Greener Solvents

Dr. Tamer Andrea
Queen's University

GreenCentre Canada

GreenCentre Canada

changing chemistry, changing the world

The Commercialization Gap

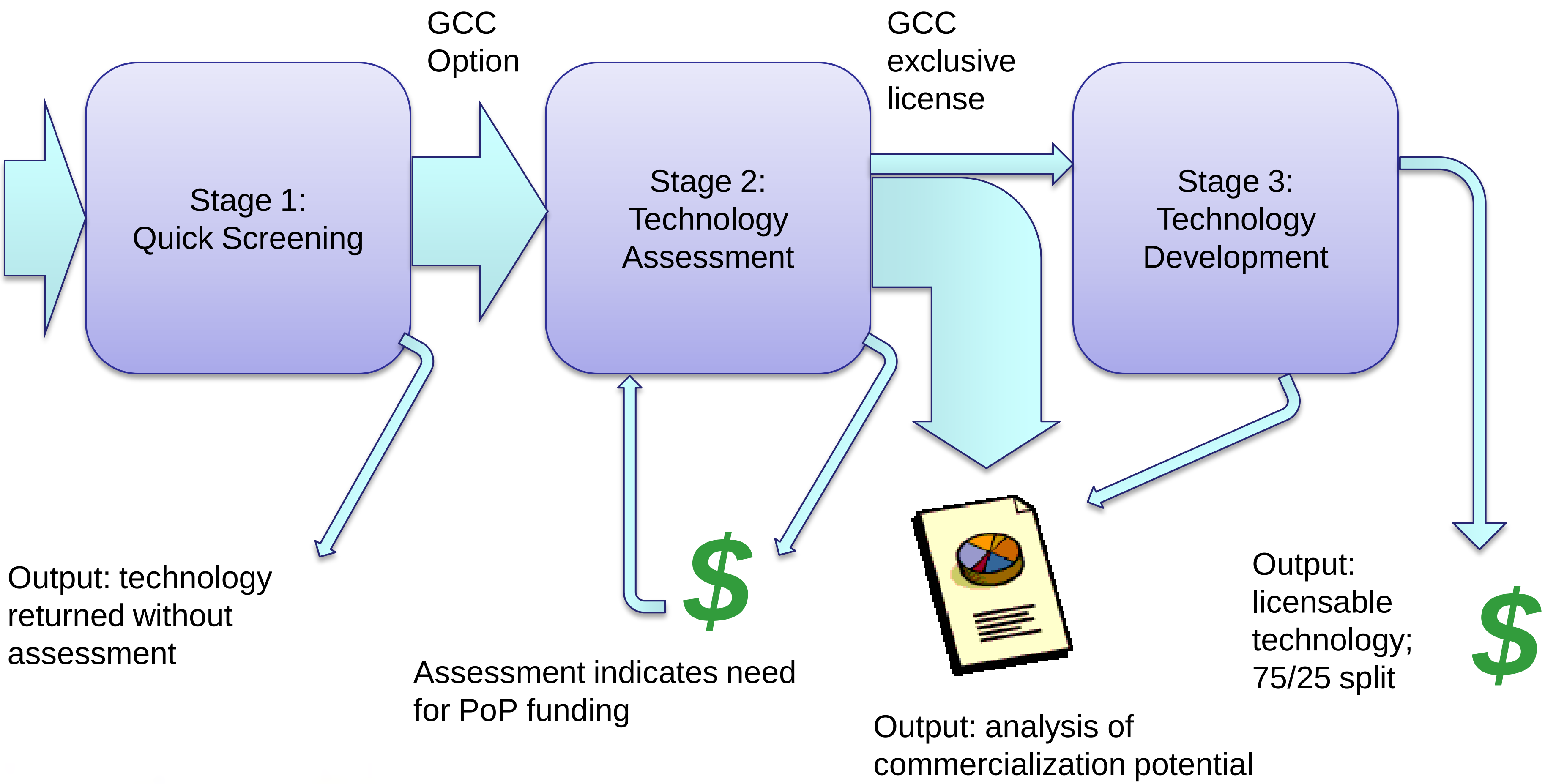
Typical stage of university technologies:

- Bench-test proof of utility
- Applications speculative and unproven
- Incomplete material characterization
- Grams of sample
- Manufacturing feasibility not studied

What Industry wants:

- Demonstrated scale-up
- Optimization
- Field-test proof of utility
- Kilograms of sample

Process for Technology Disclosures



Green Solvents

Dr. Philip Jessop
Queen's University

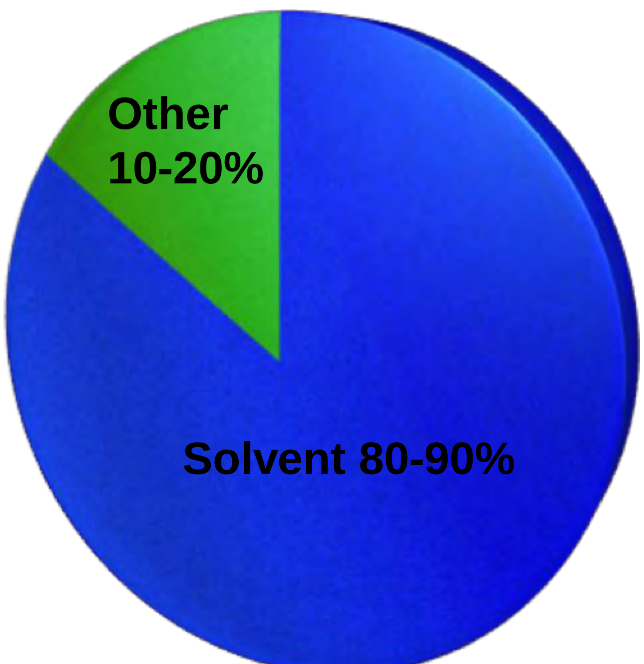
GOALS OF GREEN CHEMISTRY: REDUCE SOLVENT USE

$$\text{"E" factor} = \frac{\text{Mass of waste}}{\text{Mass of product}}$$

Industry segment	Product tonnage	E factor
Bulk chemicals	10^4 - 10^6	<1 - 5
Fine chemicals	10^3 - 10^4	5 - 50
Pharmaceuticals	10 - 10^3	25 - over 100

R. Sheldon, CHEMTECH 1994, 38.

Mass utilization in fine chemical production



http://www.caraet.com/Waste_solvent.htm

Explosion, fire at Quebec plan
two; 19 more sent to hospital

SHERBROOKE, Que. — The Canadian Press
Published Thursday, Nov. 08 2012, 3:11 PM EST

Hexane Leak Cited for Explosions At Soybean Plant

Radio Iowa, Des Moines; Associated Press

February 2008

Streets explode in Louisville, Kentucky
13 Feb 1981

Barton Solvents Plant, Jul 2007

PROBLEMS WITH CURRENTLY USED SOLVENTS

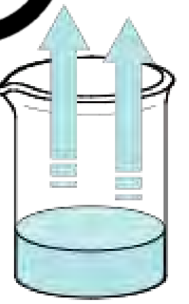
In the US in the early 1990's:

- solvent production was 26 million tons p.a.
- of tracked chemicals, many of the top chemicals released or disposed of were solvents (MeOH, toluene, xylene, CS_2, MEK, CH_2Cl_2)

Organic solvent hazards

- flammable (almost all except chlorinated solvents)

- carcinogenic (chlorinated solvents and aromatics)
- high vapour pressure (i.e. inhalation route)



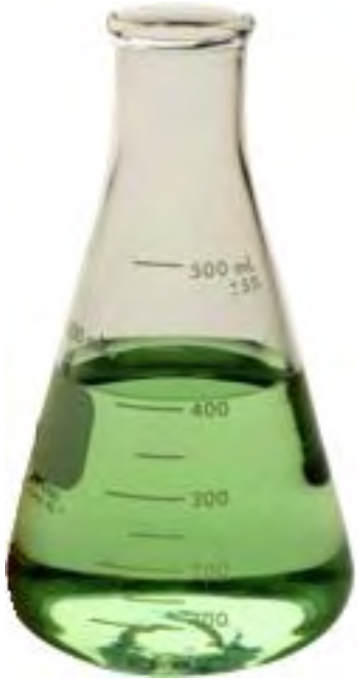
- narcotic (ether, chloroform)
- toxic (MeOH, CS_2)

- mutagens/teratogens (toluene)
- peroxides (ethers)

- smog formation

OUTLINE

1. Reducing the Impact of Solvents
2. Solvent Properties
3. Greener Conventional Solvents
4. Unconventional Solvents
5. Conclusions



DECREASING THE IMPACT OF SOLVENTS

1. **Reduce the volume of solvent**

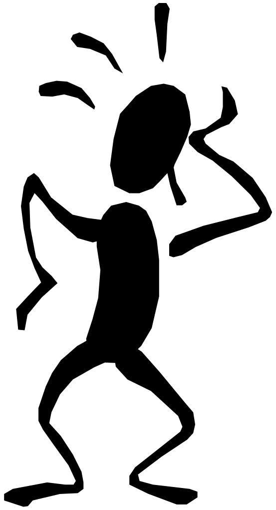
- use higher concentrations
- use solvent for more than one step

2. Make the solvents greener

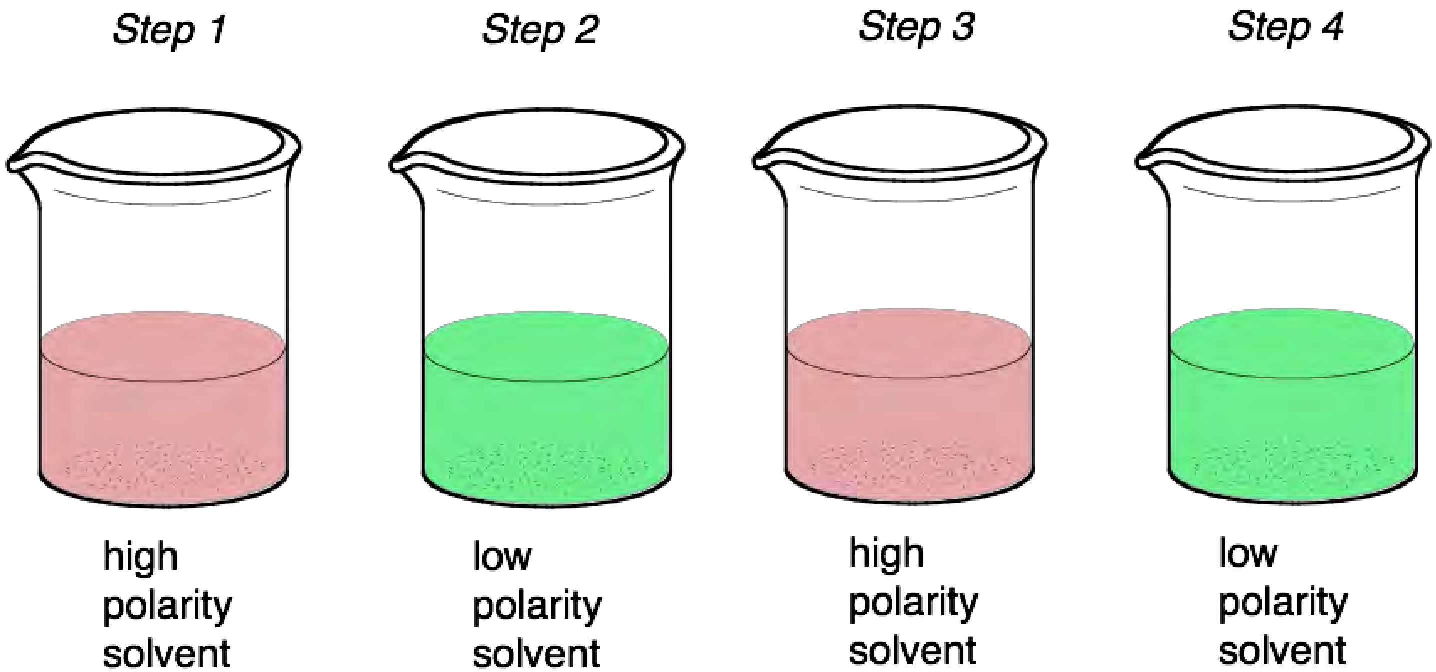
- carefully chosen conventional solvents
- new green solvents

Murphy's Law of Solvents

"The best solvent for any process step is bad for the subsequent step."



