Life Cycle Assessment of Forest Based Biofuels

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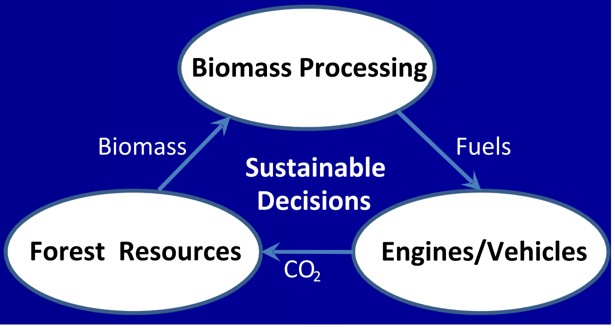
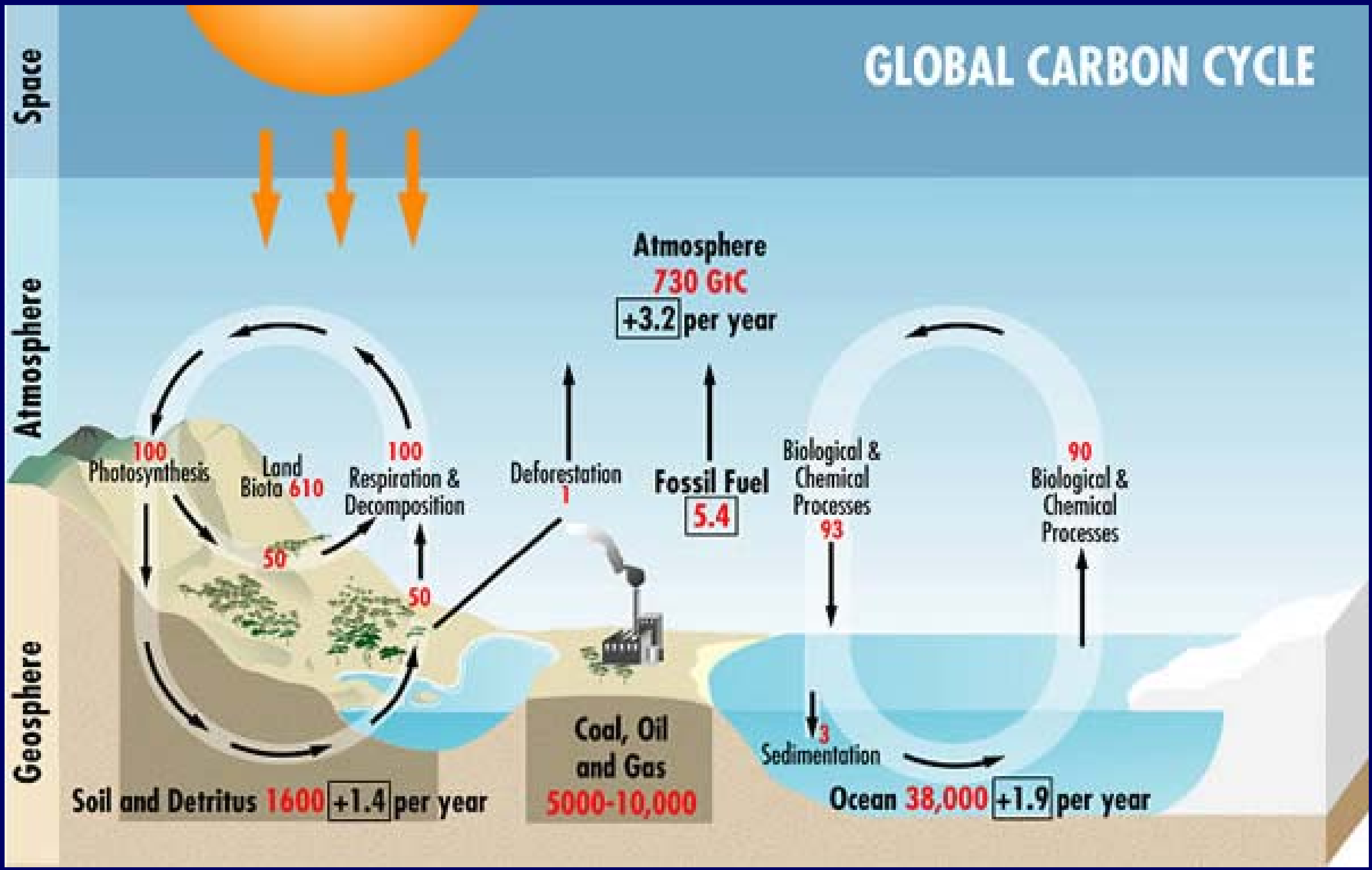
Forest Biofuels Statewide Collaboration Center Presentation
Wednesday, July 27, 2011



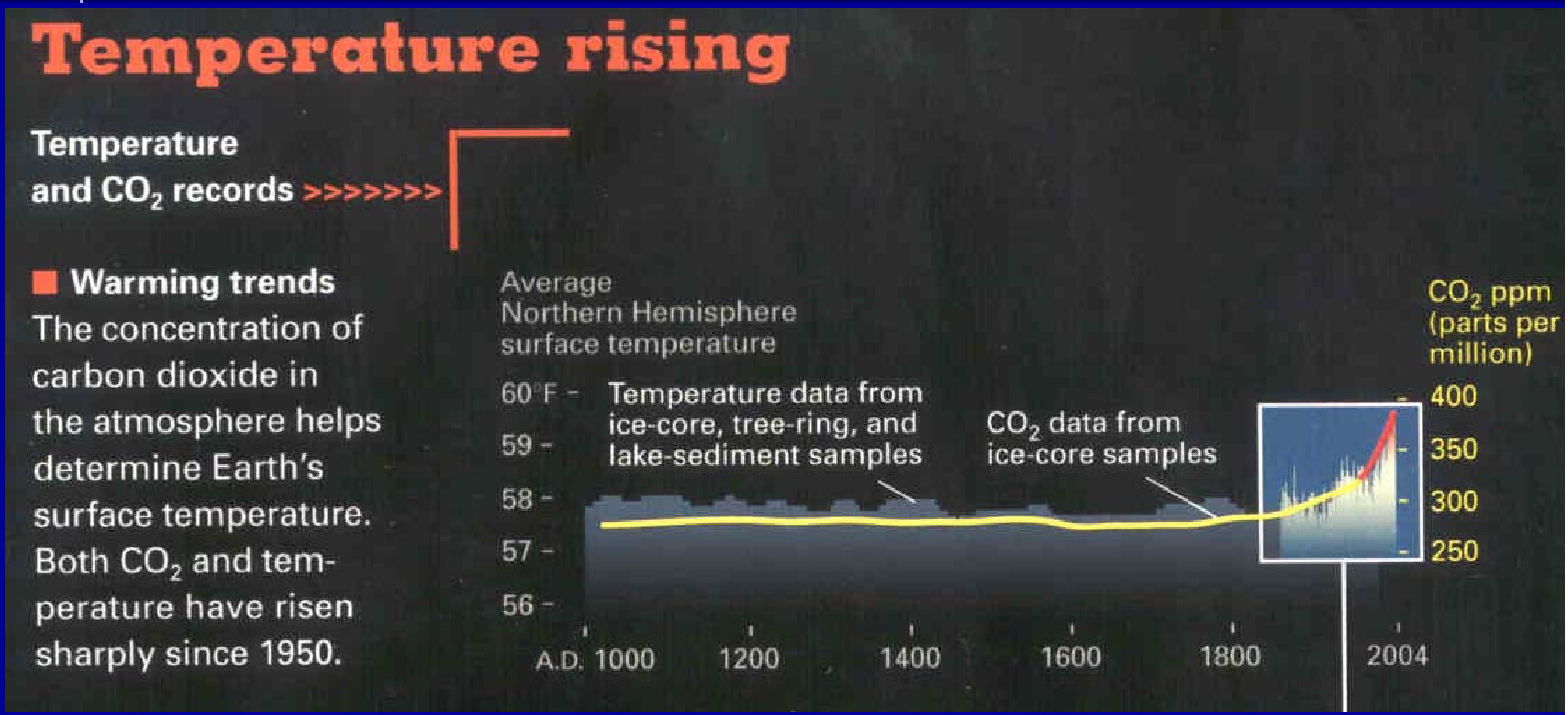
Managing the Carbon Cycle:
A Sustainable Energy Challenge

From http://www.bom.gov.au/info/climate/change/gallery/index.shtml

Combustion of Fossil Fuels acts as a Carbon Pump



CO_2 and Temperature in the Northern Hemisphere are Rising



National Geographic, September 2004, pg 20, National Geographic Society, Washington, D.C.

Wood-to-Wheels (W2W) Concept

Research Thematic Areas

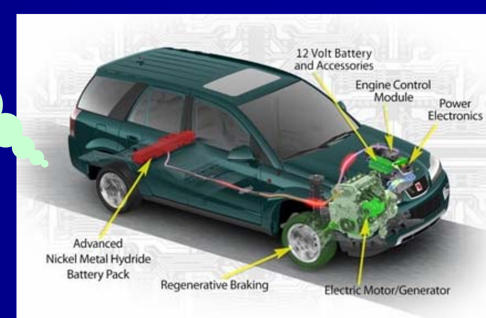
Sustainability Assessments / Decision-Making

