Renewable Energy Trust
 June 2007
 Prepared by:
 RE Consulting
 28 GARDNER DRIVE
 OXFORD, ME 04473
 207-948-4483
 Innovative Natural Resource Solutions LLC

And now the forest manager perspective...



- Logging residue includes the unmerchantable tops and small branches.

Source: Northeastern Forest Inventory & Analysis Program

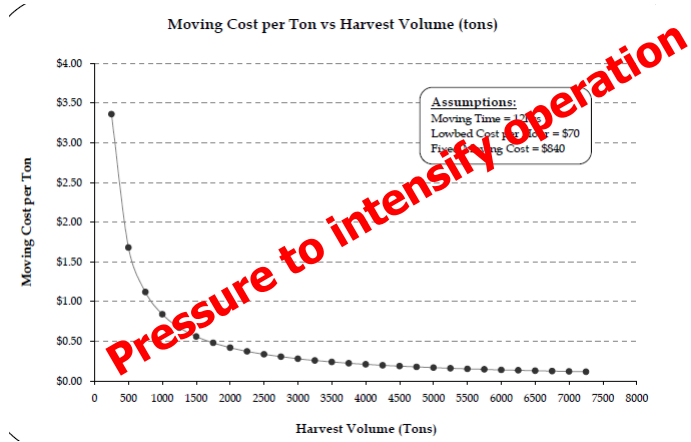
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Forest harvest operations in the NE

- Which stand will be logged?
 - Driven by high-value sawtimber
- How can you lower harvest costs?
 - Cut more volume
 - Additional revenue from pulp and fuelwood (chips, cordwood, etc.)
- What could it mean for biomass harvest if the timber-market is crashing? Or the pulp market?
- Sweden: 70 % of forest owner revenue from timber, 30% from pulp, **1% from fuel wood** (Loefstedt 1998)

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Reducing harvest costs



Source: Re-Consulting & INRS 2009



Picture: Re-Consulting & INRS 2009

Biomass Transport - Bulk Density



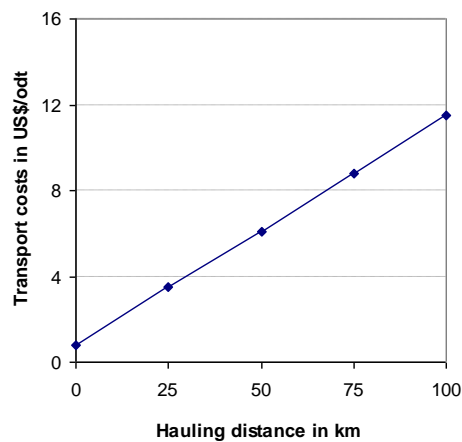
Equal weights of biomass in different forms

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Transporting wood to a bioenergy plant

Factors influencing transport cost:

- Form of biomass
- Distance
- Transport medium
- Biomass quantity



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Biomass transport costs/ energy requirement

Portland ME - Rotterdam NL (3,360 mi)

~

Burlington - Rutland VT (60 mi)

Table 3.3. Comparison of energy use per tonne-kilometre for different modes of freight transportation. Data are valid for the Netherlands, 2000. Source: Van Essen et al. (2003).

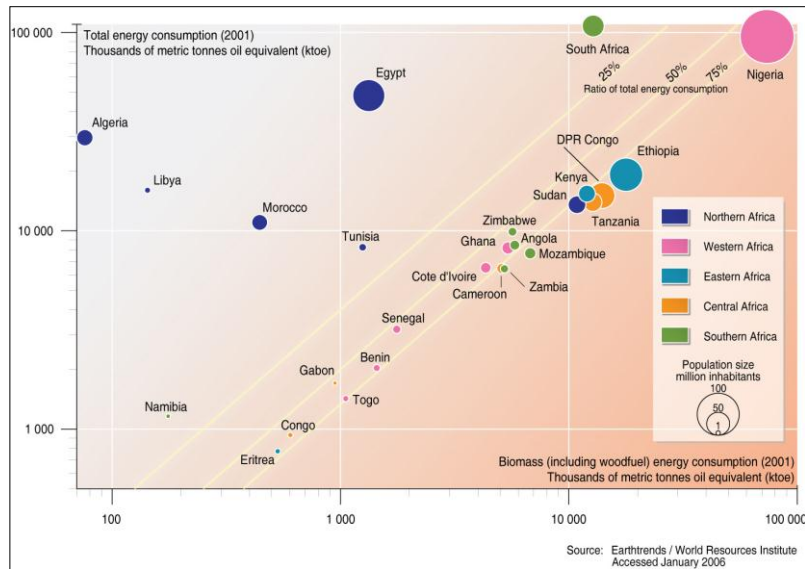
Transportation mode	Energy use per tonne-kilometre (MJ/tonne-km)
Van	8
Truck	2.8 (< 10 t) 0.8 (> 20 t)
Train	0.3 - 0.5
Aircraft	12 (500 km) 8 (6000 km)
Ship	0.15 - 1.0 (inland) 0.05 - 0.3 (sea-going)