AN IMAGINARY PROCESS

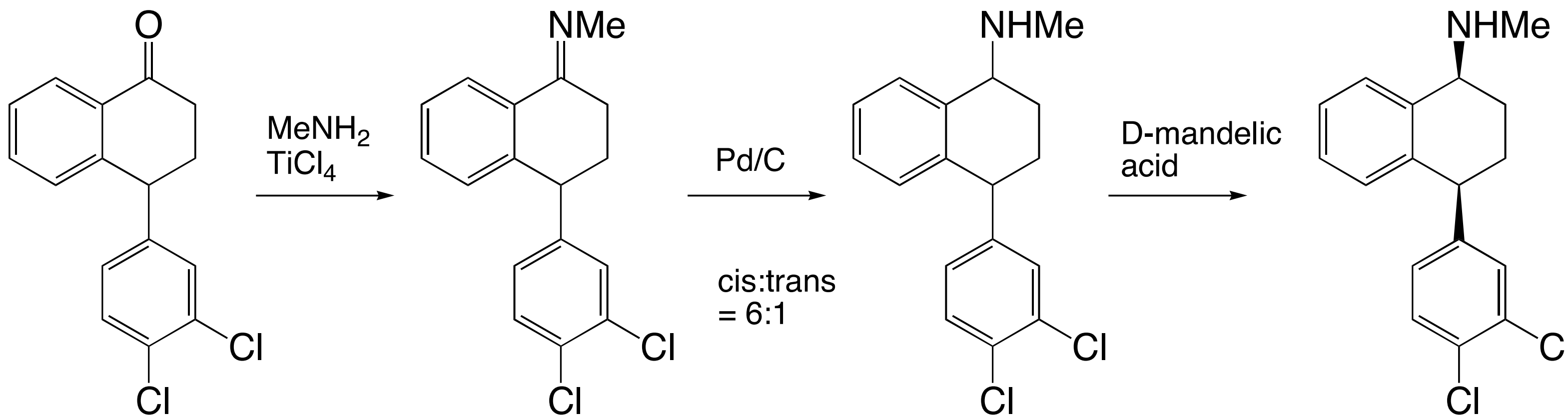


Solving Murphy's Law of Solvents

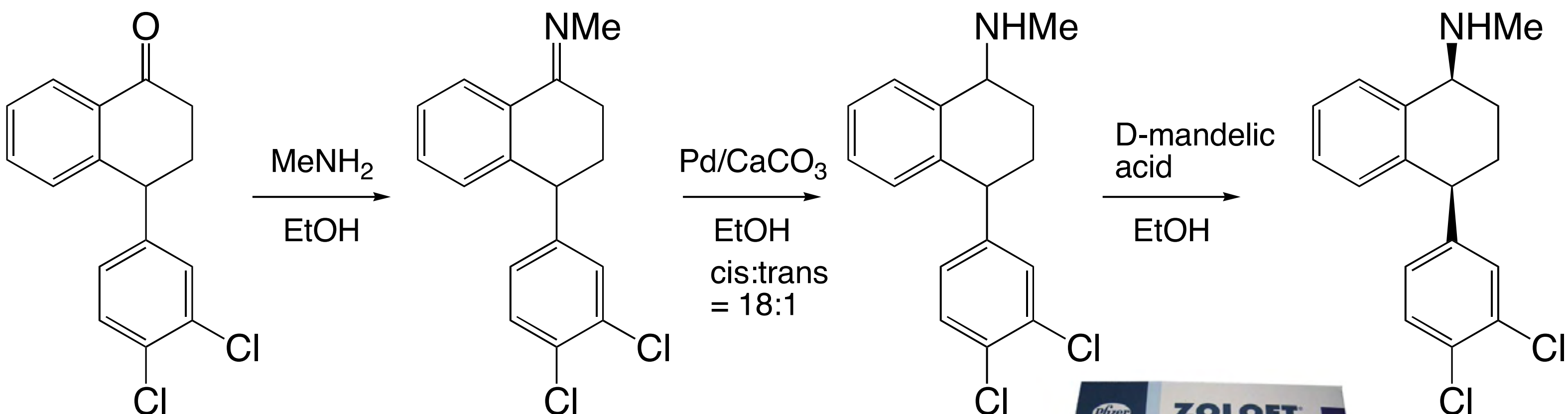
1. A Compromise Solvent

2. A Switchable Solvent

CAREFUL SELECTION OF A TRADITIONAL SOLVENT



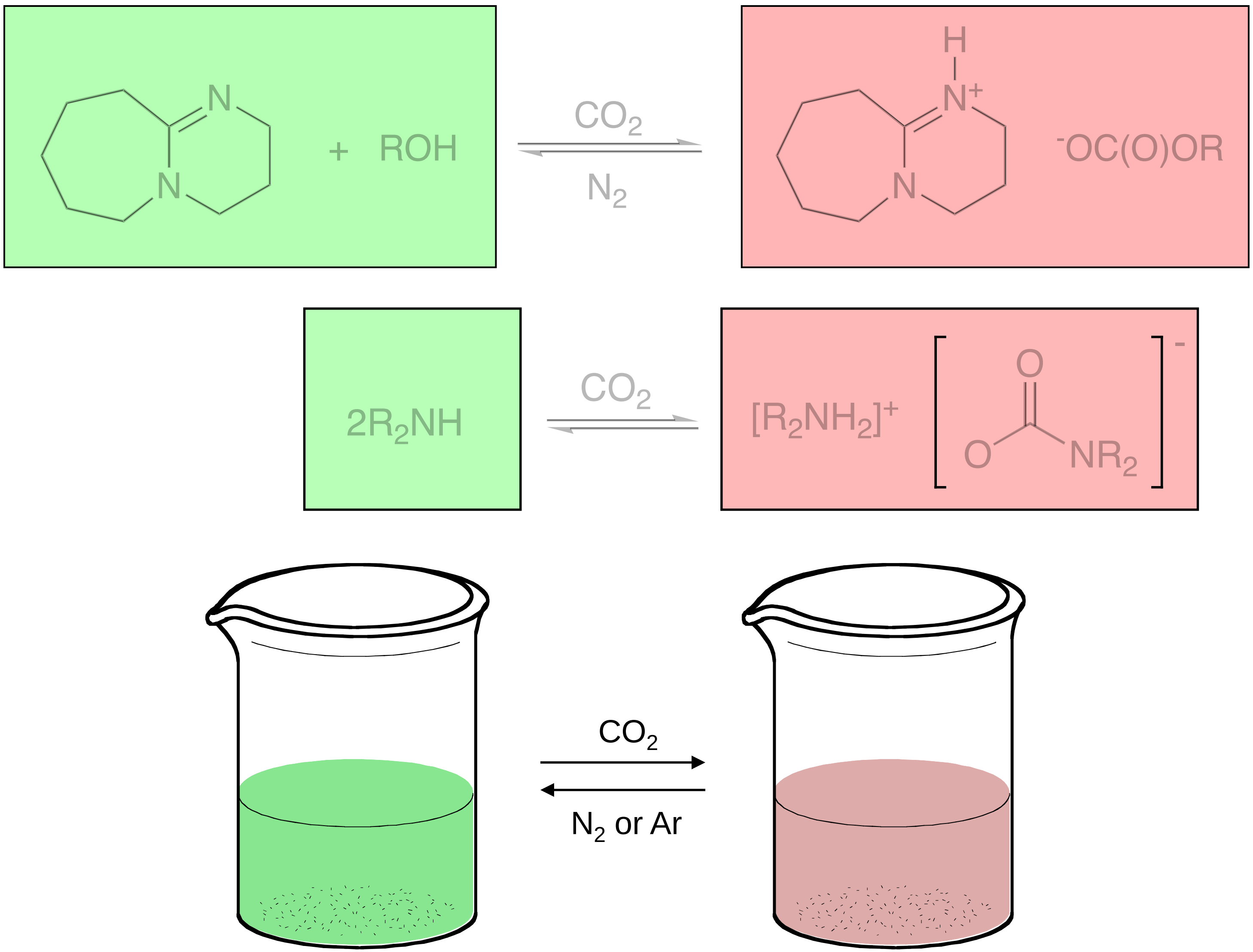
Sertraline



Sertraline

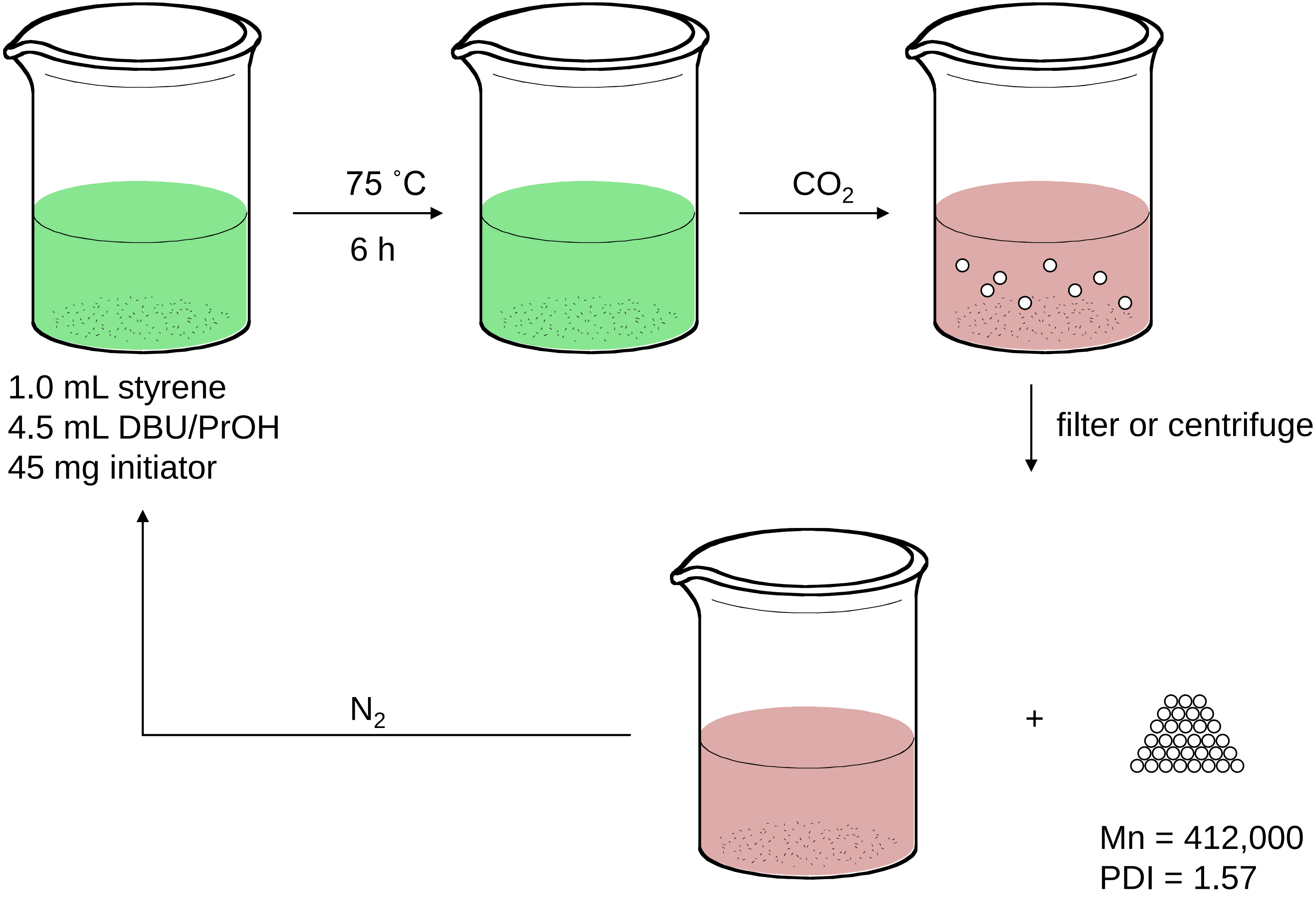
http://www.rx-pharmacy.cc/product_info.php?products_id=169

SWITCHABLE-POLARITY SOLVENT



Nature (2005) 436, 1102
Ind Eng Chem Res (2008) 47, 539

APPLICATION TO POLYSTYRENE SYNTHESIS



DECREASING THE IMPACT OF SOLVENTS

1. **Reduce the volume of solvent**

- use higher concentrations
- use solvent for more than one step

2. Make the solvents greener

- carefully chosen conventional solvents
- unconventional solvents

OUTLINE

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PROPERTIES OF CONCERN

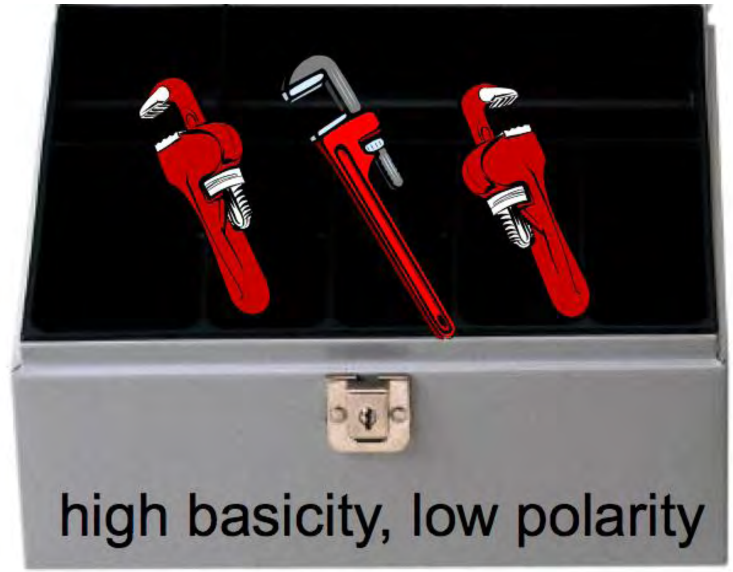
For green-ness

- boiling point / energy to distill
- flash point
- energy to distill
- cumulative energy demand
- the 10 factors