Bio-Processing Research

Photo: Glacial Lakes Energy

Woody Biomass Resource Research

CO_2



Vehicle Systems Research

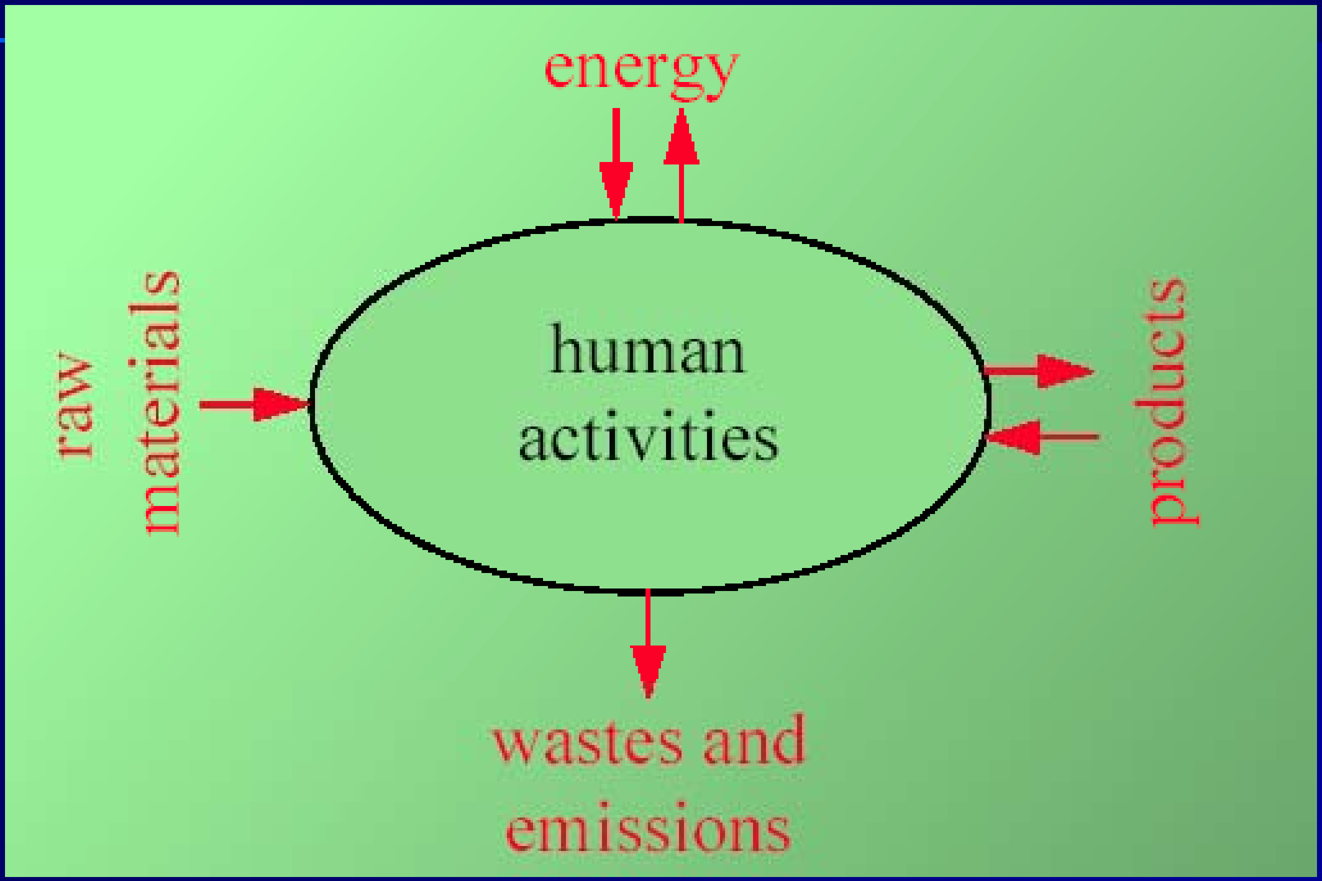
Presentation Outline

- An Overview of Life Cycle Assessment
- Goal and Scope Definition
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Comparison of Forest Feedstocks and Power Generated from Wood Versus Fossil Fuels

Uses of Life Cycle Assessment

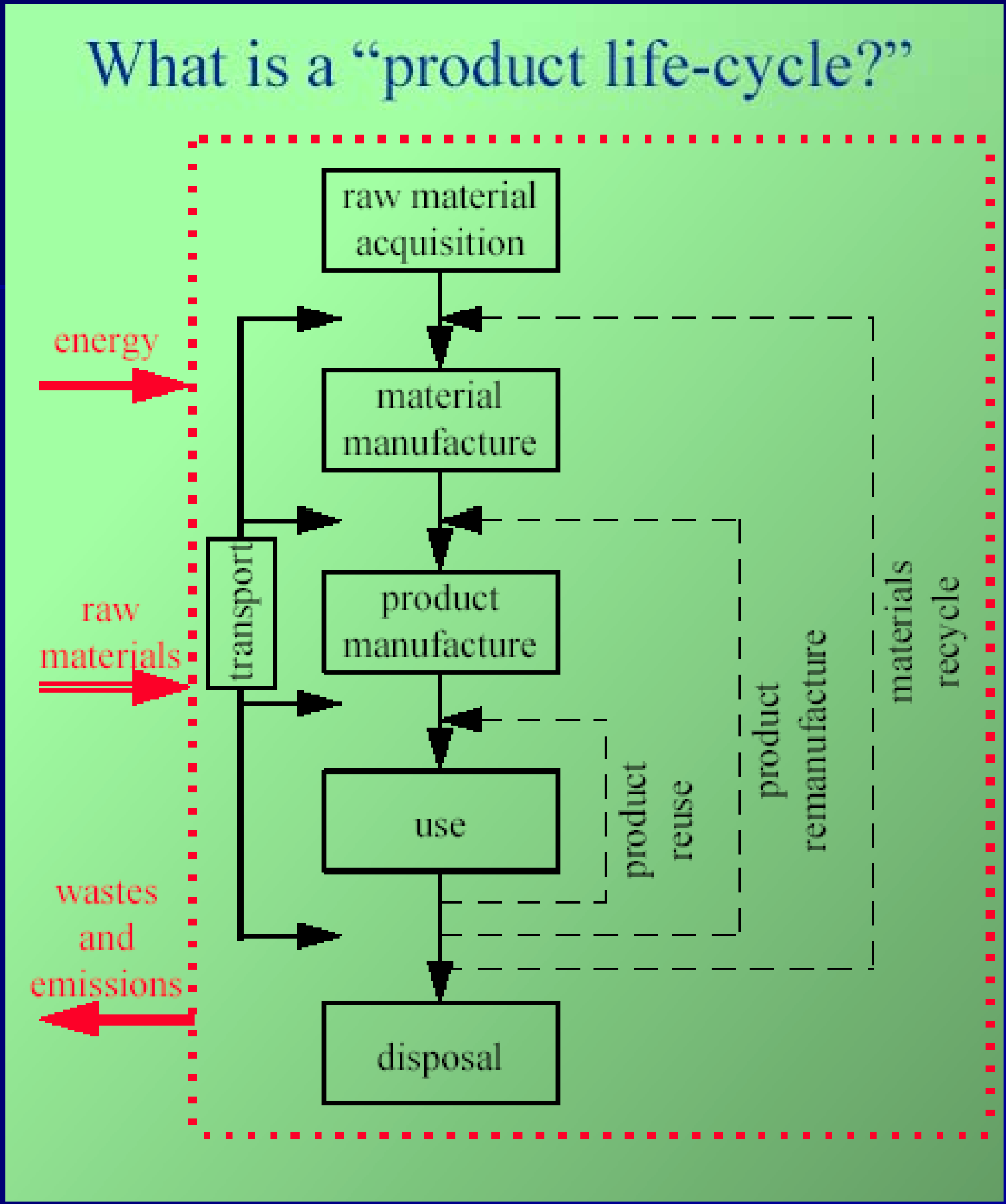
- Decision-making in industry and government
  - Strategic planning, investments, product/process design
- Marketing
  - Environmental claim, ecolabeling
- Communication with stakeholders
  - Shareholders, regulatory agencies, policy makers
- Research and Development
  - Early evaluations of projects, periodic re-evaluations

Overview of Life Cycle Assessment



D.T. Allen, University of Texas – Austin
"Life Cycle Assessment: Lesson 1"

Life Cycle Stages of a Product



D.T. Allen, University of Texas – Austin
"Life Cycle Assessment: Lesson 1"

International Standards for Life Cycle Assessment

- International Organization for Standardization
  - ISO 14040: Environmental management – Life cycle assessment – *Principles and framework*
  - ISO 14041: *Goal and scope definition and inventory analysis*
  - ISO 14042: *Life cycle impact assessment*
  - ISO 14043: *Life cycle interpretation*

ISO 14040 Principles and framework

- ISO 14040
  - Key features of the LCA methodology
    - *Scope must be from cradle to grave for products*
    - *LCA studies should be transparent*
    - *Specific requirements for comparative assertions*
  - Definition of a *functional unit*
  - Goal and scope of the study
    - *Goal: intended application, audience, reasons for the study*
    - *Scope: product system, types of impacts, data quality*

Functional Unit

- Functional Unit examples
  - Incandescent versus fluorescent lamps
    - *What is the function? – lighting of a space over time*
    - *How many lamps and of what wattage are equivalent?*
  - Fossil versus Forest-Based Transportation Fuels
    - *What is the function? – transport of a vehicle over a distance*
    - *1 MJ of forest based biofuels is equivalant to 1 JM of petroleum fuel*

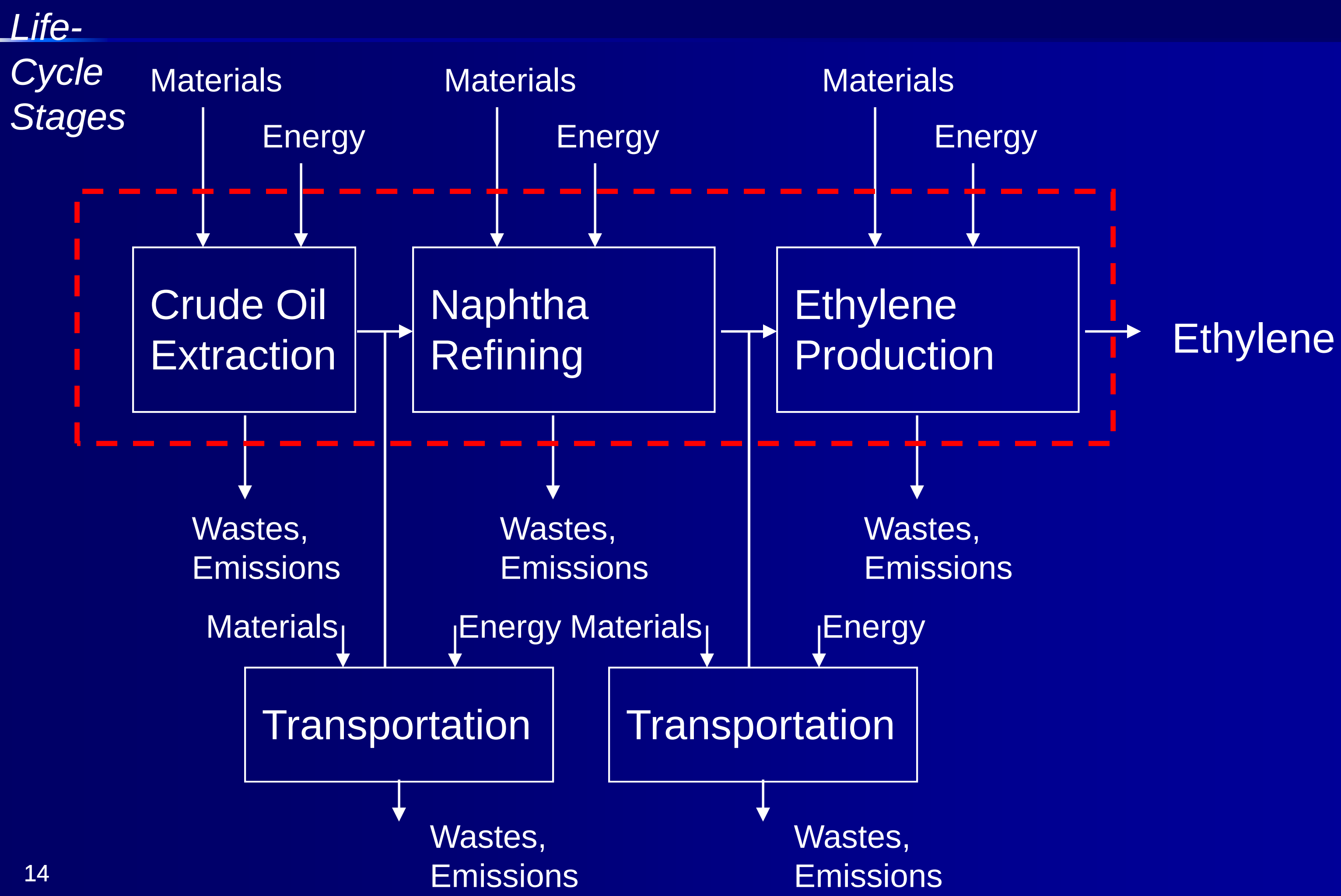
Summary of LCA Introduction

- Motivation for LCA: Reduce environmental impacts of products over their life cycle.
- LCA is used for decision-making, communication, marketing, and strategic planning
- ISO 14040-14043 cover all elements of LCA, from planning/execution to methodologies.
- Setting of goals and scope in LCA studies are among the most important elements of an LCA