Source: Blok 2006

What did we talk about??

- What is the role of bioenergy to a national/global energy mix?
- What types of bioenergy are there?
- What is the role of woody biomass in the (global, national) energy mix?
- How is biomass harvested in forests?
- What is the role of biomass in the harvest mix of a forest operation?
- What are concerns of biomass harvest in forests?
- What role can forest biomass play in VT to replace oil?

Bioenergy Use in Africa



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55

(Bio)Energy qualities

	GJ/ton
Dry wood/cellulosic biomass in general (logs, chips etc.)	16-21
Charcoal	30
Ethanol	23-31
Palm oil	42
Biodiesel	38
Bagasse	17
Diesel	45-48
Gasoline	44
Natural gas	30-55
Crude oil	42

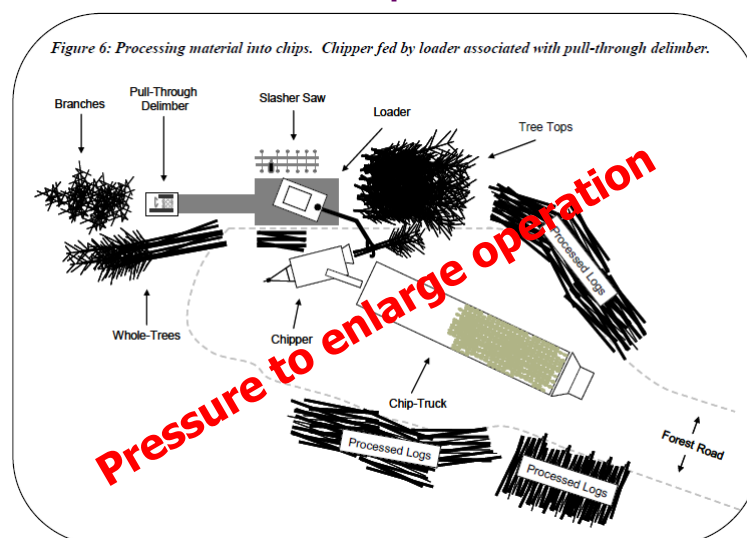
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Bioenergy by energy carrier (fuel)

Biomass fuels	+	-
▪ Gaseous	\$	conversion, trsp.
▪ Pellets	dry, handling	\$\$
▪ Liquids	trsp., J/kg	\$\$\$
▪ Cordwood	\$	bulky
▪ Chips	\$, handling	wet, quality
▪ Charcoal	trsp, J/kg	efficiency

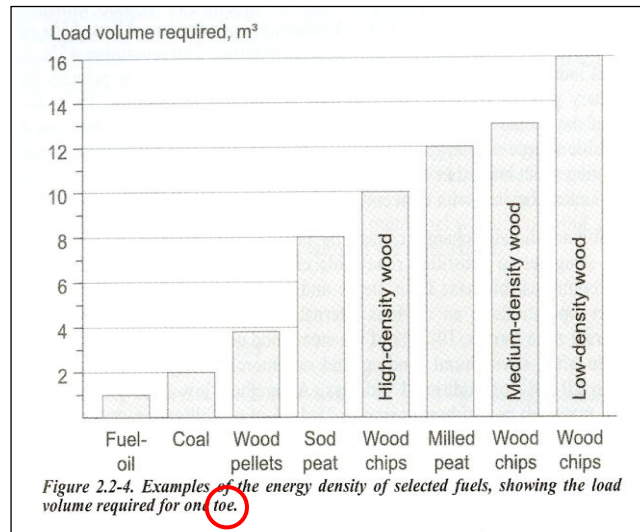
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Harvest operations



Source: Re-Consulting & INRS 2009

Energy Density



(Hakkia and Parikka 2002)

- Different types of bioenergy products and sources
- Significance of forest biomass in the US and elsewhere (why biomass if it is low quality (solid, bulky/low energy density, chunky, etc.) and scattered?)