For utility

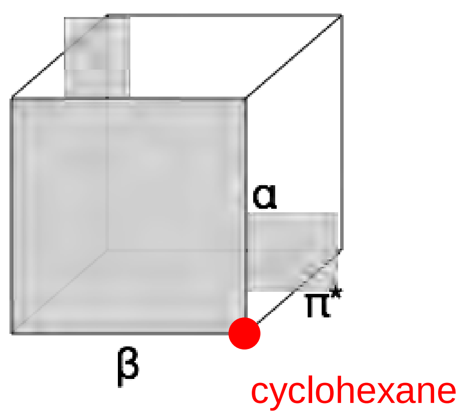
- polarity
- basicity / hydrogen-bond accepting ability
- acidity / hydrogen-bond donating ability
- viscosity

THE TOOLBOX ANALOGY



KAMLET-TAFT SOLVATOCHROMIC PARAMETERS

Solvent	α acidity or proticity or H-bond donating ability	β basicity or H-bond accepting ability	π* polarity & polarizability
cyclohexane	0	0	0
benzene	0	0.1	0.59
MeCN	0.19	0.31	0.75
NEt_3	0.14	0.71	0
water	1.17	0.47	1.09



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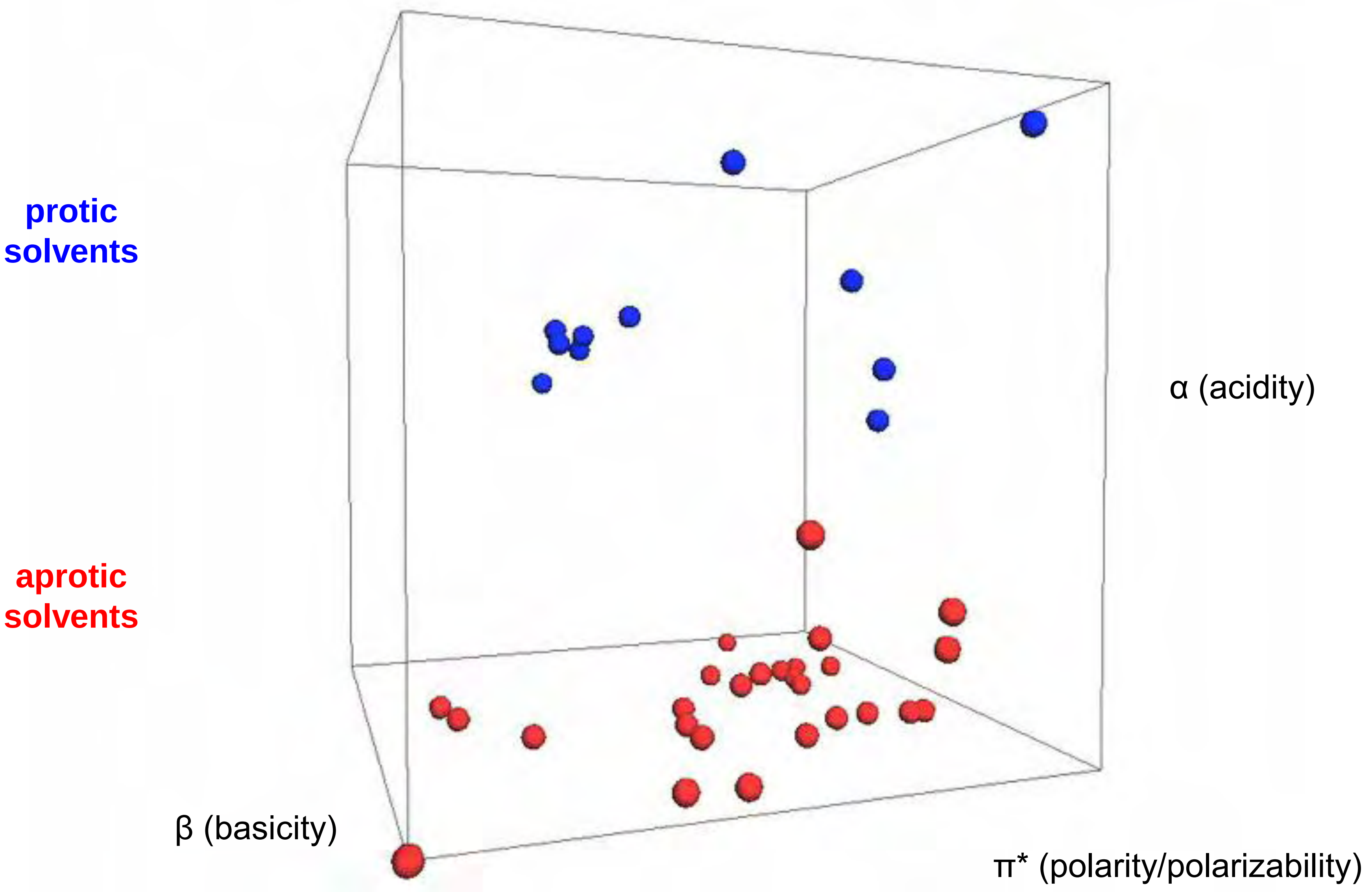
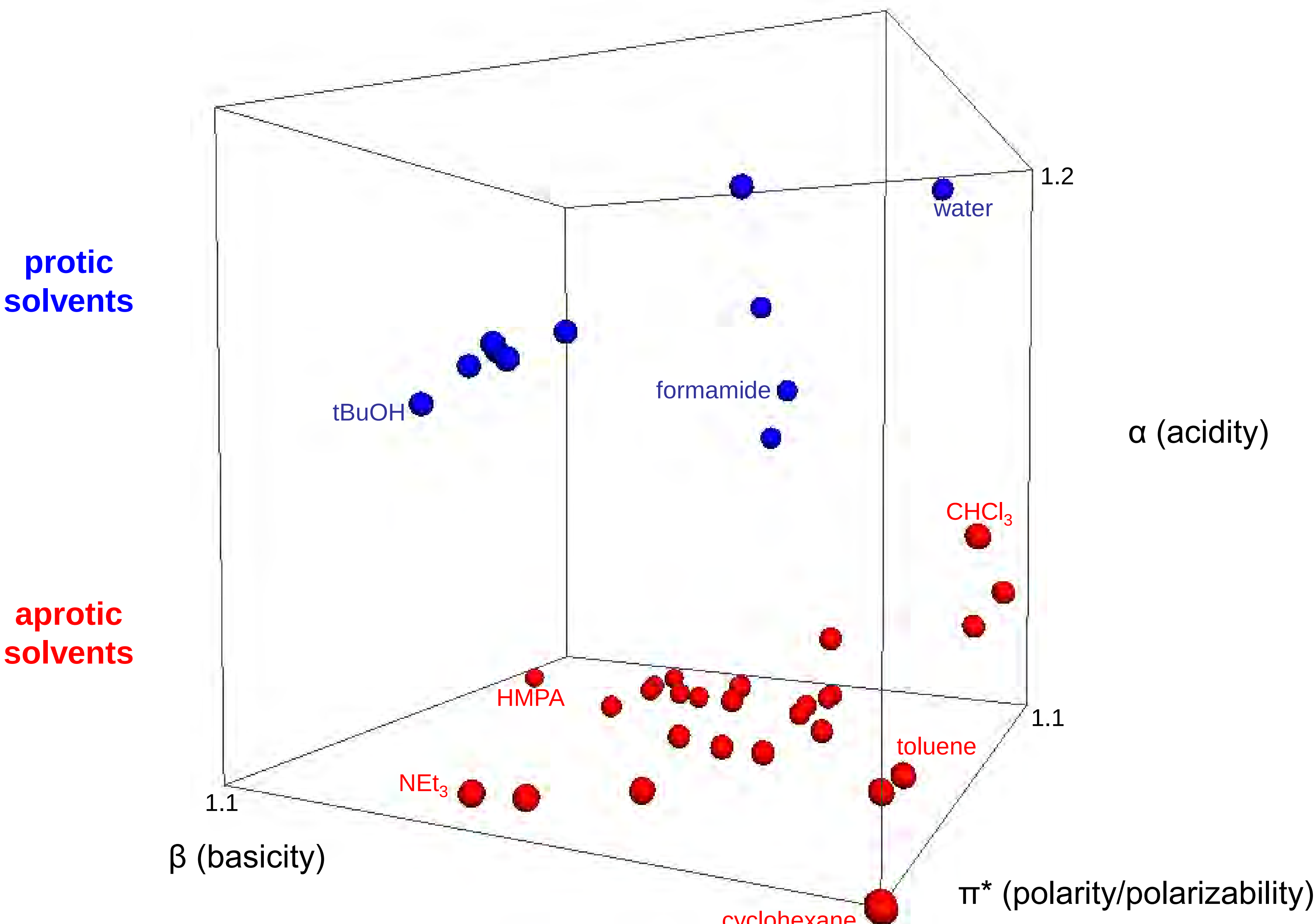
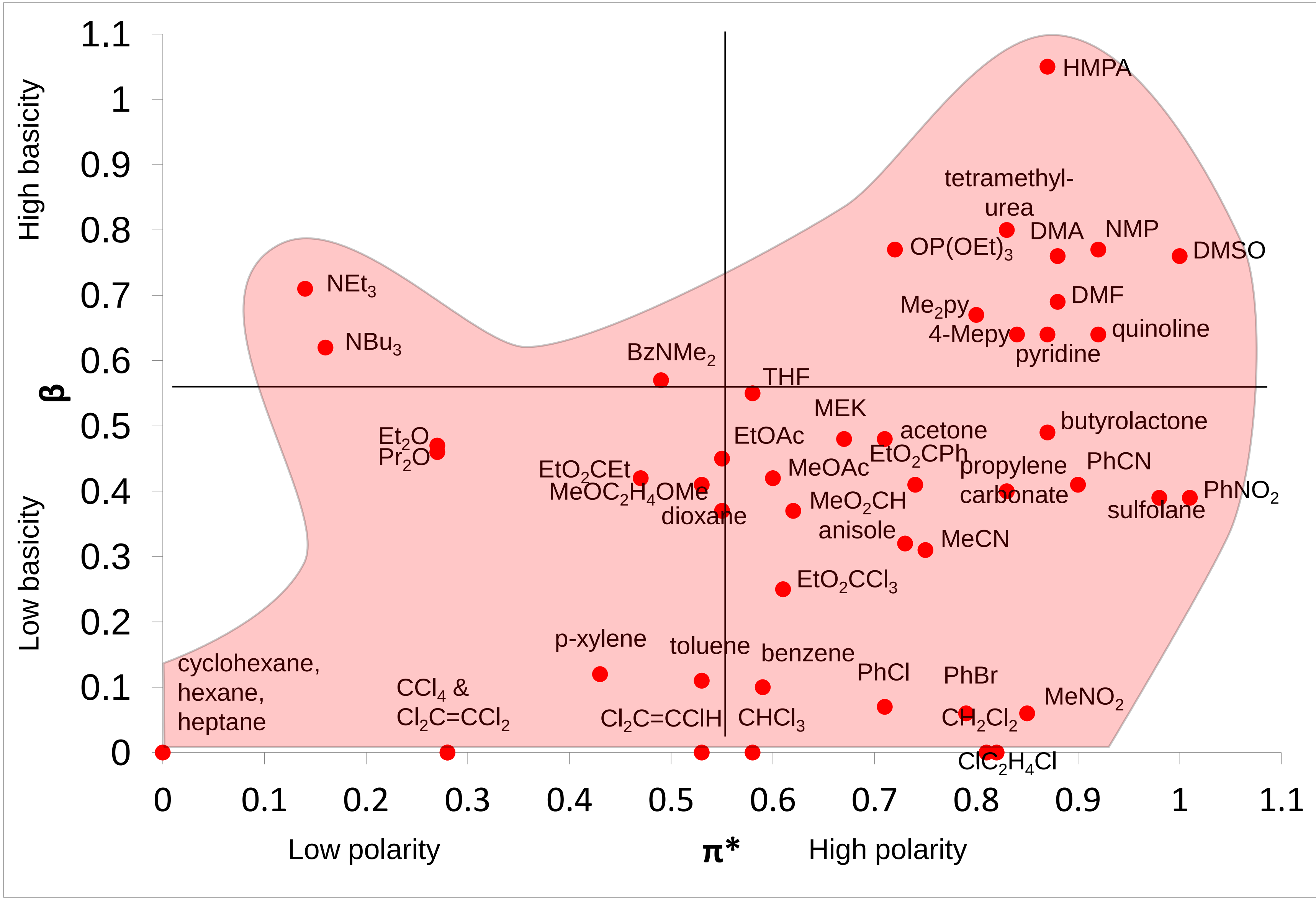