Life Cycle Inventory (LCI)

- ISO 14041
- Categories of inventory data
- Allocation method
- Data quality requirements

Inventory for ethylene production



Categories of Inventory Data

- Energy resources (process heating and electricity)
  - *Oil, natural gas, coal, nuclear, hydro, wind, solar, biomass*
- Other raw materials
  - *Fe, NaCl, water, air, $CaCO_3$, Ni, Zn, etc.*
- Emissions
  - *to air, water, land*
- Other categories
  - *Land area use (often used in Europe and Japan)*

Inventory Categories (Ethylene Example)

Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Table 13.2-1 Life-Cycle Inventory Data for the Production of 1 kg of Ethylene (Boustead, 1993).

Category	Input or Output	Unit Average
Energy content fuels, MJ	Coal	0.94
	Oil	1.8
	Gas	6.1
	Hydroelectric	0.12
	Nuclear	0.32
	Other	<0.01
	Total	9.2
Feedstock, MJ	Coal	<0.01
	Oil	31
	Gas	29
	Total	60
Total Fuel + Feedstock		69

Boustead, I., Eco-profiles of the European Plastics Industry, Report 1-4, European Center for Plastics in the Environment, Brussels, May 1993.

Inventory Categories (Ethylene Example), cont.

Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Raw Materials, mg	Iron ore	200
	Limestone	100
	Water	1,900,000
	Bauxite	300
	Sodium chloride	5,400
	Clay	20
	Ferromanganese	<1
Air emissions, mg	Dust	1,000
	Carbon monoxide	600
	Carbon dioxide	530,000
	Sulfur oxides	4,000
	Nitrogen oxides	6,000
	Hydrogen sulfide	10
	Hydrogen chloride	20
	Hydrocarbons	7,000
	Other organics	1
	Metals	1

Inventory Categories (Ethylene Example), cont.

Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Water emissions, mg	Chemical oxygen demand	200
	Biological oxygen demand	40
	Acid, as H+	60
	Metals	300
	Chloride ions	50
	Dissolved organics	20
	Suspended solids	200
	Oil	200
	Phenol	1
	Dissolved solids	500
	Other nitrogen	10
Solid waste, mg	Industrial waste	1,400
	Mineral waste	8,000
	Slags and ash	3,000
	Nontoxic chemicals	400
	Toxic chemicals	1

Data quality requirements

- Time-related coverage of data:
  - *How current is data? Averaged over what period?*
- Geographic coverage of data collection:
  - *Local, regional, national, continental, global?*
- Technology coverage of data:
  - *Average of process mix?, best available technology?*

Summary of life cycle inventory

- Possibly the most challenging part of LCA.
- ISO 14041 provides guidelines
- Categories: energy, raw materials, ...
- Commercial software tools are available, but the most accurate inventories may be generated internally for manufacturers.
- Time-related, geographic, and technology coverage of inventory data – reduce uncertainty

Life Cycle Impact Assessment (LCIA)

- ISO 14042
- Mandatory requirements for LCIA
  - *Identify* impact categories,
  - *classify* inventory elements into impact categories,
  - *characterize* impacts for each inventory element
- Optional features of LCIA
  - *normalization*
  - *valuation*

Identification of Impact Categories

Global warming

Stratospheric ozone depletion

Smog formation (O_3)

Acidification

Human health impacts

Ecosytem health

Eutrophication

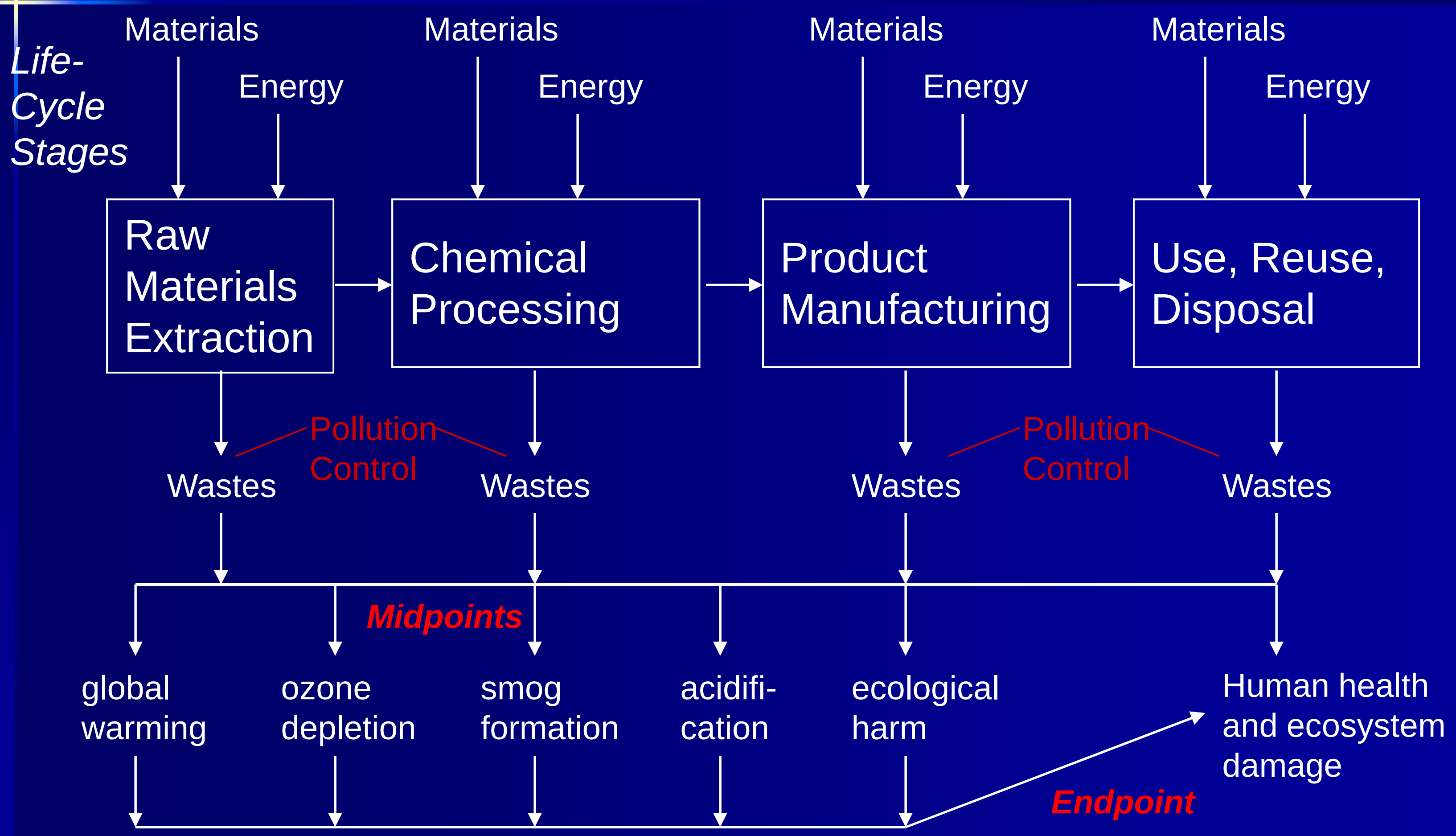
Biodiversity

Resource depletion

Classify Inventory Elements into Categories

Inventory Elements	**Impact Categories**
CO_2 Emissions ----------------------------------	*Global Warming*
NO_3^- in Wastewater ------------	*Human Health, Eutrophication*
Toluene Emissions -----------------------	*Human Health, Smog*
CFCs Emissions -------------	*Global Warming, Ozone Depletion*
Coal Use --------------------	*Fossil Energy, Resource Depletion*
Water Use -----------------------	*Resource Depletion, Land Use*

Characterize Environmental Impacts



Ozone Depletion Potential

Table D-2 Ozone-Depletion Potentials for Several Industrially Important Compounds.

Chemical	Formula	τ (yrs)	k (cm^3 $molecule^{-1}$ s^{-1})	X	ODP
Methyl bromide	CH_3Br				0.6
Tetrachloromethane	CCl_4	47.0	3.1×10^{-10}	4	1.08
1,1,1-trichloroethane	CH_3CCl_3	6.1	3.2×10^{-10}	3	.12
CFC (hard)					1.0
CFC (soft)					.055
CFC-11	CCl_3F	60.0	2.3×10^{-10}	3	1.0
CFC-12	CCl_2F_2	120.0	1.5×10^{-10}	2	1.0
CFC-13	$CClF_3$				1.0
CFC-113	CCl_2FCClF_2	90.0	2.0×10^{-10}	3	1.07
CFC-114	$CClF_2CClF_2$	200.0	1.6×10^{-10}	2	0.8
CFC-115	CF_3CClF_2	400.0			0.5
HALON-1201	$CHBrF_2$				1.4
HALON-1202	CBr_2F_2				1.25
HALON-1211	$CBrClF_2$				4.0
HALON-1301	$CBrF_3$				16.0
HALON-2311	$CHClBrCF_3$				0.14
HALON-2401	$CHBrFCF_3$				0.25
HALON-2402	$CBrF_2CBrF_2$				7.0
HCFC-22	CF_2HCl	15.0	1.0×10^{-10}	1	.055
HCFC-123	$C_2F_3HCl_2$	1.7	2.5×10^{-10}	2	.02
HCFC-124	C_2F_4HCl	6.9	1.0×10^{-10}	1	.022
HCFC-141b	$C_2FH_3Cl_2$	10.8	1.5×10^{-10}	2	.11
HCFC-142b	$C_2F_2H_3Cl$	19.1	1.4×10^{-10}	1	.065
HCFC-225ca	$C_3HF_5Cl_2$				.025
HCFC-225cb	$C_3HF_5Cl_2$				.033

τ is the tropospheric reaction lifetime (hydroxyl radical reaction dependent) (WMO, 1990a–1992b).
k is the reaction rate constant with atomic oxygen at 298 K (release of chlorine in the stratosphere).
X is the number of chlorine atoms in the molecule.