How to structure decisions if bioelectricity is a good option?

The three components of bioenergy:

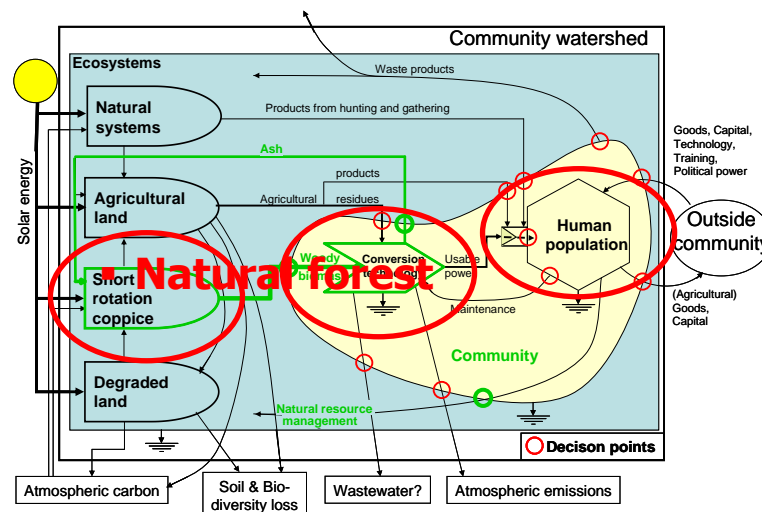
- Feedstock supply
- Conversion technology: Available technology
- Energy allocation: Demand (heat? electricity?)

Others:

- Available financing
- Etc.

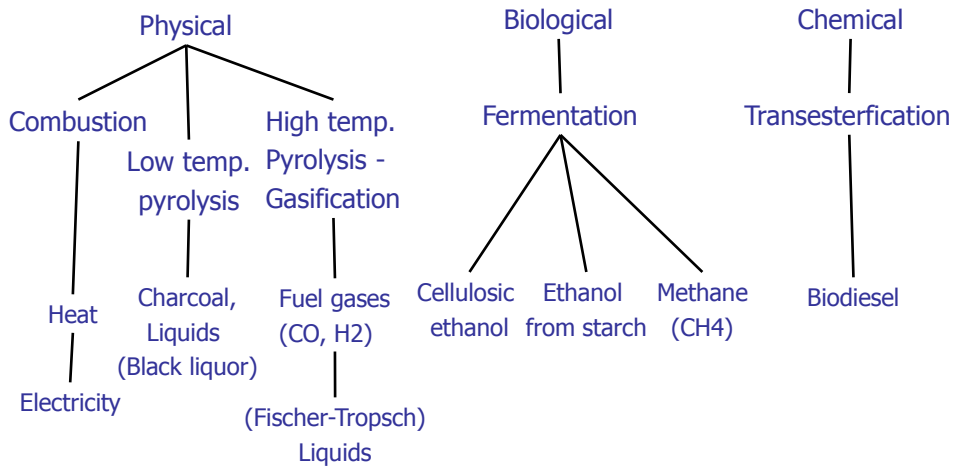
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A systems approach to bioenergy



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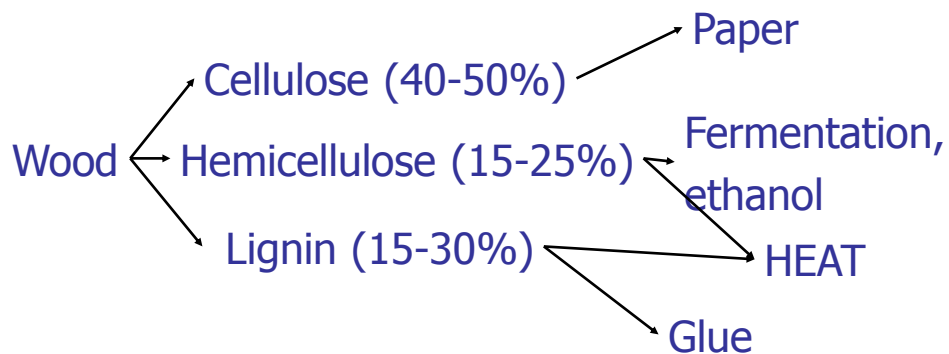
Bioenergy by conversion pathways



what about heat from methane????