KAMLET-TAFT SOLVATOCHROMIC PARAMETERS

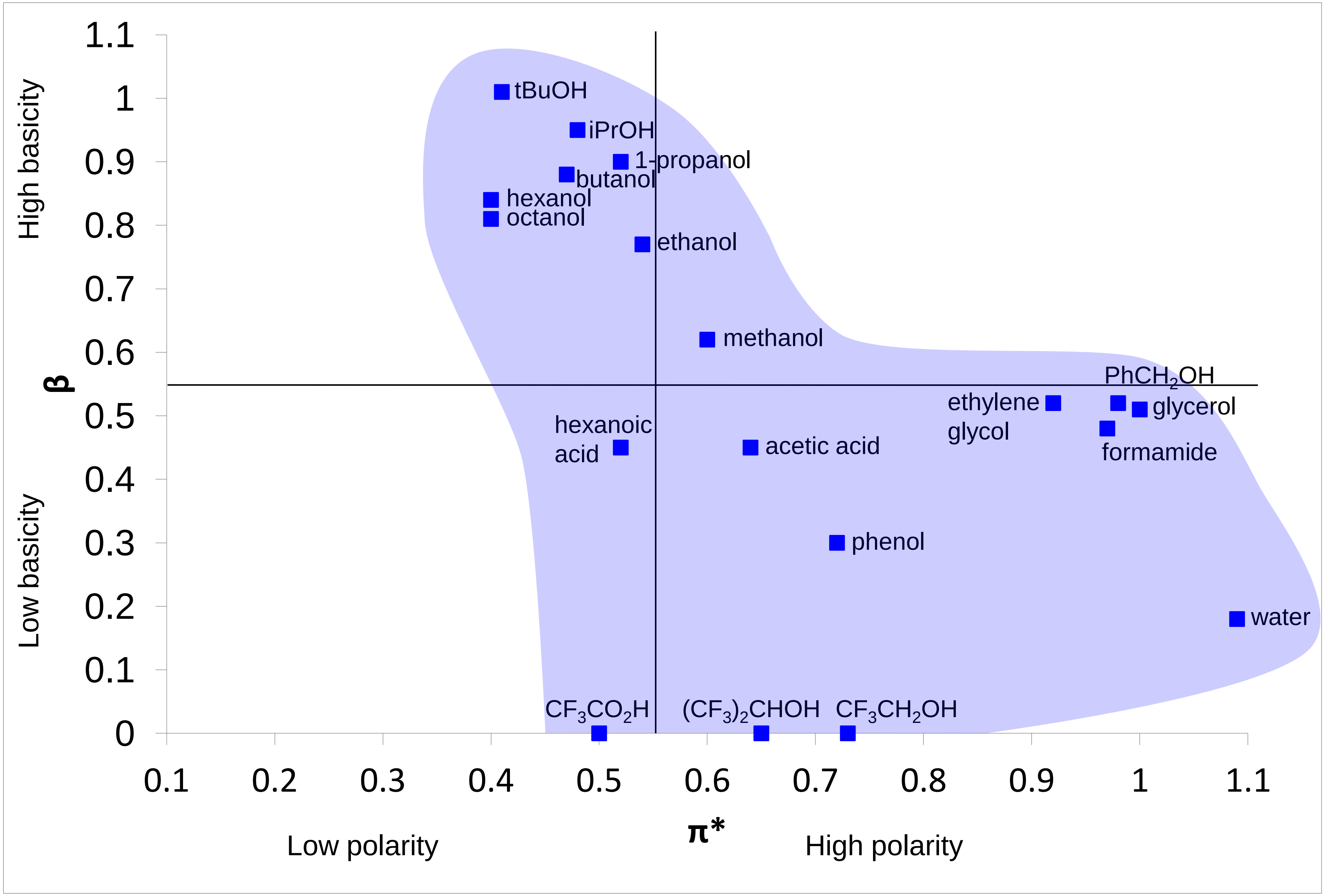


SURVEY OF SOLVENTS (APROTIC)



Jessop, *Green Chem* (2012) *14*, 1245

SURVEY OF SOLVENTS (PROTIC)



Jessop, *Green Chem* (2012) *14*, 1245

OUTLINE

1. Reducing the Impact of Solvents
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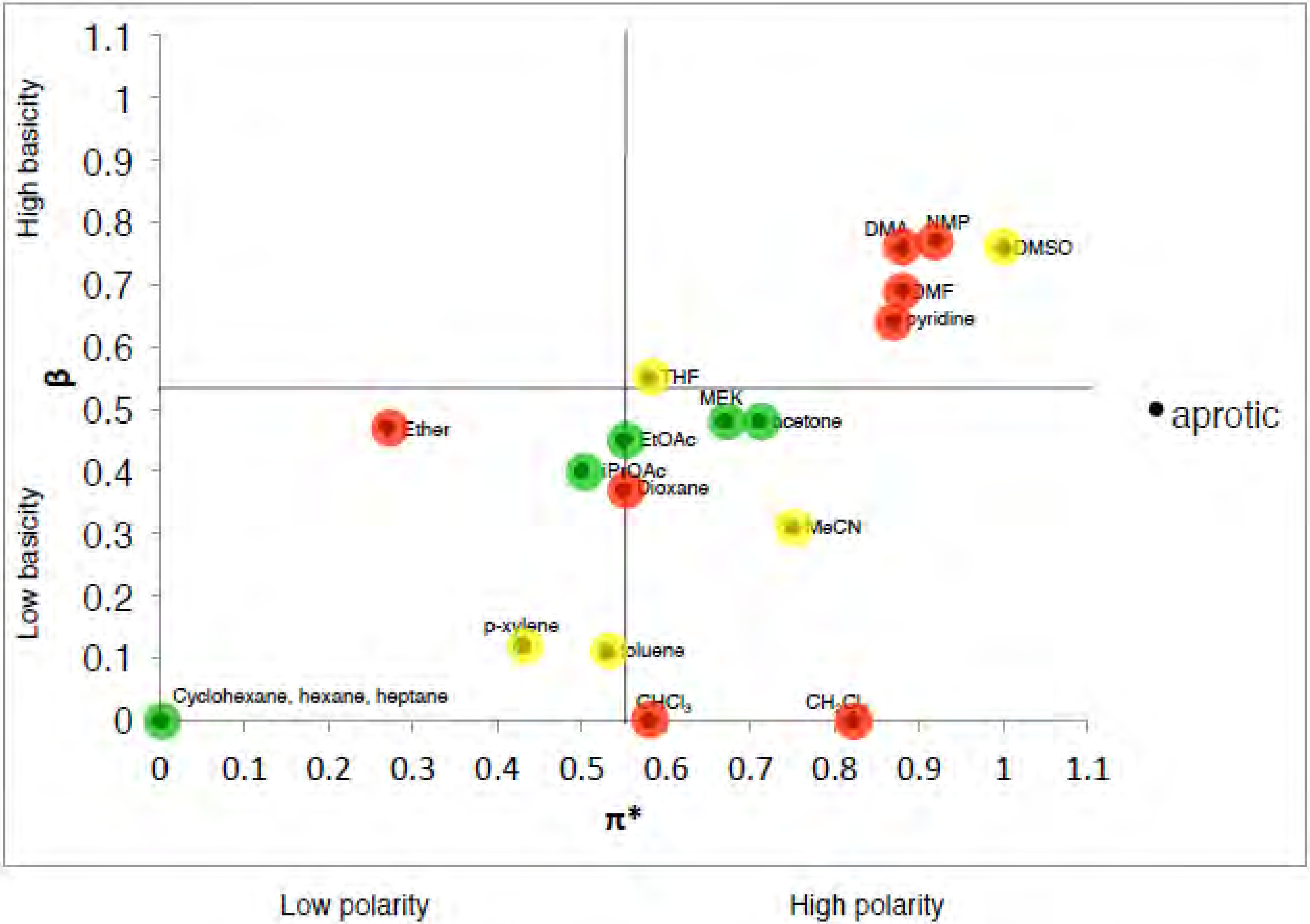
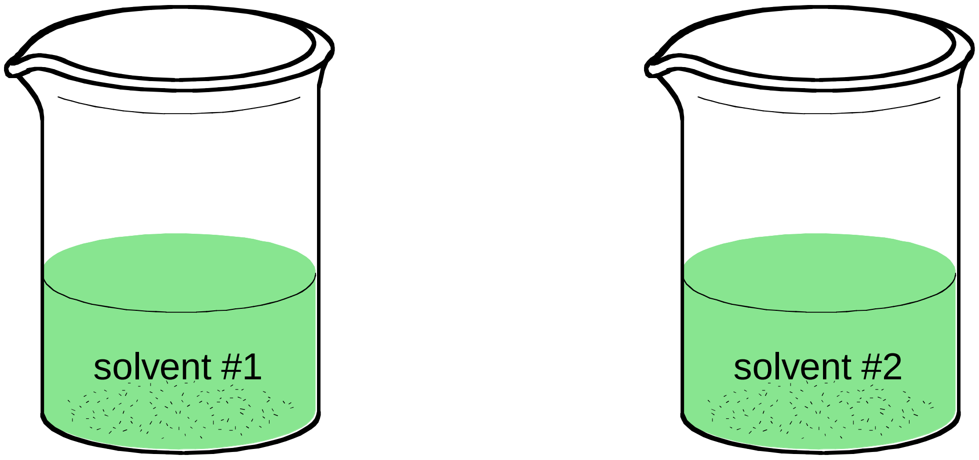
PFIZER SOLVENT SELECTION GUIDE

Water	Cyclohexane	Pentane
Acetone	Toluene	Hexane(s)
Ethanol	Methylcyclohexane	Di-isopropyl ether
2-Propanol	TBME	Diethyl ether
1-Propanol	Isooctane	Dichloromethane
Heptane	Acetonitrile	Dichloroethane
Ethyl Acetate	2-MeTHF	Chloroform
Isopropyl acetate	THF	NMP
Methanol	Xylenes	DMF
MEK	DMSO	Pyridine
1-Butanol	Acetic Acid	DMAc
t-Butanol	Ethylene Glycol	Dioxane
		Dimethoxyethane



High basicity
Low basicity
β
π*
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
DMA
NMP
DMSO
DMF
pyridine
THF
MEK
acetone
Ether
EtOAc
iPrOAc
Dioxane
MeCN
p-xylene
toluene
Cyclohexane, hexane, heptane
$CHCl_3$
CH_2Cl_2
aprotic
Low polarity
High polarity

WHICH SOLVENT IS GREENER?