Appendix D in:
Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Global Warming Potential

Table D-1 Global Warming Potentials for Greenhouse Gases (CO_2 is the benchmark).

Chemical	Formula	τ (yrs)	BI ($atm^{-1}\ cm^{-2}$)	GWP[a]
Carbon dioxide	CO_2	120.0		1
Methane	CH_4			21
NOx				40
Nitrous oxide	N_2O			310
Dichloromethane	CH_2Cl_2	0.5	1604	9
Trichloromethane	$CHCl_3$			25
Tetrachloromethane	CCl_4	47.0	1195	1300
1,1,1-trichloroethane	CH_3CCl_3	6.1	1209	100
CFC (hard)				7100
CFC (soft)				1600
CFC-11	CCl_3F	60.0	2389	3400
CFC-12	CCl_2F_2	120.0	3240	7100
CFC-13	$CClF_3$			13000

BI = infrared radiation absorbance band intensity

Appendix D in:
Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Acid Rain Potential

Table D-3 Acid Rain Potential for a Number of Acidifying Chemicals.

Compound	Reaction	α	MW_i (mol/kg)	η_i, (mol H^+/ kg "i")	ARP_i
SO_2	$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2$	2	.064	31.25	1.00
NO	$NO + O_3 + 1/2\ H_2O \rightarrow H^+ + NO_3^- + 3/4\ O_2$	1	.030	33.33	1.07
NO_2	$NO_2 + 1/2\ H_2O + 1/4\ O_2 \rightarrow H^+ + NO_3^-$	1	.046	21.74	0.70
NH_3	$NH_3 + 2\ O_2 \rightarrow H^+ + NO_3^- + H_2O$	1	.017	58.82	1.88
HCl	$HCl \rightarrow H^+ + Cl^-$	1	.0365	27.40	0.88
HF	$HF \rightarrow H^+ + F^-$	1	.020	50.00	1.60

Adapted from Heijungs et al., 1992

Appendix D in:
Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Smog Formation Potential

Table D-4 Maximum Incremental Reactivities (MIR) for Smog Formation (O_3).

Alkanes	*normal*	MIR	*branched*	MIR
	methane	0.015	isobutane	1.21
	ethane	0.25	neopentane	0.37
	propane	0.48	iso-pentane	1.38
	n-butane	1.02	2,2-dimethylbutane	0.82
	n-pentane	1.04	2,3-dimethylbutane	1.07
	n-hexane	0.98	2-methylpentane	1.50
	n-heptane	0.81	3-methylpentane	1.50
	n-octane	0.60	2,2,3-trimethylbutane	1.32
	n-nonane	0.54	2,3-dimethylpentane	1.31
	n-decane	0.46	2,4-dimethylpentane	1.50
	n-undecane	0.42	3,3-dimethylpentane	0.71
	n-dodecane	0.38	2-methylhexane	1.08
	n-tridcane	0.35	3-methylhexane	1.40
	n-tetradecane	0.32	2,2,4-trimethylpentane	0.93
	Average	**0.55**	2,3,4-trimethylpentane	1.60

Appendix D in:
Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

Health Impact Indicators

- Lethal dose or concentrations – Acute exposure
- Reference concentrations – Chronic exposure
- Regulatory limits – Health-based standards
- R-Phrases – European health categories

Valuation Approaches

Table 13.3-5 Strategies for Valuing Life-cycle Impacts (Christiansen, 1997).

Life-cycle impact assessment approach	Description
Critical volumes	Emissions are weighted based on legal limits and are aggregated within each environmental medium (air, water, soil).
Environmental Priority System (Steen and Ryding, 1992)	Characterization and valuation steps combined using a single weighting factor for each inventory element (see example below). Valuation based on willingness-to-pay surveys.
Ecological scarcities	Characterization and valuation steps combined using a single weighting factor for each inventory element. Valuation based on flows of emissions and resources relative to the ability of the environment to assimilate the flows or the extent of resources available.
Distance to target method	Valuation based on target values for emission flows set in the Dutch national environmental plan.

Allen and Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prentice Hall, 2002

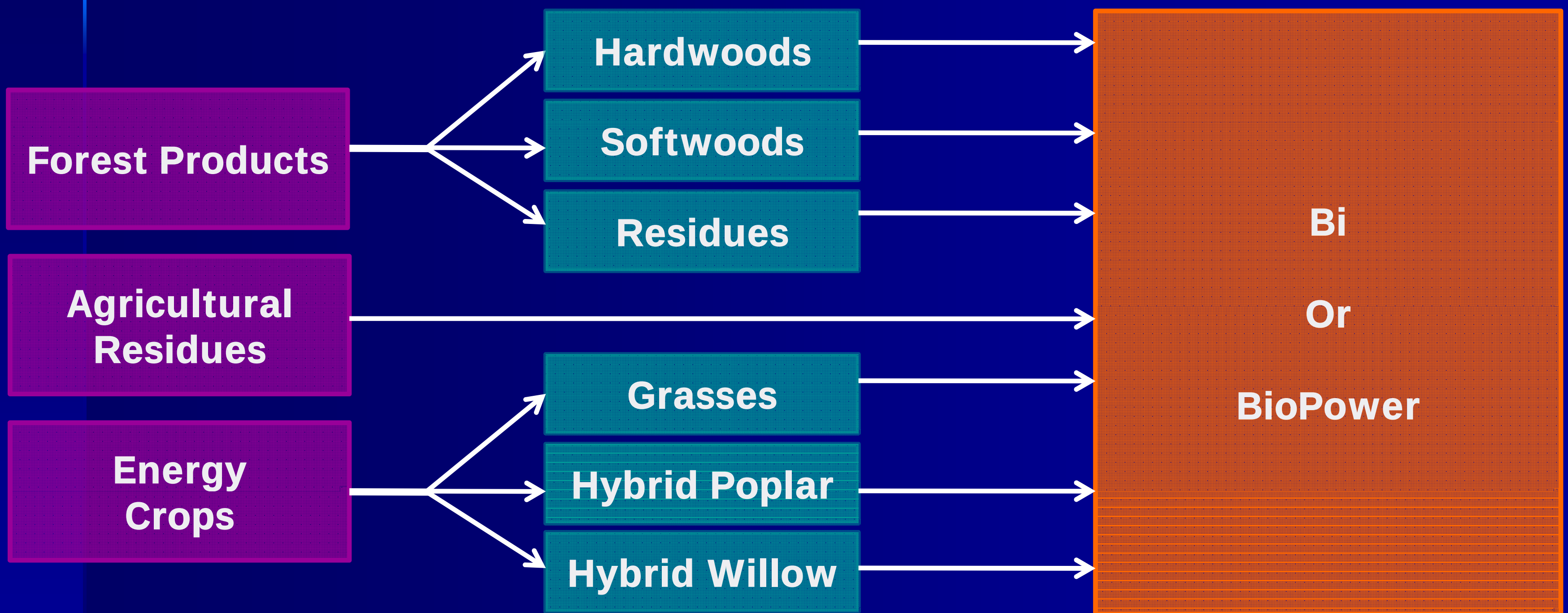
Summary of Life Cycle Impact Assessment

- ISO 14042 provides guidelines
- *Identify* categories of environmental impacts, *classify* pollutants into categories, *characterize* potency of pollutants for impact categories.
- *Relative risk* calculation using emission estimation, environmental fate modeling, and impact potency.
- Commercial software tools are available (the same tools as shown in the inventory section).

Summary of Life Cycle Assessment

- Motivation for LCA: Reduce environmental impacts of products over their life cycle.
- LCA is used for decision-making, communication, marketing, and strategic planning
- ISO 14040-14043 cover all elements of LCA, from planning/execution to methodologies.
- Software tools are available to aid in LCA studies – Demo version of SimaPro 7.2 is useful introduction.

Potential Cellulosic Feedstocks in the Upper Midwest



Forest Feedstocks of Interest in MI

Harvest residues: 4-10 dry $t \cdot ac^{-1}$ from a single harvest, perhaps 0.5 dry $t \cdot ac^{-1} \cdot yr^{-1}$, with no inputs

Mill Residues: production depends on mill capacity and production efficiency

Other removals: 5-25 dry $t \cdot ac^{-1}$ from a thinning treatment, with no inputs

Roundwood to Chips: more than 4 dry $t \cdot ac^{-1} \cdot yr^{-1}$ in Aspen, perpetually and with no inputs

Dr. Robert Froese, School of Forest Resources and Environmental Sciences, Michigan Tech

Plantation Feedstocks of Interest in MI

Hybrid Poplar: 4-10 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ on a 10-year rotation starting from bare land

Low-Intensity, High-Diversity perennials: 2-4 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ perpetually with low inputs

Hybrid Willow: 3-14 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ on a 3-year cycle for a 21 year rotation starting from bare land

Switchgrass monoculture: 4-10 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ in a single fall harvest, perpetually and starting from bare land

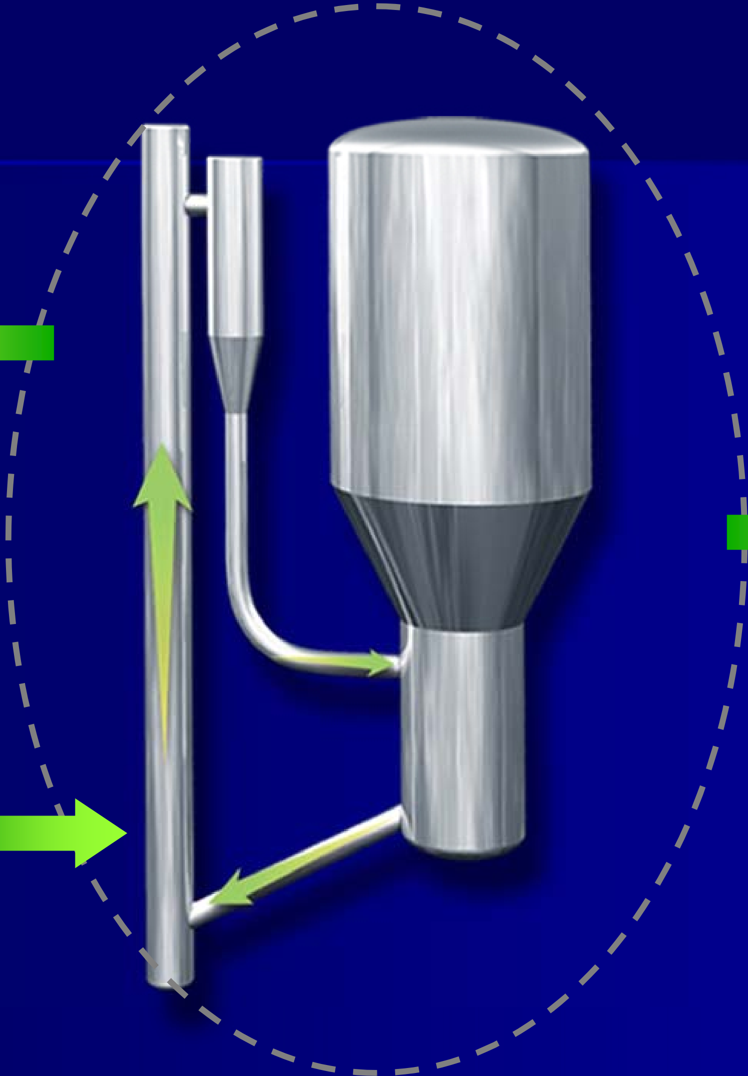
Dr. Robert Froese, School of Forest Resources and Environmental Sciences, Michigan Tech