Modified from NREL 2005

Maximizing revenue streams: Paper mill to Biorefinery



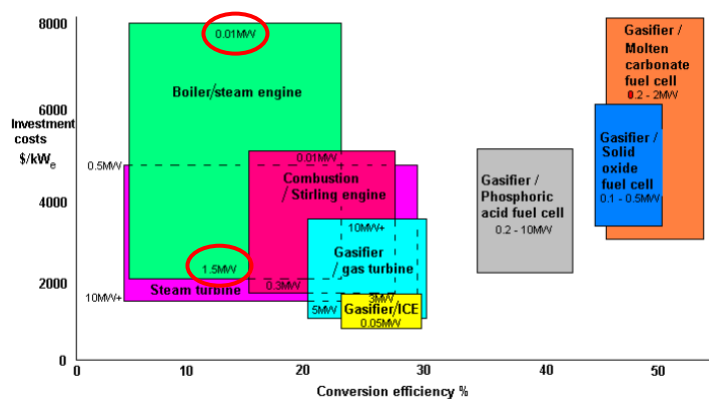
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Determinants for choosing bioelectricity technologies

- Scale
- Decentralized/distributed vs. centralized supply
- Off-grid/island solutions vs. grid connected
- Biomass characteristics and origin (e.g. waste, dedicated energy crops, etc.)
- Etc.

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Conversion technologies driven by scale, capital, efficiency

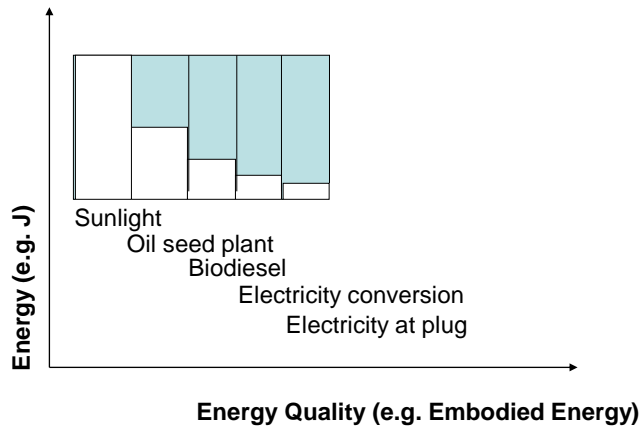


(Note: \$/kW_e are New Zealand dollars: NZ\$1 = \$US0.50 approximately)

Source: Sims, 2003

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Energy qualities - A bioenergy hierarchy



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Efficiency

- Efficiency = OUTPUT / INPUT
 - Energy efficiency
 - Resource
 - Financial
 - Time efficiency
- } The same?

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Mechanical efficiency examples of some technologies

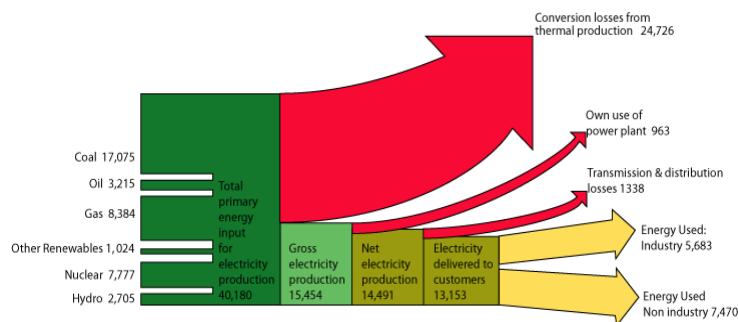
- Heat production (general fuels) up to 98 %
- Electricity wood to steam 5 -30 %
- Gasification 20-30 %
- Combined Heat and Power (CHP) up to 98 %
- Hydropower 40-50 %
- Solar panels max. 25 %
- Gasoline engine 15-25 %
- Diesel engine 25-40 (50)%
- Electric engine ~50 %
- Fuel cell 40-60 %
- Stirling engine 20-40 %
- Gas turbines 20-40(60)%

- Human and animal power ~20 %
- Photosynthesis ~2-5 %

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Energy efficiency and a systems approach