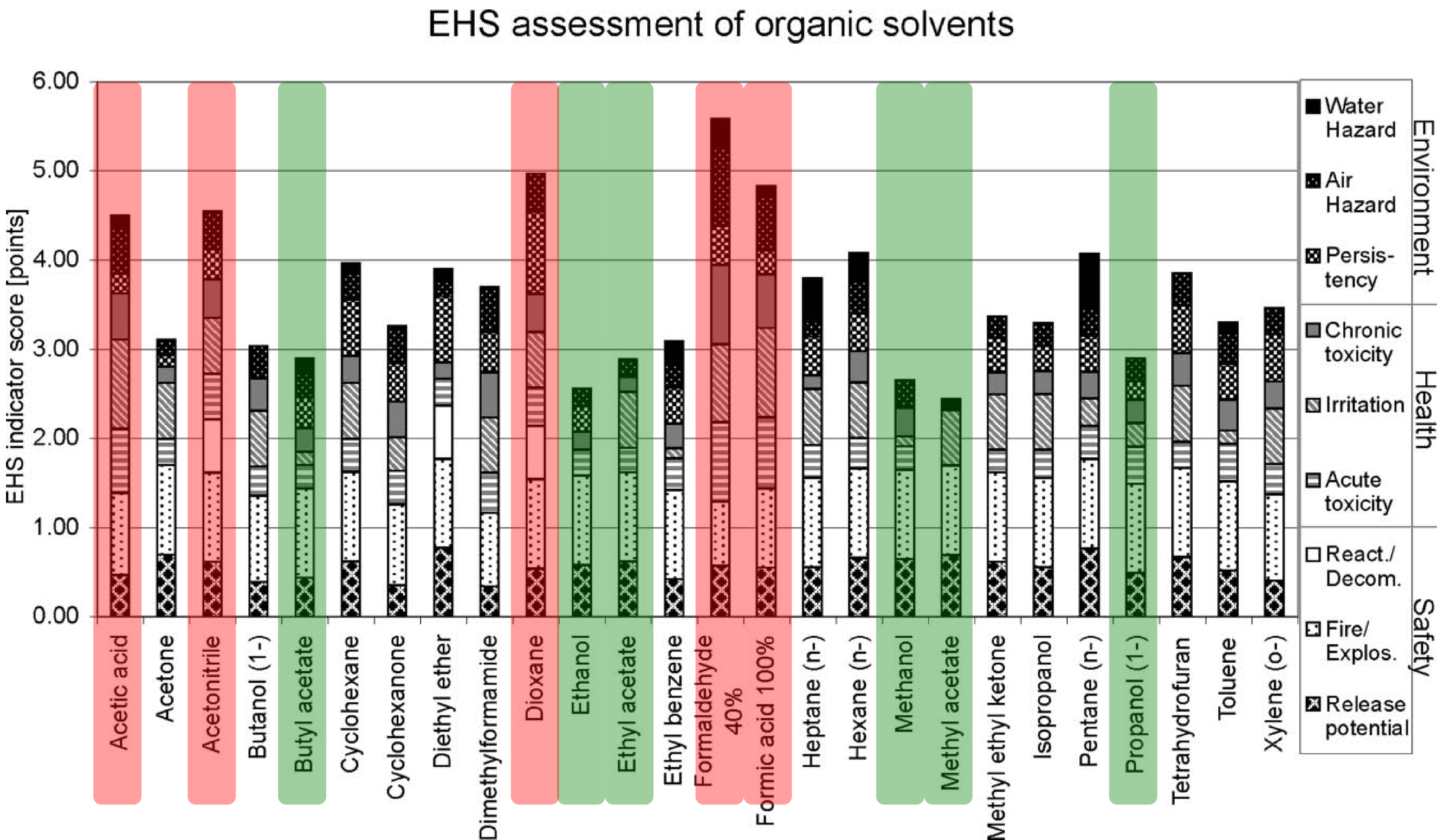
General Comparison

- solvent impact
- solvent impact including manufacture
- energy to manufacture / cumulative energy demand

Application-Specific Comparision

- ISO LCA

ENVIRONMENTAL AND HEALTH RISKS

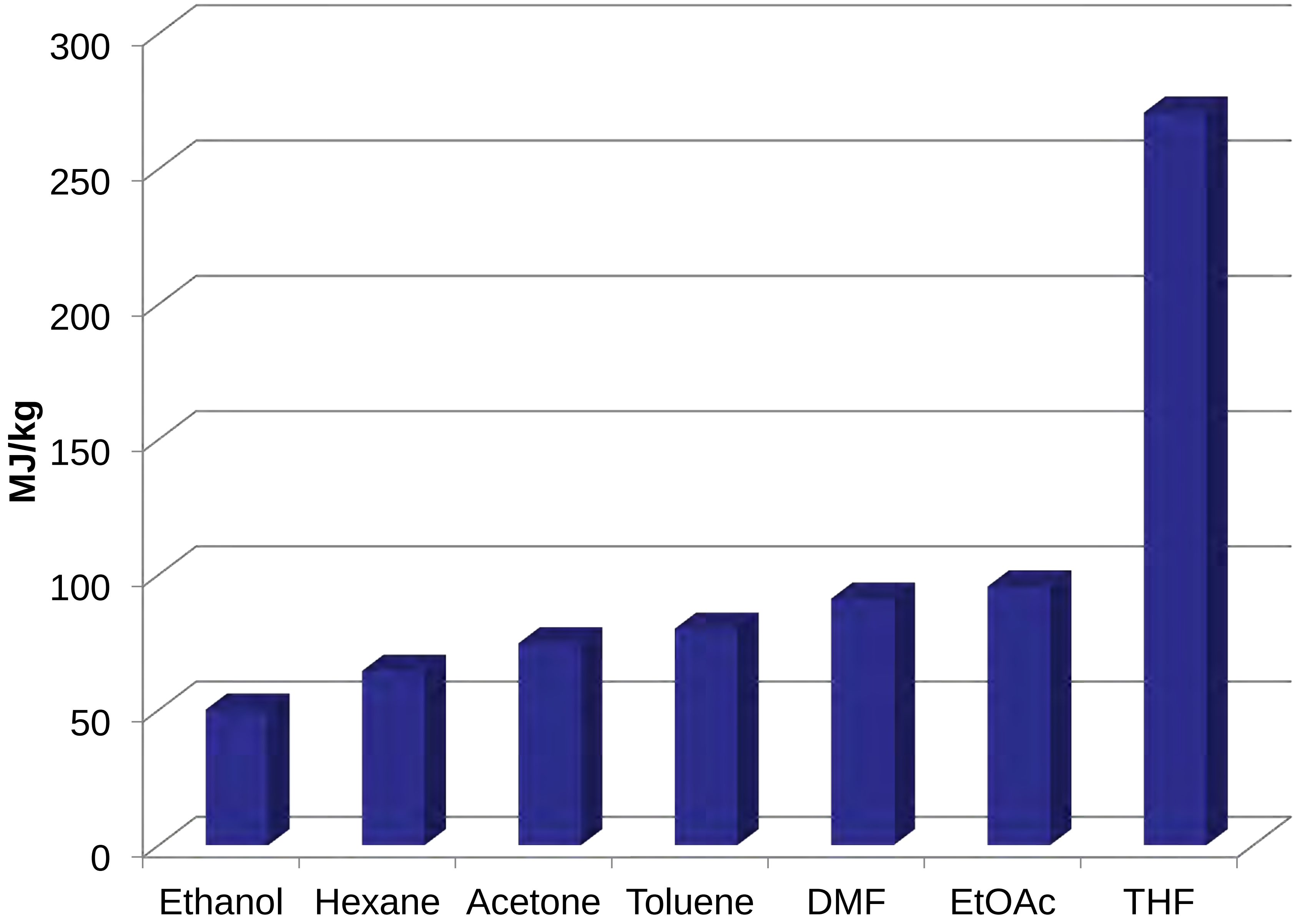


Alcohols
Acetate esters

Acids
Acetonitrile
Dioxane
Formaldehyde

Capello et al., *Green Chem* (2007) 9, 927

ENERGY REQUIREMENT FOR MANUFACTURE



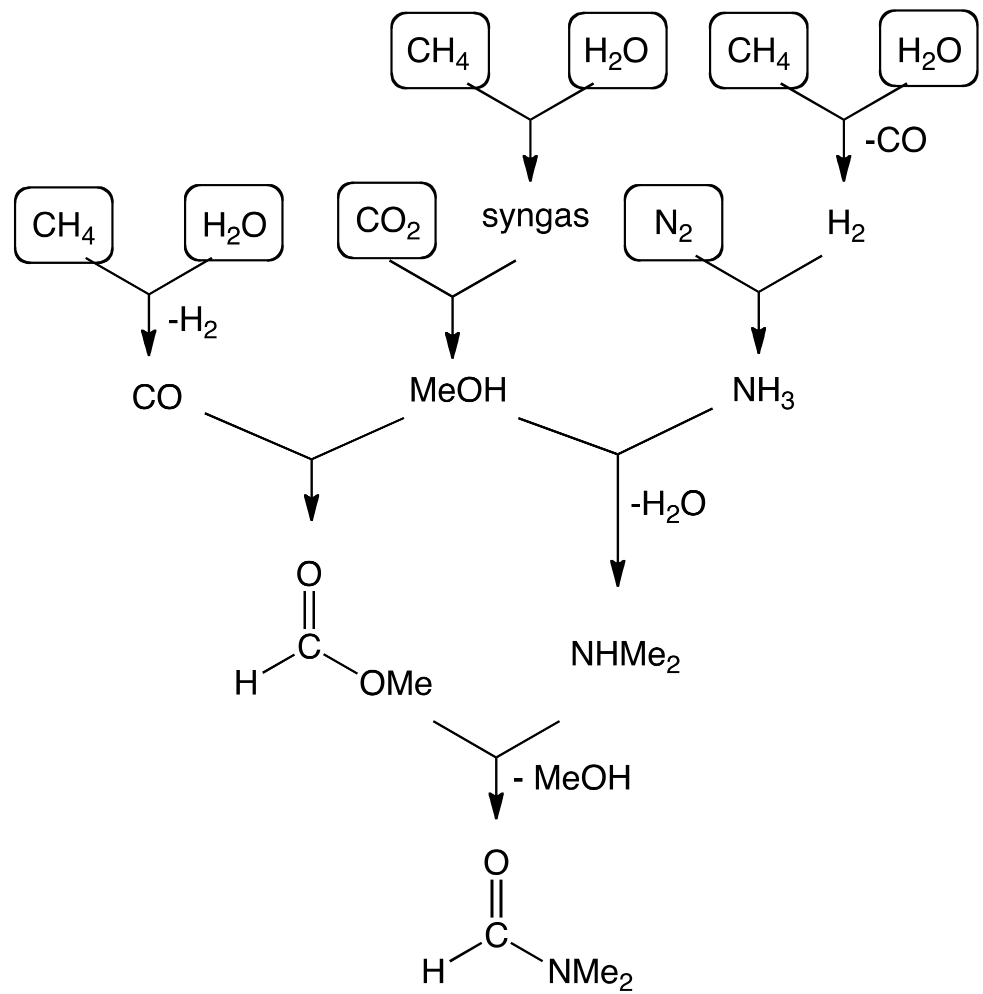
Capello et al., *Green Chem* (2007) *9*, 927

ENERGY REQUIREMENTS FOR A SOLVENT

How is hexane made?

$$\text{oil} \xrightarrow{\text{distillation}} \text{hexane}$$

How is DMF made?



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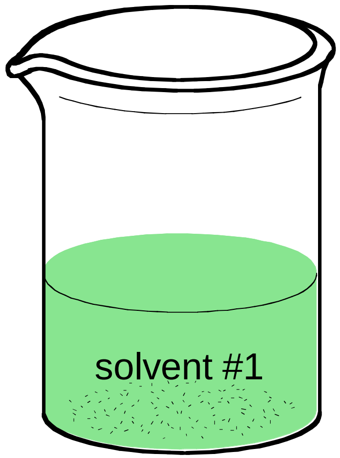
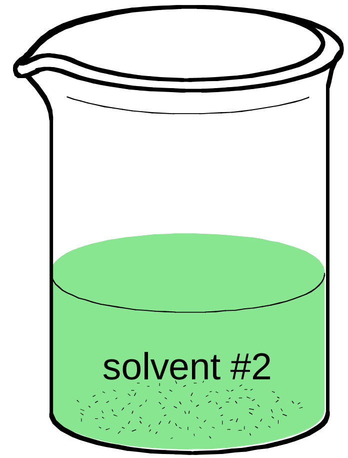




General Comparison

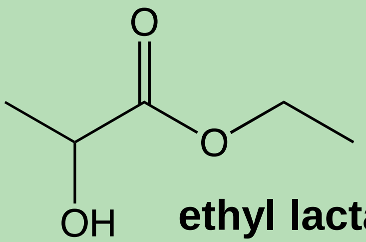
- solvent impact
- solvent impact including manufacture
- energy to manufacture / cumulative energy demand

Application-Specific Comparision

- ISO LCA

Why would this give a different result?