Rapid Thermal Processing RTP^{TM} Technology

Envergent
TECHNOLOGIES
A Honeywell Company

Pyrolysis Oil

Solid Biomass



uop
A Honeywell Company
plus
ENSYN

Commercially Proven Patented Technology

ENV 5233-04

RTP™ Product Yields

400 BDMTPD of Hardwood Whitewood

Feed, wt%	
Hardwood Whitewood	100
Typical Product Yields, wt% Dry Feed	
Pyrolysis Oil	70
By-Product Vapor	15
Char	15

Yields For Various Feeds

Biomass Feedstock Type	**Typical Pyrolysis Oil Yield, wt% of Dry Feedstock**
Hardwood	70 – 75
Softwood	70 – 80
Hardwood Bark	60 – 65
Softwood Bark	55 – 65
Corn Fiber	65 – 75
Bagasse	70 – 75
Waste Paper	60 – 80

Cellulosic Feedstock Flexible With High Yields of Pyrolysis Oil

RTP Pyrolysis Oil Properties

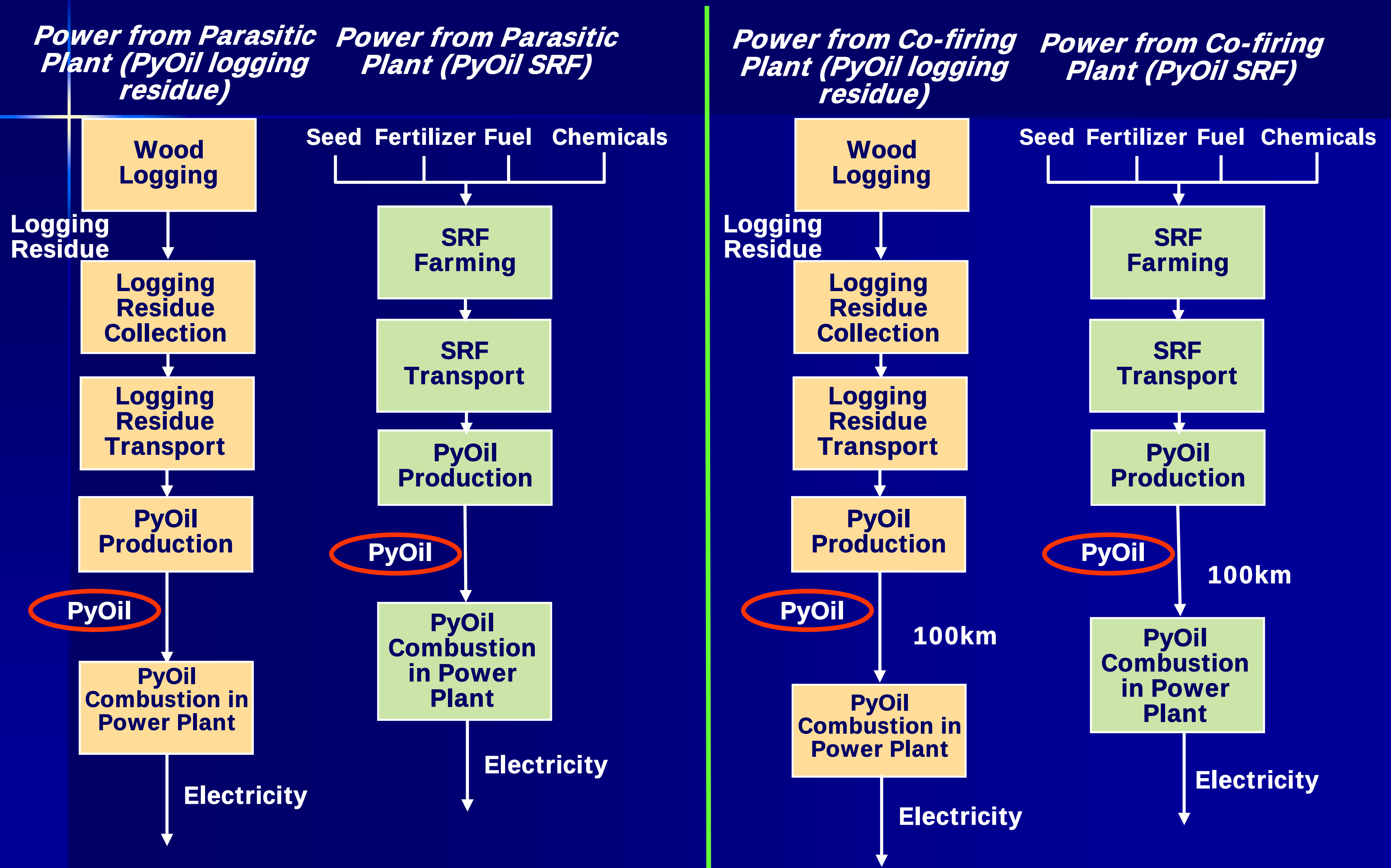
- Pourable and transportable liquid fuel
- High oxygenate content
- Contains 55-60% the energy content of crude-based fuel oils
- As produced, can be corrosive

Comparison of Heating Value of Pyrolysis Oil and Typical Fuels

Fuel	MJ / Litre	BTU / US Gallon
Methanol	17.5	62,500
Pyrolysis Oil (Wood)	**21.0**	**75,500**
Pyrolysis Oil (Bark)	**22.7**	**81,500**
Ethanol	23.5	84,000
Light Fuel Oil / Diesel	38.9	138,500

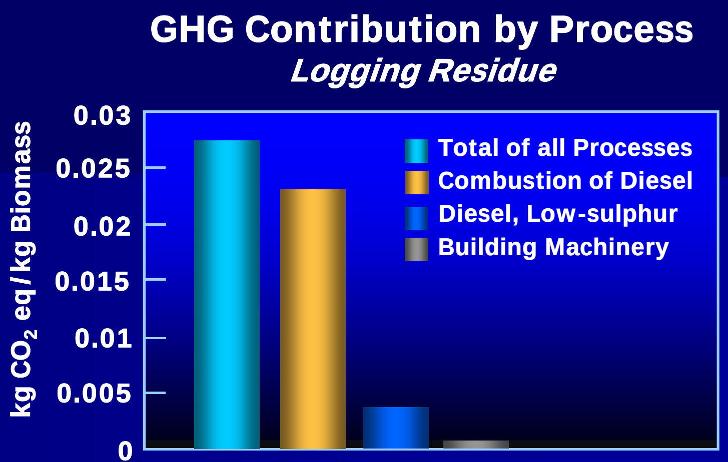
Suitable for Energy Applications

Life Cycle Pathway Diagrams

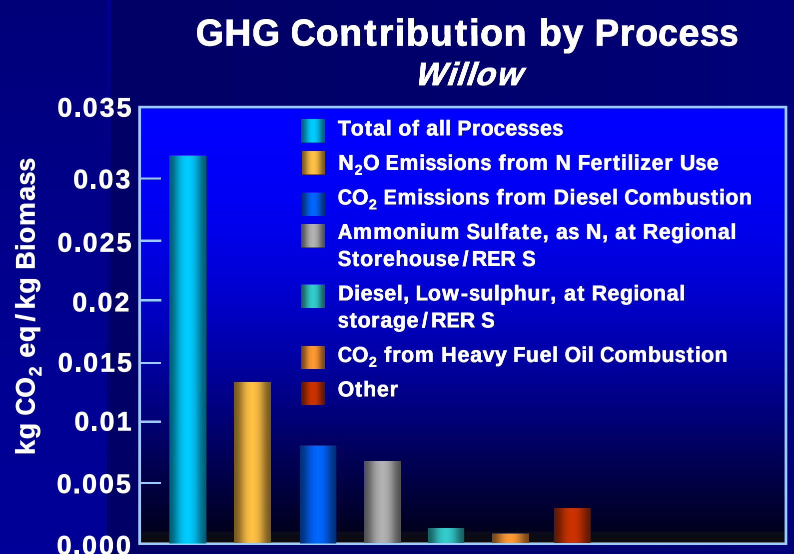


Feedstock Cultivation and Harvesting GHG Emissions

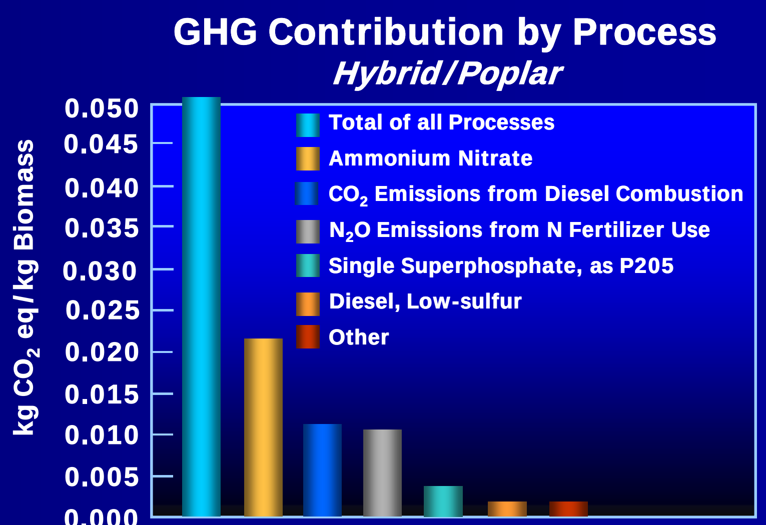
	Residue	SRF Crops	
	Logging	Willow	Poplar
Biomass Yield			
odt/ha/yr	0.62	11.95	13.50
GHG			
kg CO_2-eq/kg Biomass	0.027	0.032	0.053



Reis and Shonnard, 2007



Heller et al., 2003



Gasol et al., 2008

Pyrolysis Oil Production
GHG Emissions

gCO_2 eq /MJ	PyOil Logging Residue	PyOil Willow	PyOil Poplar	PyOil Waste
Biomass Cultivation and Harvesting	2.08	2.41	4.0	0
Biomass Transportation	3.84	0.87	0.82	0
Pyrolysis	8.59	8.59	8.59	8.59
Total	14.51	11.88	13.42	8.59

$$r_{circle} = \frac{2}{3} * \tau * \sqrt{\frac{F}{\pi * Y * f}}$$ (Wright et. al. 2008)