- 50 MW:
 - 30 % electricity - 3 % grid losses = 27 %
- 0.2 MW:
 - 15 % electricity + 60 % heat = 75 %



US power production, WADE 2008₀

Some bioelectricity facts and key factors

- Energy in a barrel of oil: 6.1 GJ (~159 liter)
- 1GJ = 273 kWh
- Solar radiation at earth surface ~200Wm²
- **1 odt/woody biomass = 16- 21 GJ**
- Load factors of electricity plants: 80-95 %
- Installed capacity vs net electricity output

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Energy Content

- Energy content per unit of C is fairly similar across most types of biomass and peat and coal
- Energy value can be estimated from C analysis and moisture content measurements (Klass 1998)
- HHV (MJ/dry kg) = 0.4571 (%C on dry basis) – 2.70



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Siting considerations

- Keep biomass trsp low; where is biomass?
- Where is heat demand? Multiply revenue streams
- Distribution infrastructure/grid availability
- Grid losses (up to 40 %)
- Where is (one big/cluster?) electricity consumer?

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Prevalent bioenergy related cost issues

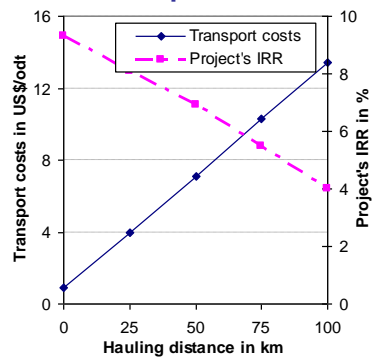
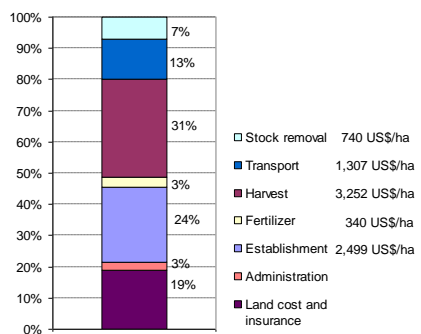
- - Initial capital investment
- - Biomass supply and price volatility
- - Volatile political context (subsidies? Emission regulations?)
- + Labor
- + Heat, power, combined heat and power (CHP) transport fuels

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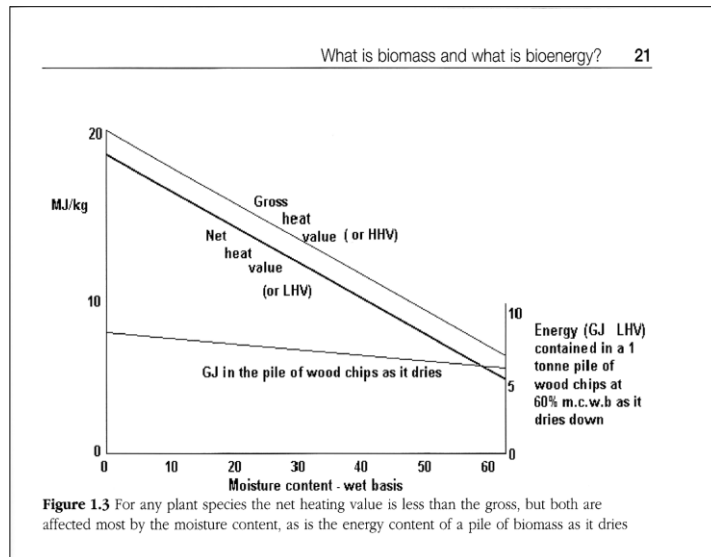
Biomass costs

- Cost at farm gate, cost at plant gate
- Willow short rotation examples



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Moisture and Energy Content

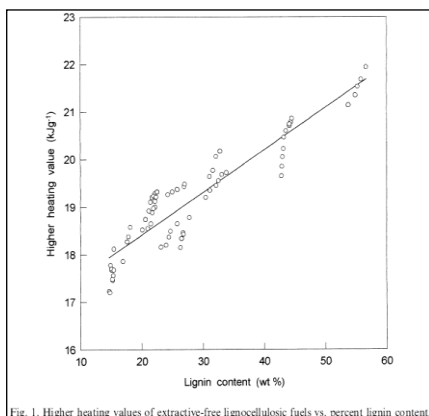


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(Sims 2002)

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Wood Components



(Demirbas 2001)