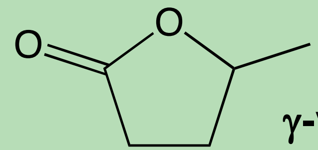
PROPOSED NEW GREEN ORGANIC SOLVENTS



ethyl lactate

low toxicity, biodegradable, renewable

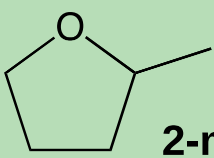
Aparicio, *Green Chem.* (2009) *11*, 65



γ-valerolactone

low toxicity, biodegradable, renewable

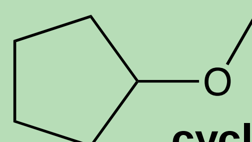
Horvath, *Green Chem.*, 2008, *10*, 238



2-methyltetrahydrofuran

renewable

Aycock, *Org. Process Res. Dev. 2007, 11, 156*

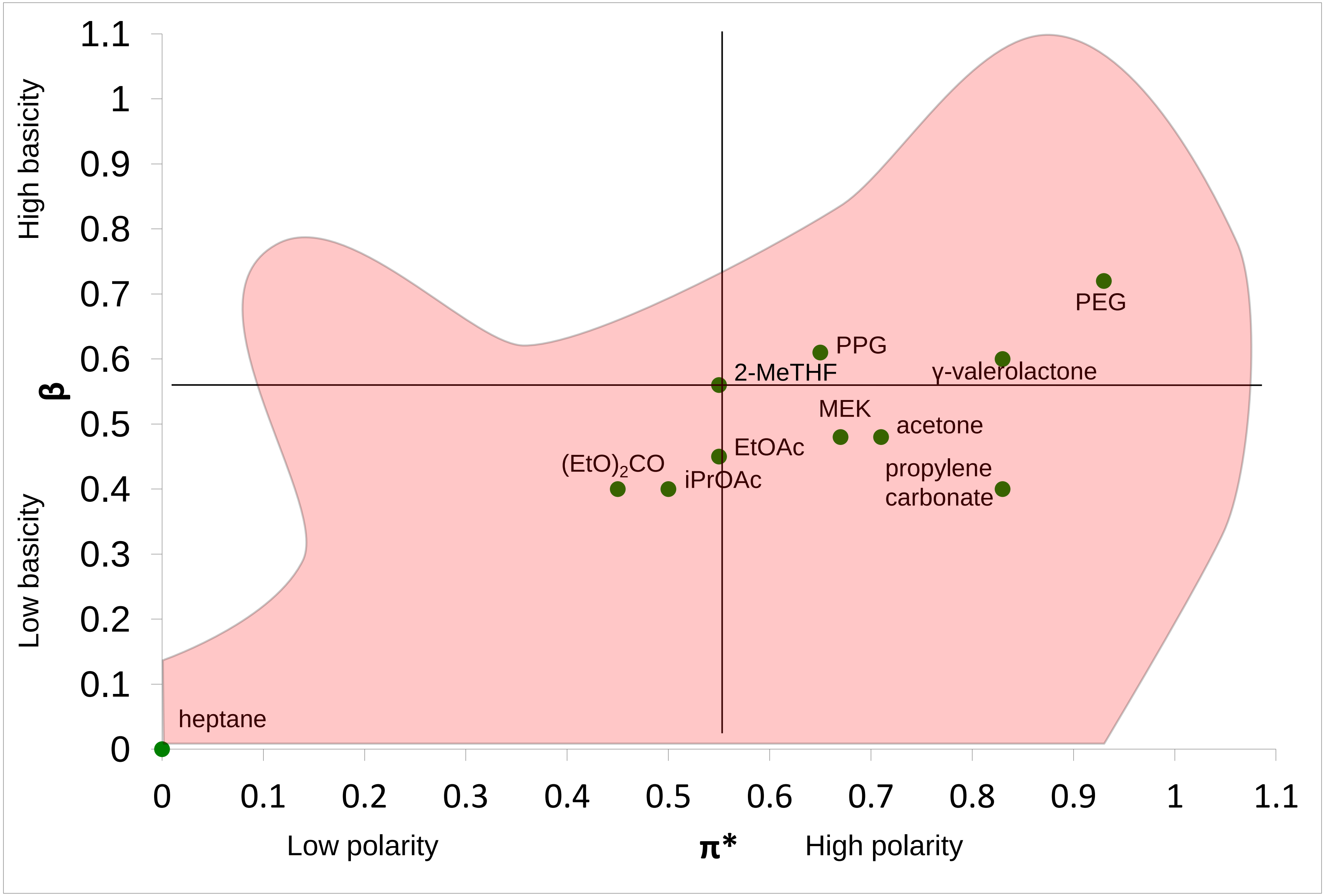


cyclopentylmethylether

doesn't form peroxides, low solubility in water

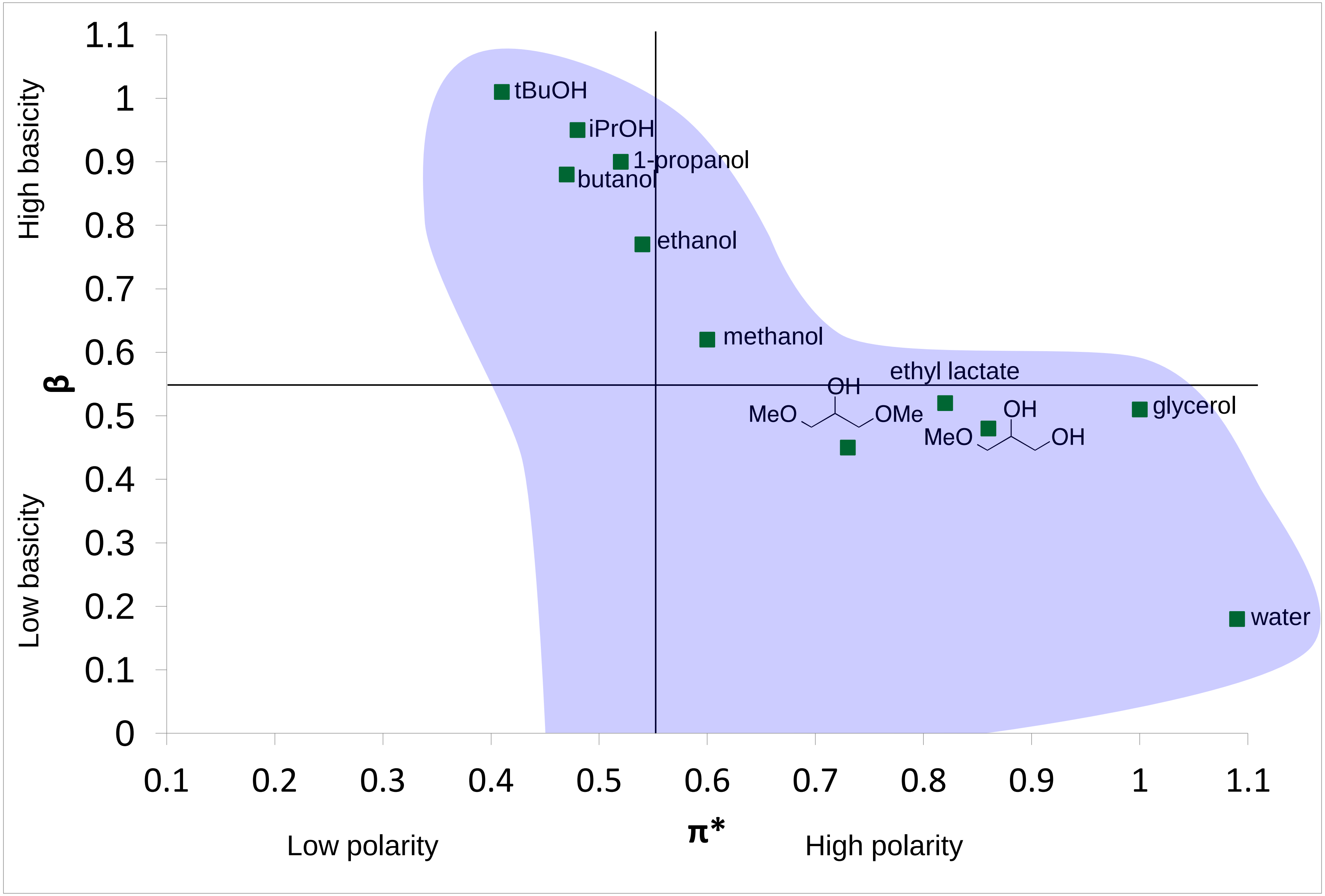
Watanabe, *Org. Process Res. Dev. 2007, 11, 251*

GREEN SOLVENTS (APROTIC)



Jessop, *Green Chem* (2012) *14*, 1245

GREEN SOLVENTS (PROTIC)



Jessop, *Green Chem* (2012) *14*, 1245

OUTLINE

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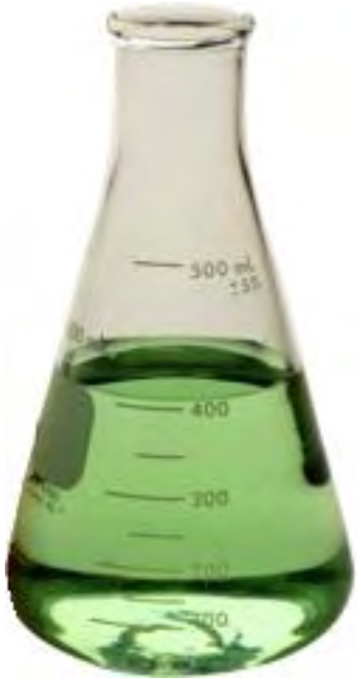


UNCONVENTIONAL SOLVENTS

water

liquid polymer

switchable solvent

supercritical CO_2

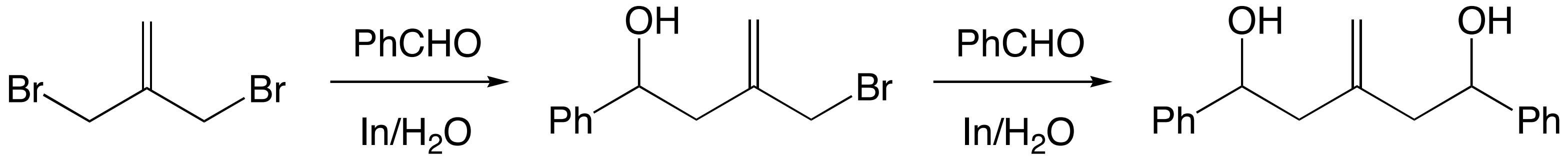
ionic liquid

CO_2-expanded liquid

IN WATER

Why not water?

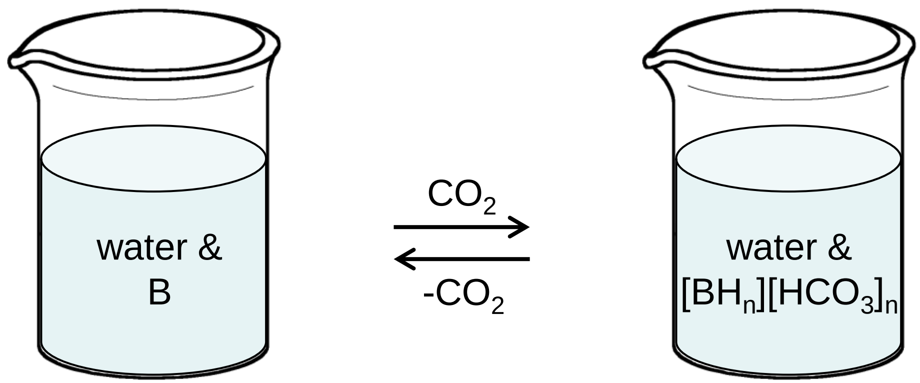
http://students.washington.edu/~haoli/photo_gallery/archives/olympic/

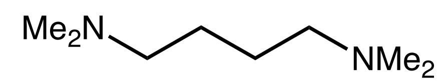


0.5 h
75% yield

Li, 1995

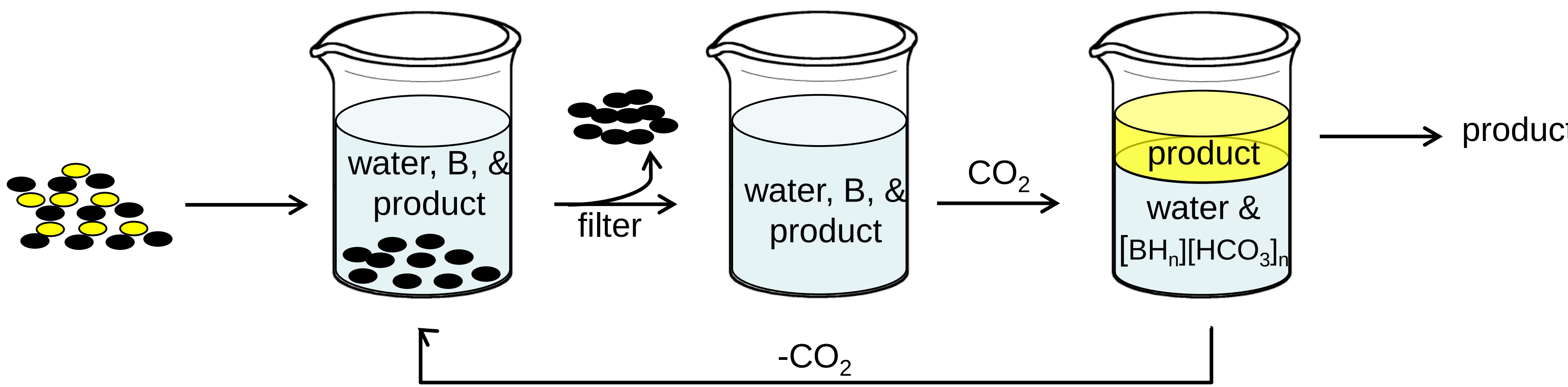
SWITCHABLE WATER





- low ionic strength
- low osmotic pressure
- good solvent for polar organics

- high ionic strength
- high osmotic pressure
- poor solvent for polar organics



Mercer, Jessop, et al. *ChemSusChem* (2010) *3*, 467
Mercer, Jessop, et al. *Green Chem* (2012) *14*, 832