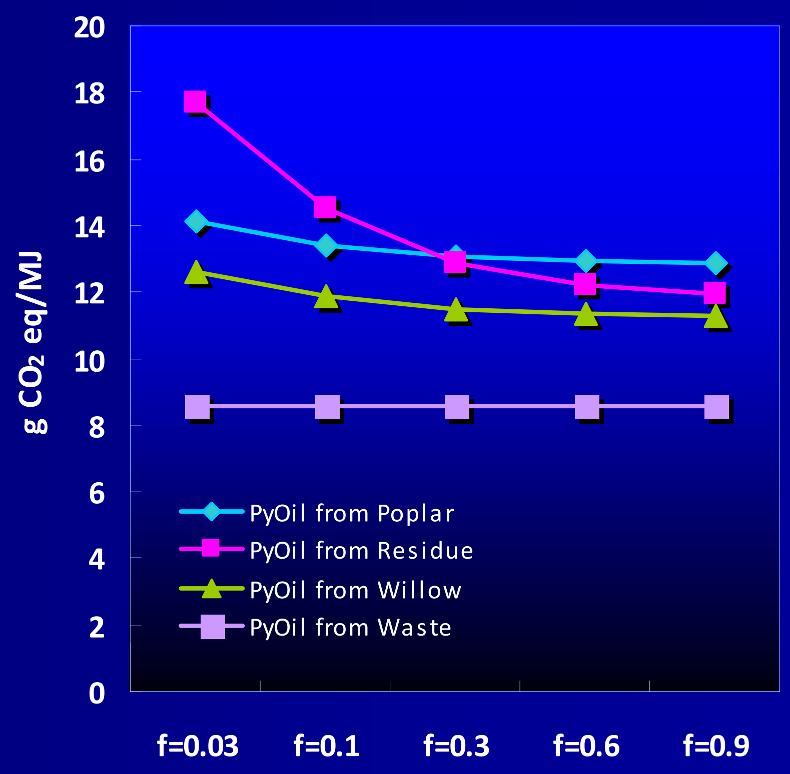
τ: the tortuosity factor of the road (1.5)
f : fraction of land devoted to biomass crops (0.1)
F: feedstock biomass required (400*365 metric tons / acre / yr)
Y: yield of biomass (metric tons / acre / yr)

Sensitivity Analysis of Transportation:
f Value (Fraction of Land in Cultivation)

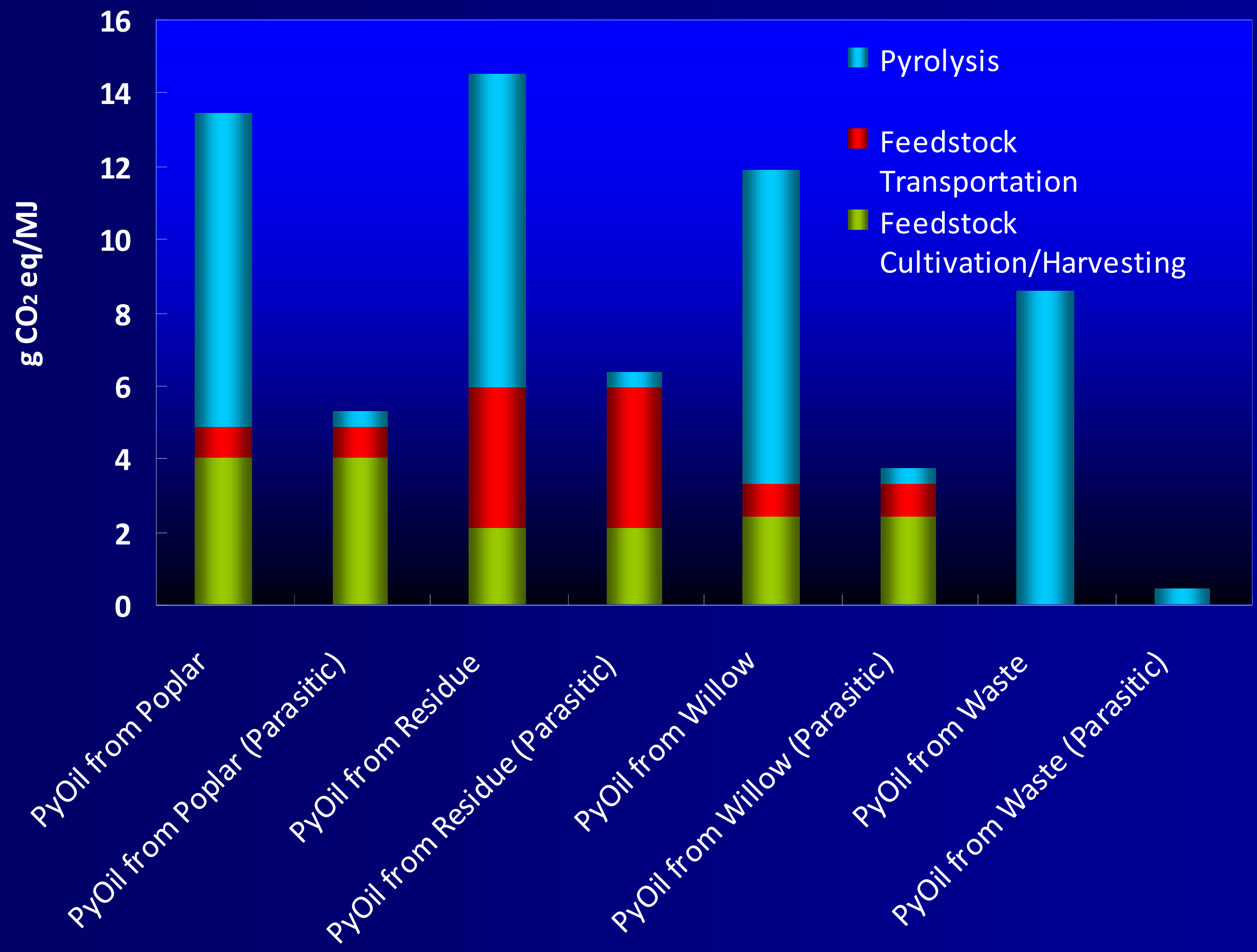
Transportation Distance vs. f

	f=0.03	*f=0.1*	*f=0.3*	*f=0.6*	*f=0.9*
r_{circle} (miles) Poplar	20.05	10.98	6.34	4.48	3.66
r_{circle} (miles) Willow	21.34	11.69	6.75	4.77	3.90
r_{circle} (miles) Residue	93.74	51.34	29.64	20.96	17.11

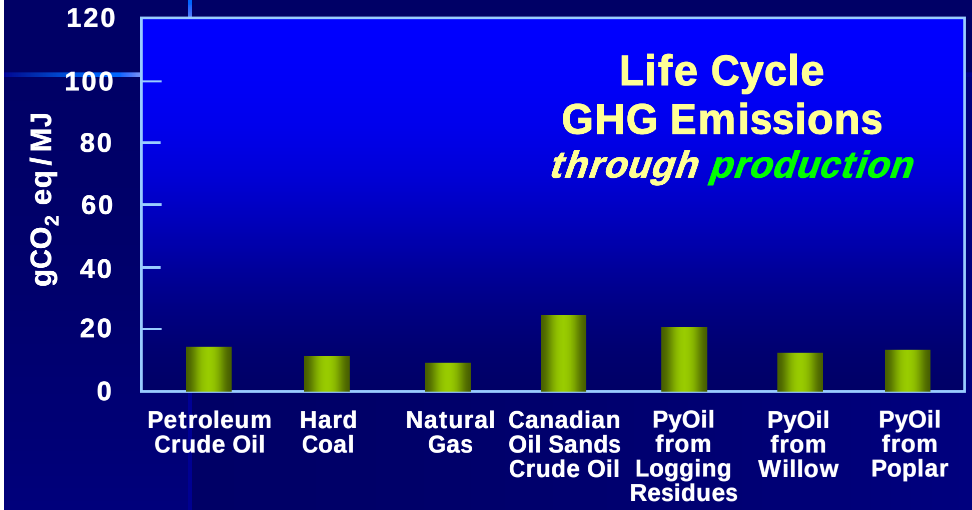
PyOil GHG Emissions vs f



Sensitivity Analyses of Power Source Imported Power (US Grid Mix) vs. Parasitic System



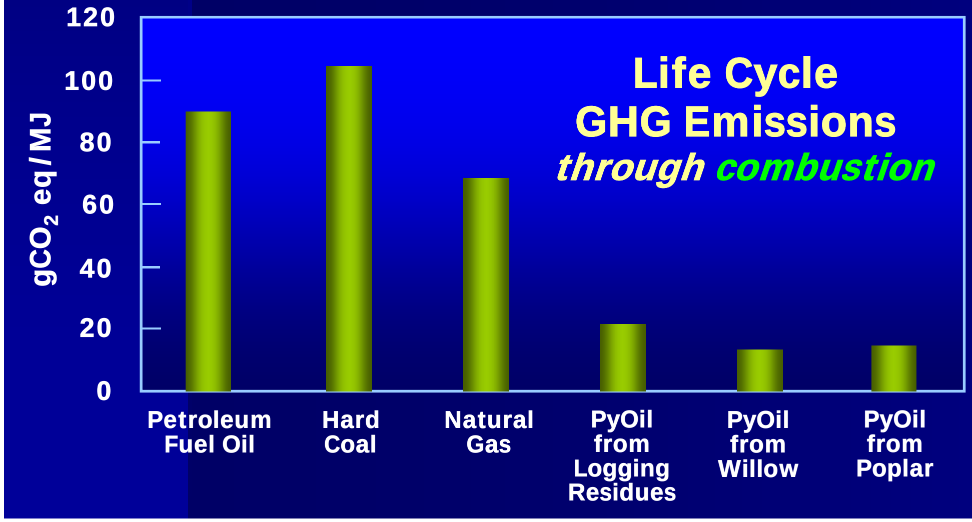
Pyrolysis Oil (non-parasitic) vs. Fossil Fuel Comparison of GHG Emissions