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- Biomass feedstocks including
 - Corn cobs
 - Tobacco leaf
 - Wheat straw
 - Hardwoods
 - Softwood
 - Tobacco stalk
 - Hazelnut shell
 - Olive cake
- $HHV = 0.0889(L) + 16.8218$
 - L is extractive free lignin content
 - $R^2 = 0.874$
- Wood only
 - $HHV = 0.0893(L) + 16.9742$
 - $R^2 = 0.9658$
- Non woody biomass
 - $HHV = 0.0877(L) + 16.4951$
 - $R^2 = 0.9302$

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Higher Heating Value (HHV)

- the **gross** amount of heat energy released when biomass is combusted at standard atmospheric conditions and 60% relative humidity
- includes the calorific value of the fuel (bone or oven dry) and the latent heat of vaporization of the water in the fuel
- Also called the Gross Heating Value (GHV), Calorific Value (CV) or Calorimetric Value (CV)



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Lower Heating Value (LHV)

- the **net** amount of heat released when biomass is combusted at standard atmospheric conditions and 60% relative humidity
 - Also called Net Heating Value (NHV) or Lower Calorific Value (LCV), Net calorific value (NCV), Effective Heating Value (EHV)
- The difference between HHV and LHV is the latent heat of vaporization, which depends on the moisture content of the fuel and its hydrogen content



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HHV and LHV

- Water generated during combustion of biomass comes from
 - the moisture in the fuel
 - H and O combine
- $LHV_{dry} = HHV - 2.45 \times 0.09 \times H_2$
 - LHV_{dry} = lower heating value of dry biomass (MJ kg⁻¹ dry mass)
 - HHV = higher heating value of dry biomass (MJ kg⁻¹ dry mass)
 - H_2 = hydrogen content of dry biomass (%)



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Moisture Content

- Need to understand the moisture content (%M.C. of the fuel)
- For wood ranges widely from <10% for wood residues up to 65%
- Other biomass sources can have m.c. of up to 90% (e.g. biosolids)
- The m.c. of wood is influenced by climate, species, harvesting method, time of harvest, length and method of storage

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Moisture Content

- Fuels are often compared on a dry weight basis (0% moisture content)
 - odt – oven dry tons
 - bone dry weight is same as oven dry
- Green weight is less rigorously defined term but is used to express the weight of freshly harvested biomass
- Biomass is often bought and sold on a green weight basis



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Measuring Moisture Content

- Measure fresh or wet weight of material, dry at 105°C to a constant weight

$$\text{m.c. wet basis} = \frac{\text{Total wet weight of wood} - \text{oven-dry weight}}{\text{Total weight of wood}} \times 100$$

$$\text{m.c. dry basis} = \frac{\text{Total wet weight of wood} - \text{oven-dry weight}}{\text{Oven-dry weight}} \times 100$$



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Moisture Effects

- If a conversion facility has been designed to use high moisture fuels, no technical problems will occur but high moisture content will impact the overall feasibility of the energy production:
 - the more water fuel contains -> lower heating value -> fuel efficiency is lower
 - the more water fuel contains -> bigger boiler volume needed -> more expensive boiler
 - transportation of water is expensive because there is no benefit to the overall energy system
 - most automated systems cannot react to rapid variations in moisture content resulting in incomplete combustion, which can change emission profiles



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Bulk Density

- Important to understand for transportation and storage requirements
- Varies by
 - form of biomass or piece size (i.e. solid wood, stacked roundwood, billets, or wood chips)
 - piece shape
 - moisture content
 - species
- Lower density means more air space
 - allows for more drying
 - require more storage space
 - increases transportation costs



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Bulk Density

Table 1.3 Typical bulk densities and moisture contents for biomass in various forms

Type of biomass	Moisture content (% w.b.)	Bulk density (kg/m ³)
Green roundwood	40–50	510–720
Green wood chips	40–50	280–410
Green wood chunks	40–50	350–530
Green sawdust	40–50	420–640
Air dry roundwood	20–25	350–530
Air dry wood chips	20–25	190–290
Air dry wood chunks	20–25	240–370
Kiln dry wood chips	10–15	160–250
Kiln dry wood chunks	10–15	200–310
Kiln dry sawdust	10–15	240–370
Wood briquettes	7–14	900–1100
Wood pellets	7–14	500–700
Straw bales	10–15	200–500
Coal for comparison	6–10	700–800



Lower end is for softwoods, higher end of range is generally hardwoods

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