IONIC LIQUIDS

NaCl, mp 801 ˚C

$NaBF_4$, mp 384 ˚C

$[P^{i}Bu_3Me]O_3SC_6H_4Me$, mp < RT

Nonvolatile

Nonflammable

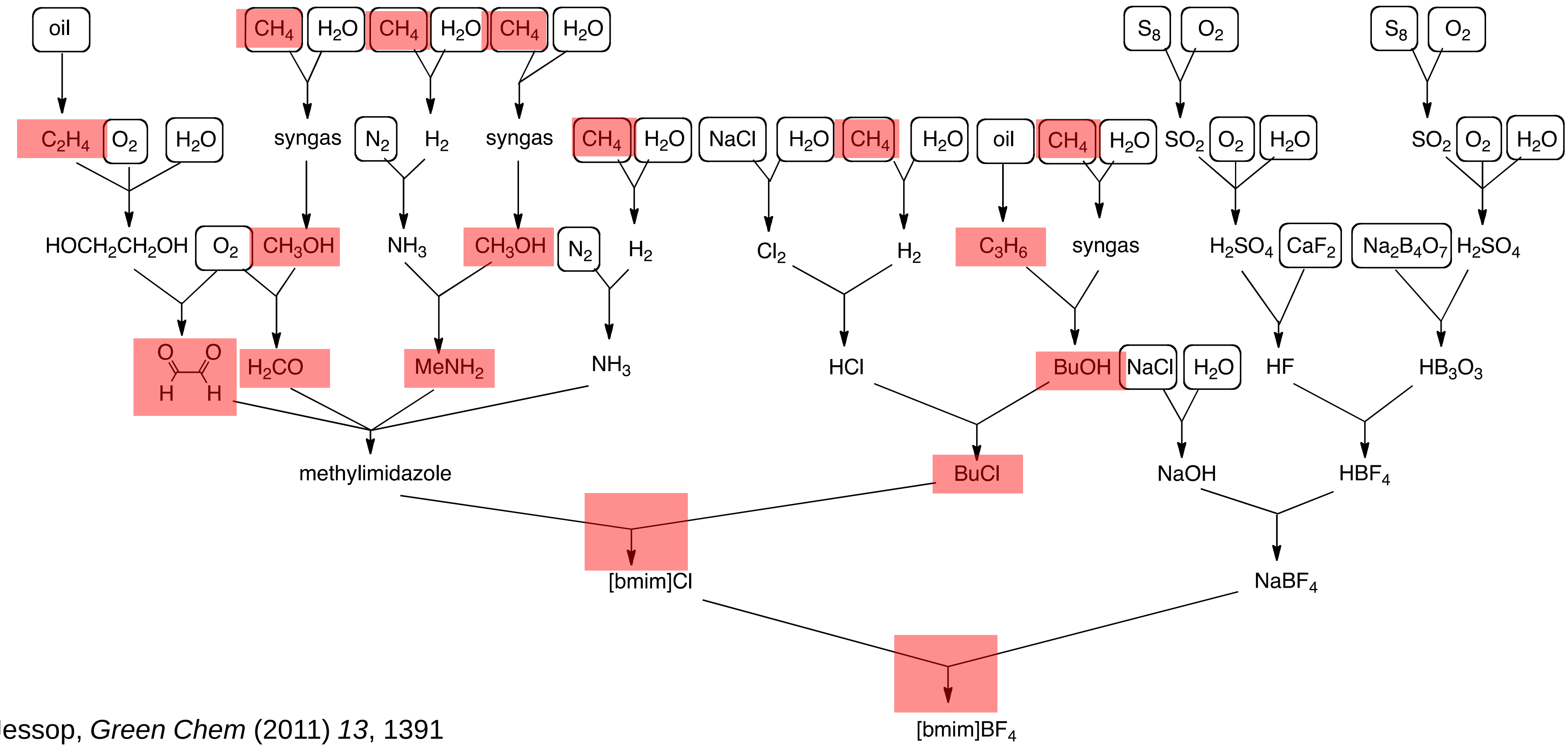
Doesn’t create smog

No inhalation hazards

BY GENERAL COMPARISON, ARE IONIC LIQUIDS GREEN?

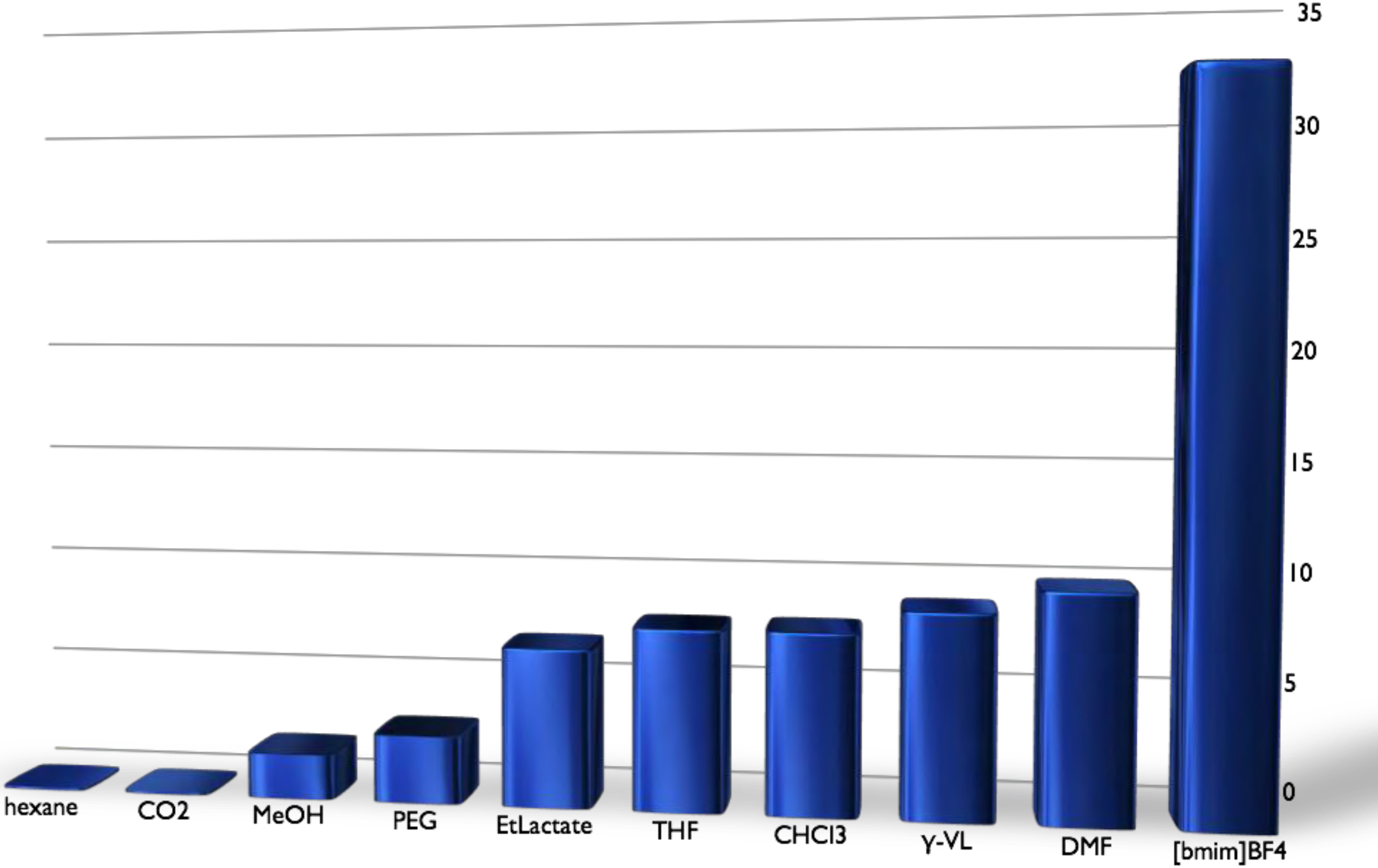
	ADP	GWP	ODP	HTP	FAETP	MAETP	TETP	POCP	AP	EP	VOC
[Bmim][BF_4]	5.8E-2	3.5E+0	6.1E-7	6.1E-1	5.2E-2	4.4E+3	1.2E-2	4.5E-3	4.2E-2	1.8E-3	1.6E-2
H_2O	3.3E-6	5.7E-4	8.4E-10	1.8E-4	3.5E-5	6.4E-1	1.2E-5	5.5E-7	4.5E-6	1.7E-7	1.6E-6
LPDE	2.6E-2	1.4E+0	3.1E-7	1.8E-1	4.5E-2	3.5E+2	6.7E-3	5.0E-3	1.2E-2	9.1E-4	1.1E-2
acetone	3.8E-2	2.0E+0	0.0E+0	2.3E-2	3.1E-3	5.4E+1	9.8E-4	4.2E-4	1.4E-2	1.6E-3	4.6E-3
benzene	3.1E-2	1.6E+0	9.4E-7	1.3E-1	2.0E-2	6.9E+1	3.8E-4	1.9E-3	1.0E-2	9.6E-4	9.1E-3