Pyrolysis Oil Production foot print similar to other energy alternatives

Assumed biomass transport distances

- 200 km for logging residues
- 25 km for short rotation forest crops



Pyrolysis Oil *Life Cycle* foot print *Greener* than other alternatives

- 70-88% lower GHG emissions
- SO_x emissions similar to Natural Gas

ENV 5233-15

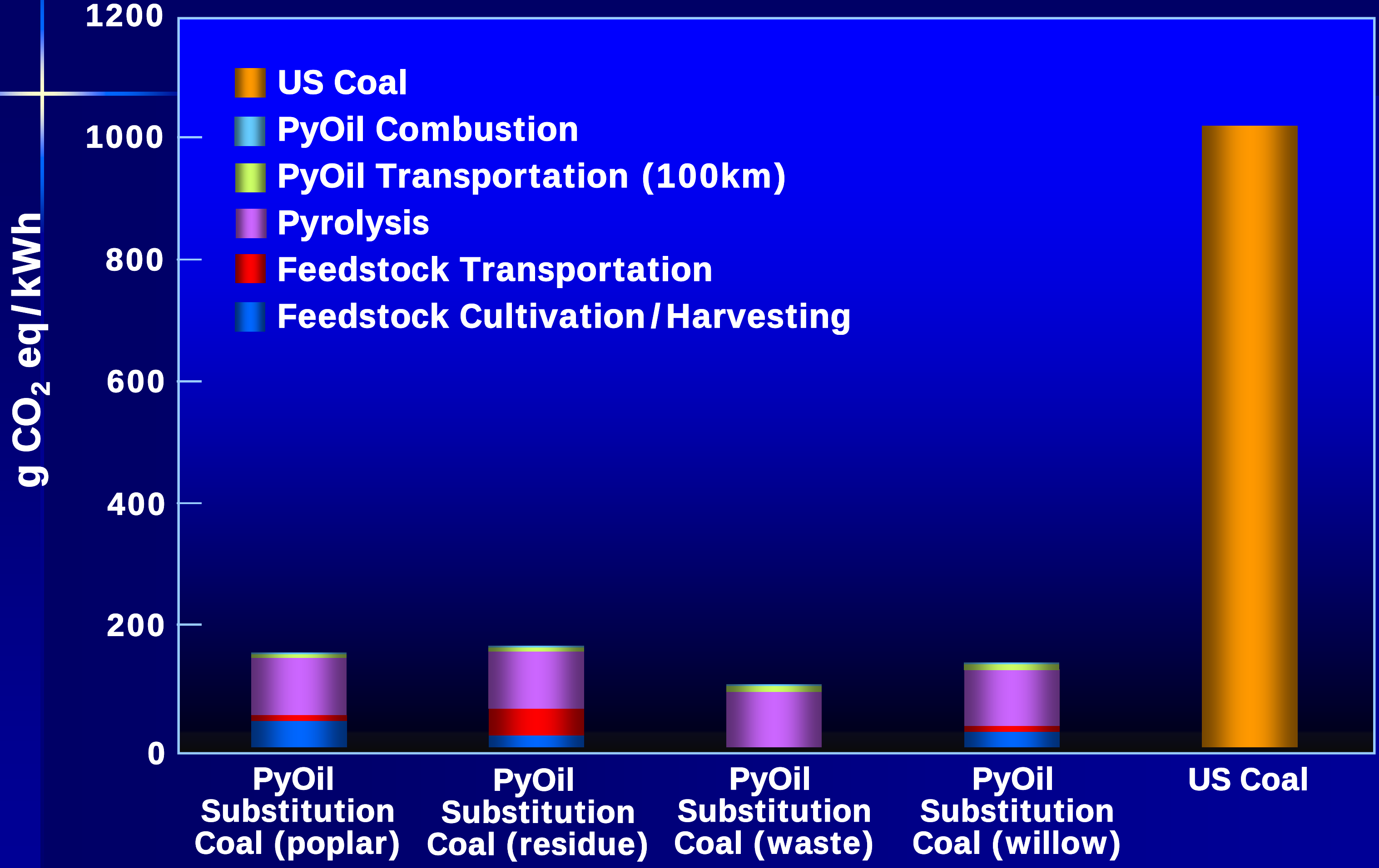
LCA Results for Pyrolysis Oil to Power
400 BDMTPD

Multiple Scenarios Evaluated

- Co-firing Cases (lowest capital)
  - Fuel Oil Power Plant
  - Coal Power Plant
  - Natural Gas Power Plant
- Advanced Power Facilities (highest efficiency)
  - Gas Turbine Combined Cycle (GTCC) with heat recovery
  - Distributed Diesel Generator located at site
- Comparison to Direct Biomass Combustion (BC)
  - Dedicated facility at 18% efficiency (existing BC1)
  - Dedicated facility at 25% efficiency (modern BC2)

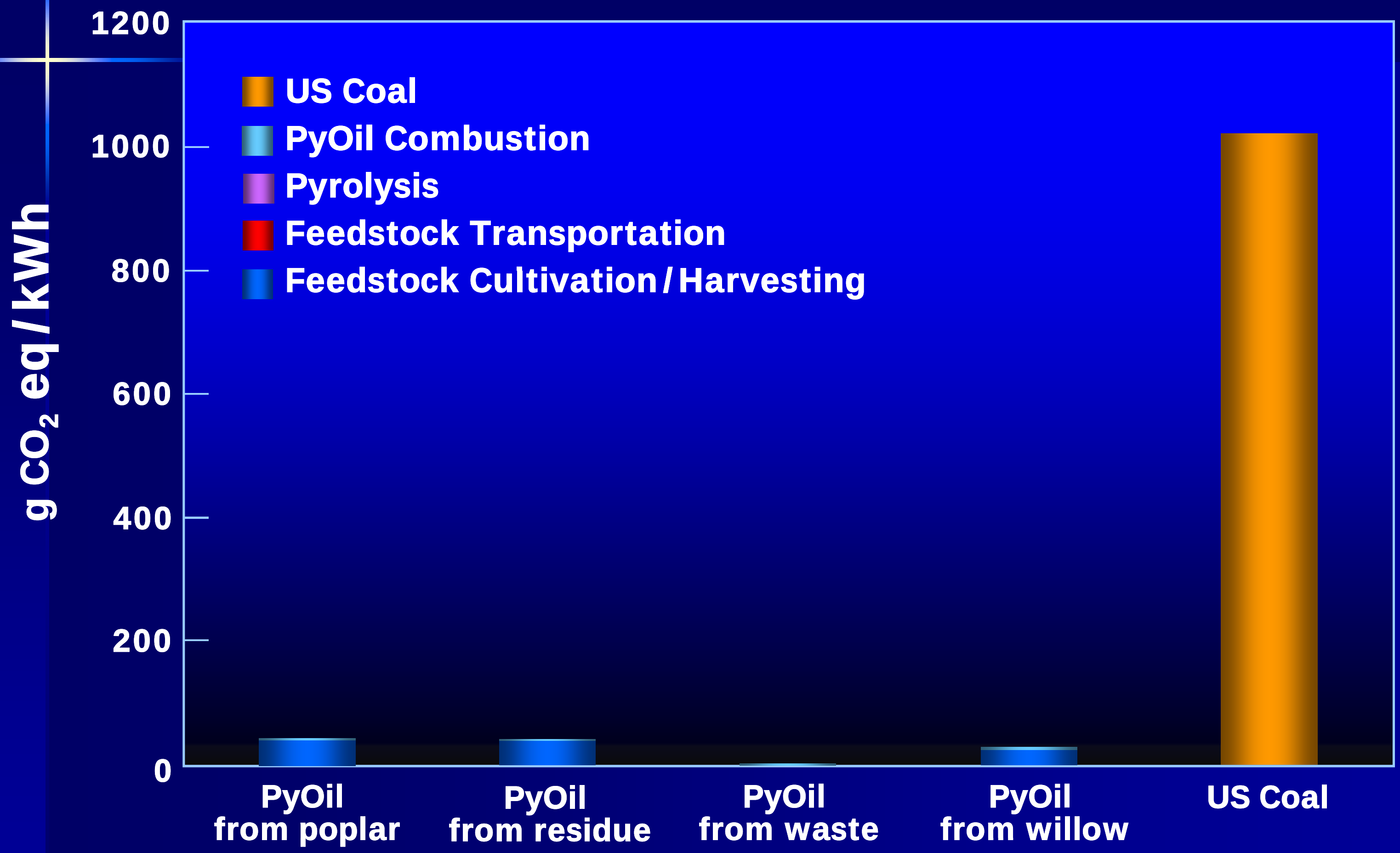
Pyrolysis Oil Co-fired in Coal Power Plant

(400 tonnes/day biomass feed, 33% efficiency)



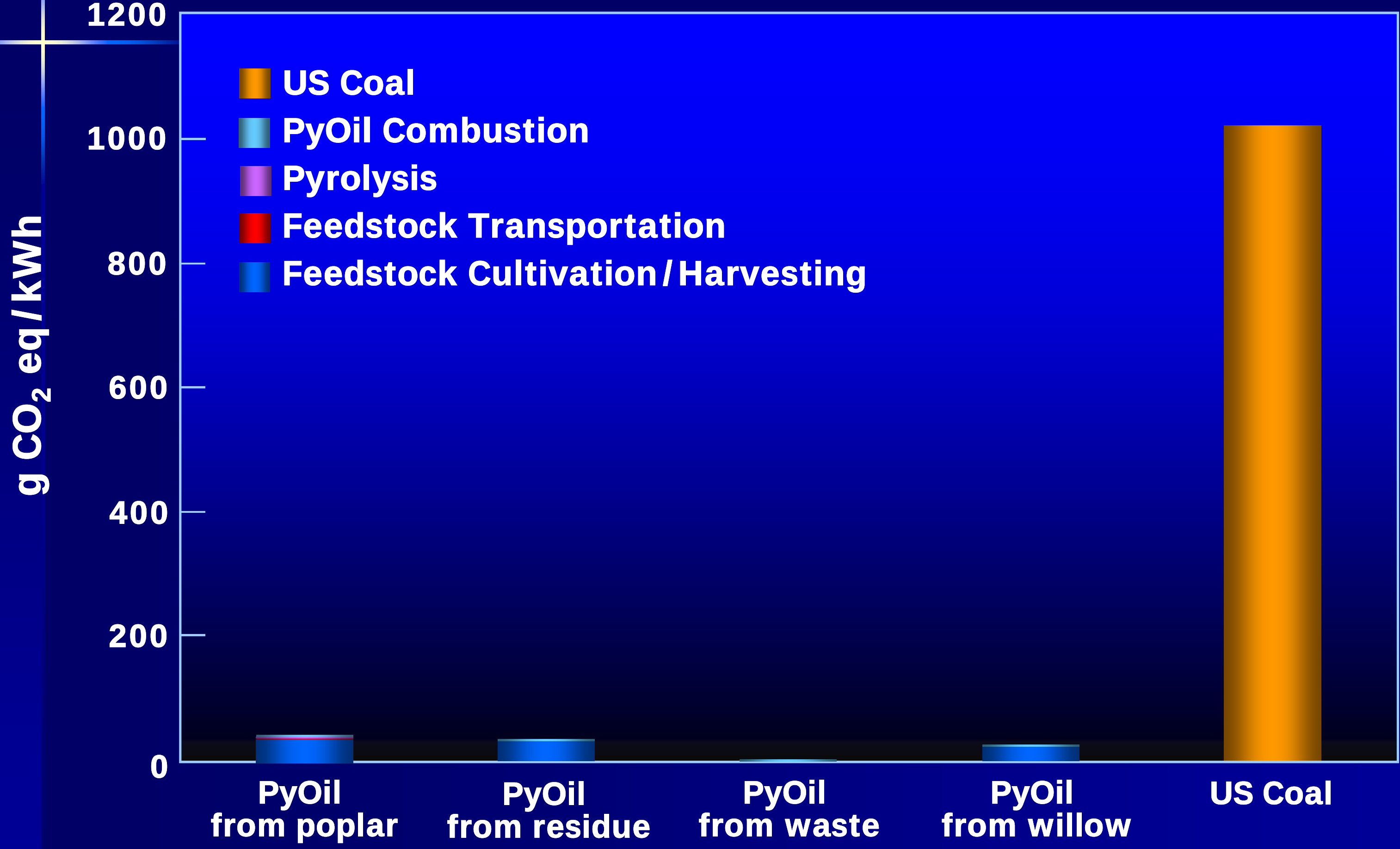
GHG Savings 84.7 % 83.5 % 89.8 % 86.3 %

Advanced Power Generation Scheme -1
Pyrolysis Oil Combusted in GTCC w/HR
(9.62MW, 42.9% efficiency, net efficiency 39%)



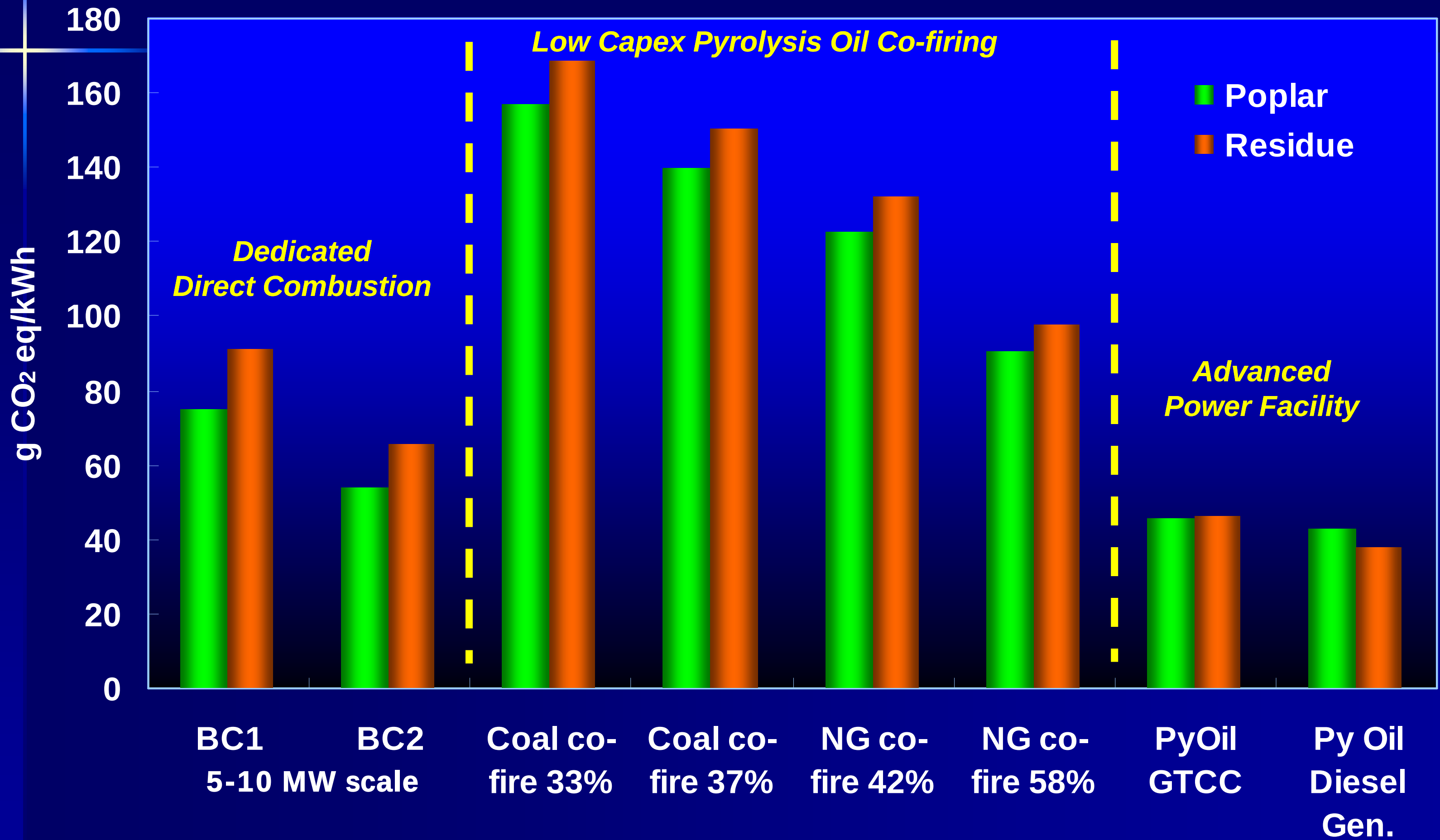
GHG Savings 95.5 % 95.5 % 99.6 % 96.9 %

Advanced Power Generation Scheme - 2
Pyrolysis Oil Combusted in Diesel Generator
(5MW at site, 45% efficiency, net efficiency 40.9%)



GHG Savings	95.8 %	96.3 %	99.6 %	97.2 %

Comparisons of LC-GHG Emissions with Direct Biomass Combustion (BC)



BC1 = existing combustion / steam turbine unit at 18 % efficiency
BC2 = modern combustion / steam turbine at 25 % efficiency

Summary and Conclusions

- There is a variety of forest resources that can be converted to pyrolysis bio-oil using RTP^{TM} process technology
- Pyrolysis bio-oil can be utilized by a wider spectrum of power generation technologies compared to biomass combustion
  - Biomass combustion: limited to co-firing with coal
  - Pyrolysis bio-oil: compatible with NG, coal, and oil systems
- Greenhouse gas emissions of pyrolysis bio-oil electricity
  - GHG impacts of RTP^{TM} pyrolysis oil production ~ fossil fuels
  - “Parasitic” pyrolysis oil production reduces GHG by ~ ½
  - Savings of GHG emissions of between 76 – 99% is achieved for pyrolysis oil electricity compared to US Grid electricity
  - High efficiency applications for pyrolysis oil electricity are more favorable compared to direct biomass combustion electricity

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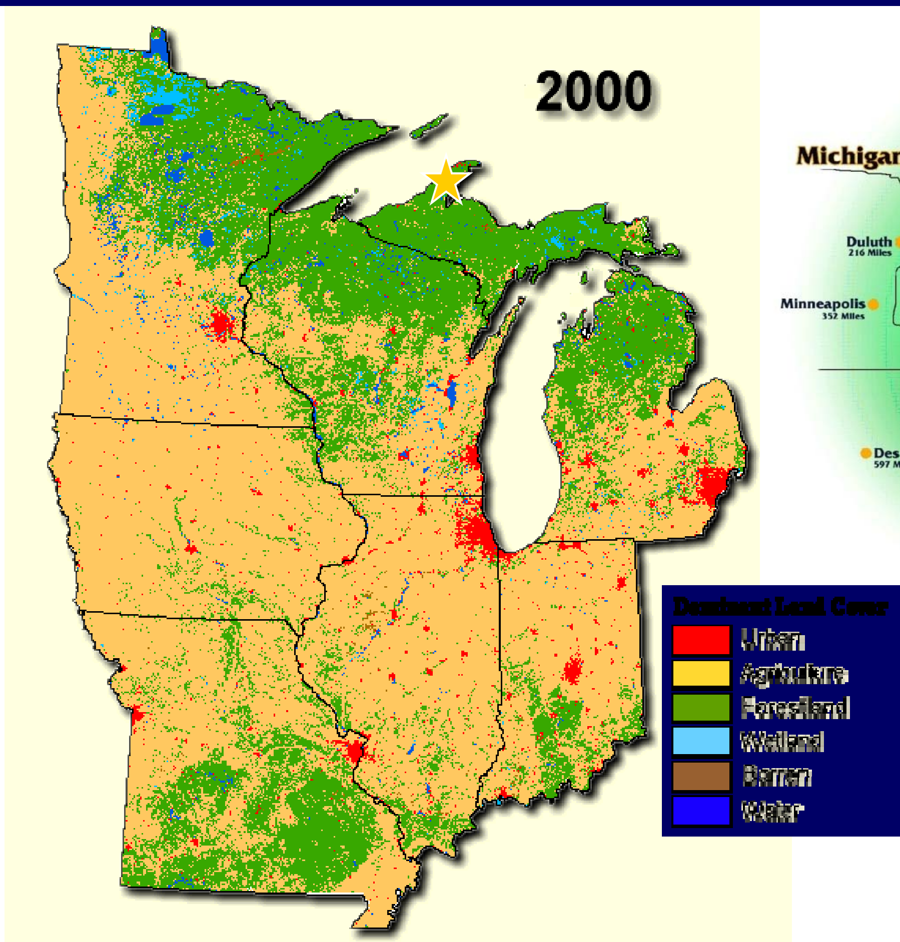
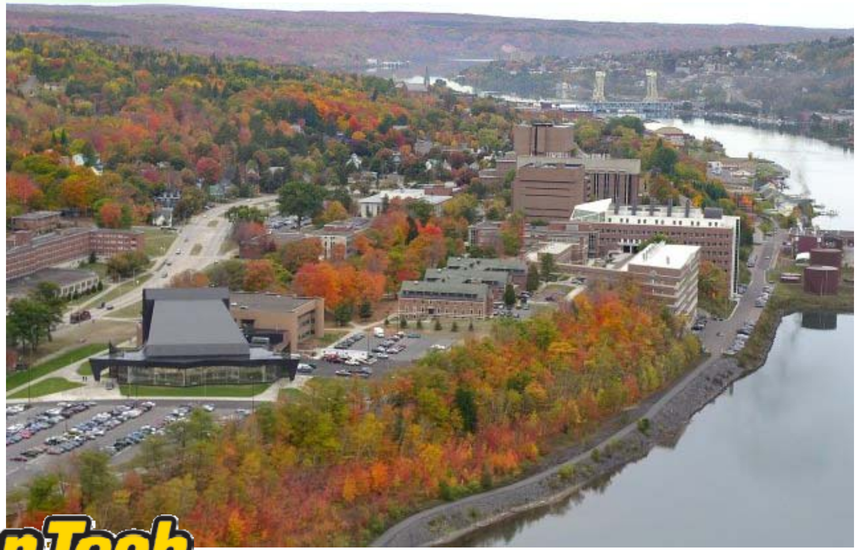
Questions?



Midwestern land cover (USFS North Central Research Station image)



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