Zhang, *Env. Sci. Tech.* (2008) *42*, 1724



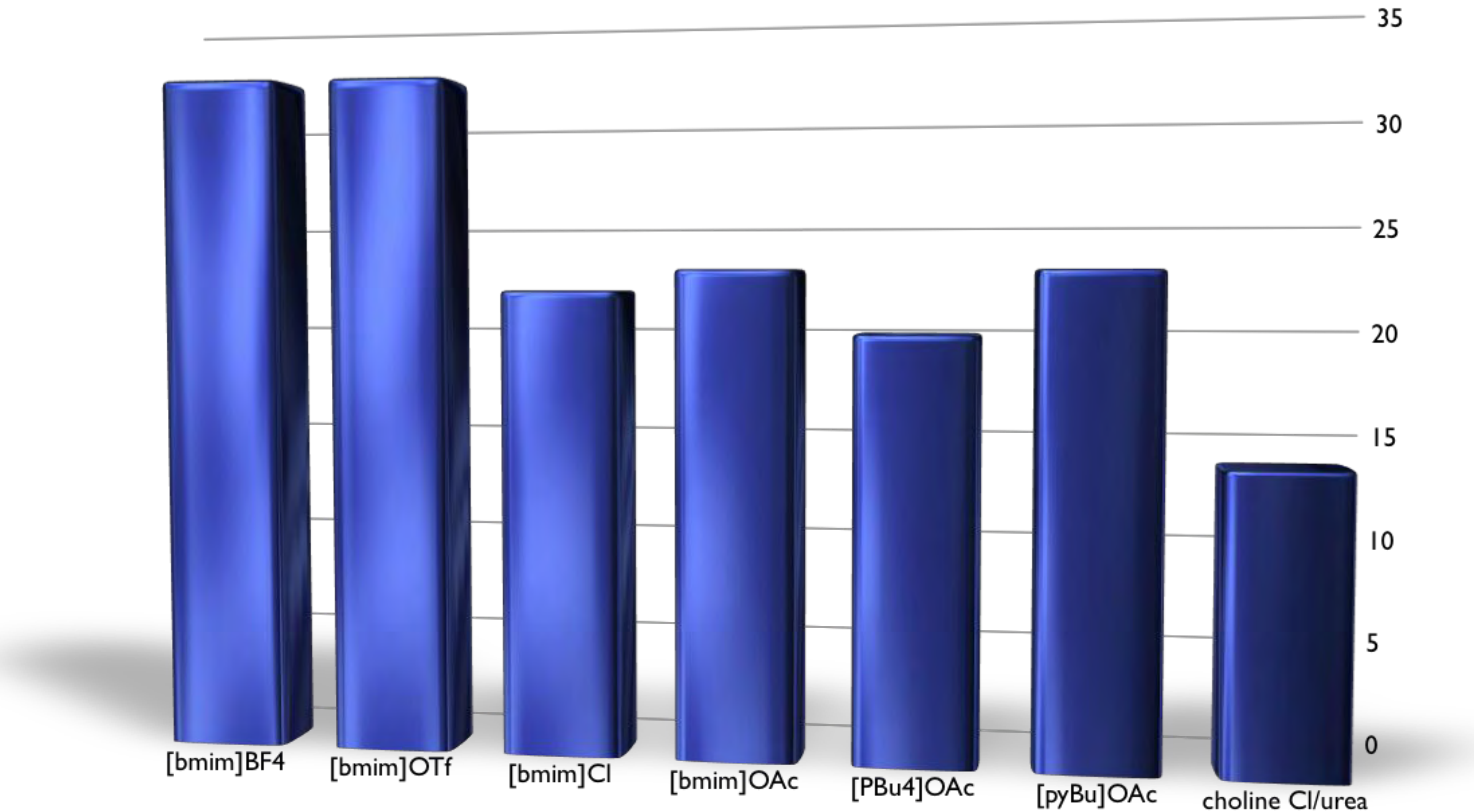
Jessop, *Green Chem* (2011) *13*, 1391

CHEMICAL STEPS IN SOLVENT SYNTHESIS

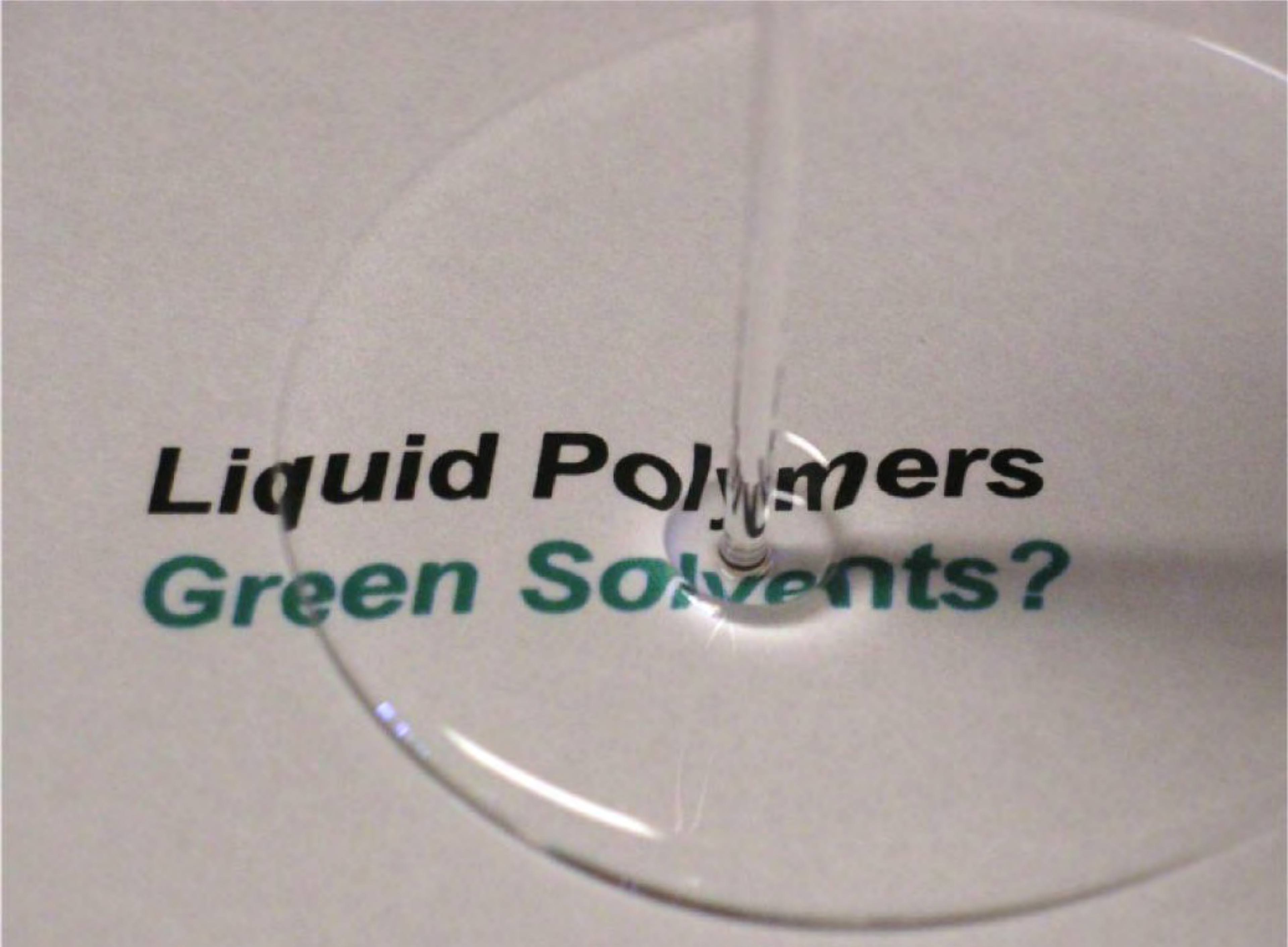


Jessop, *Green Chem* (2011) *13*, 1391

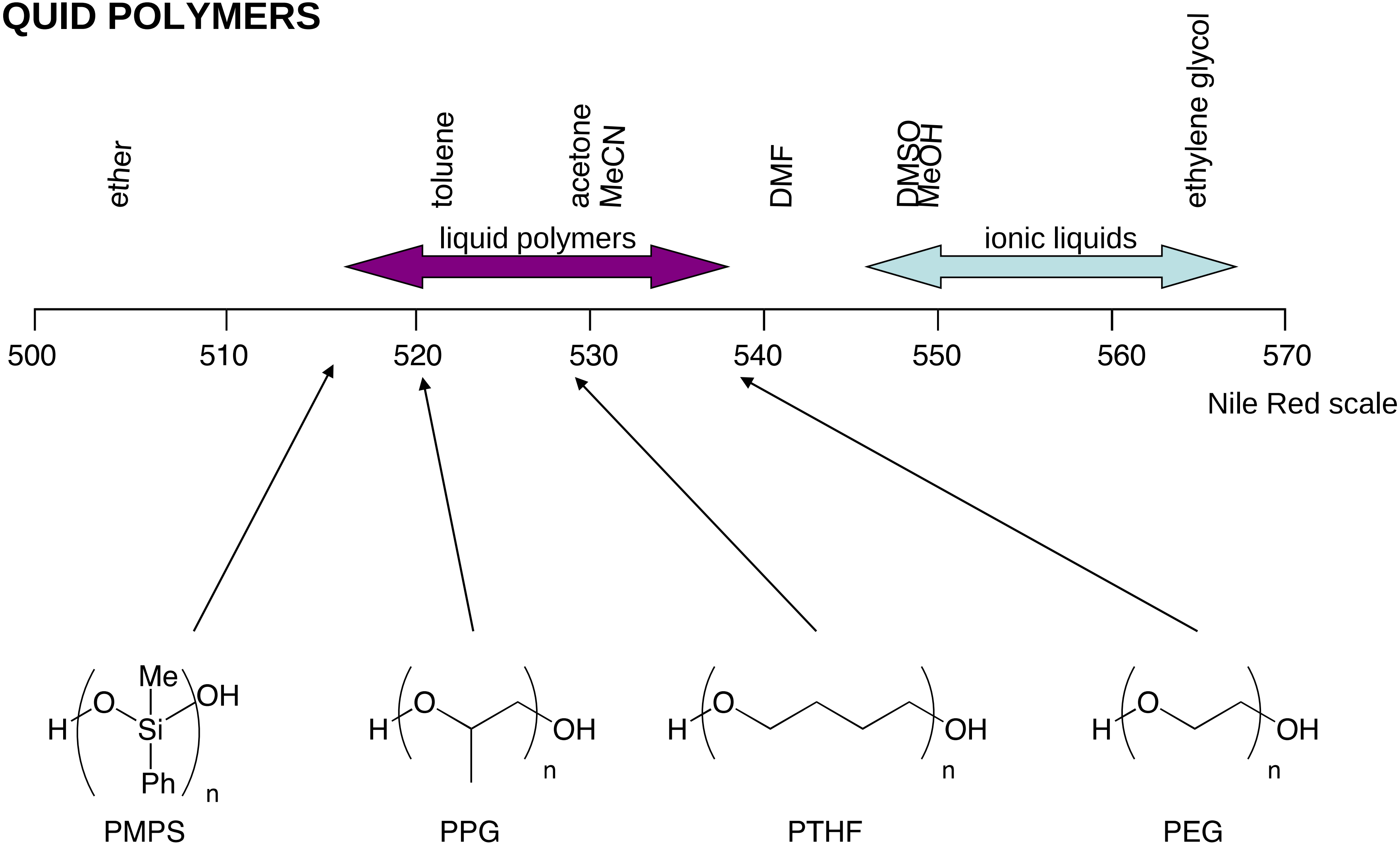
CHEMICAL STEPS IN SOLVENT SYNTHESIS



Jessop, *Green Chem* (2011) *13*, 1391

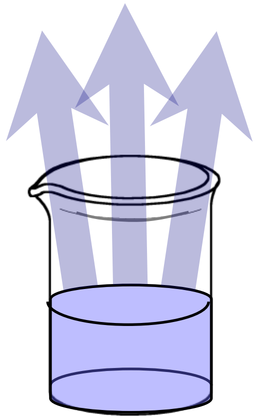

Liquid Polymers
Green Solvents?

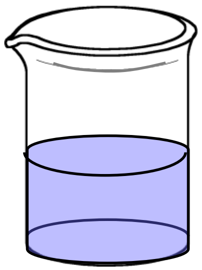
LIQUID POLYMERS



Heldebrant, Jessop et al. *Green Chem* (2006)

SOME ORGANIC SOLVENTS ARE VOLATILE





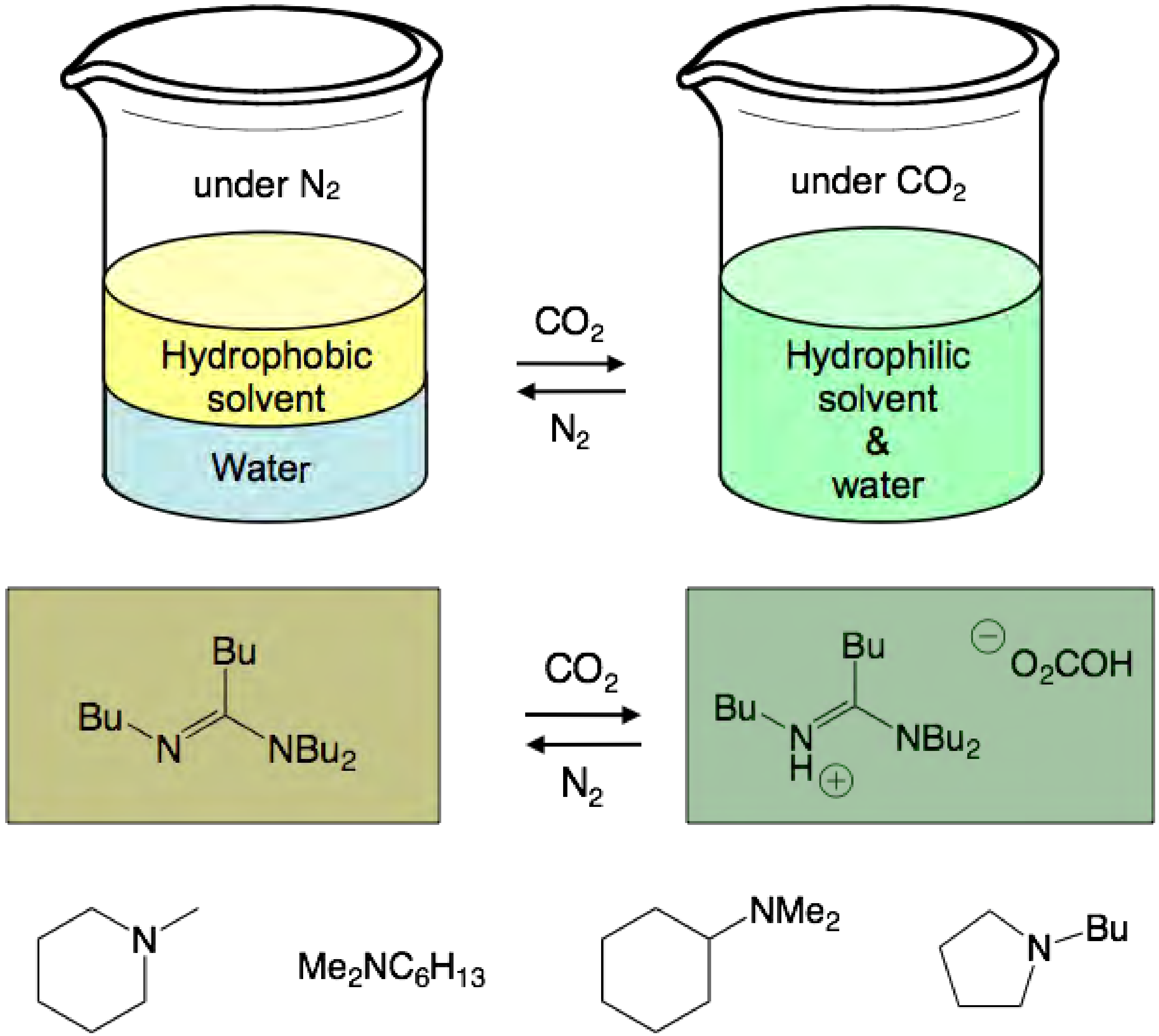
Volatile Solvents

- flammability
- high insurance costs
- vapour losses
- smog formation
- inhalation hazards
    - toxic,
    - narcotic,
    - mutagenic,
    - carcinogenic

Nonvolatile Solvents

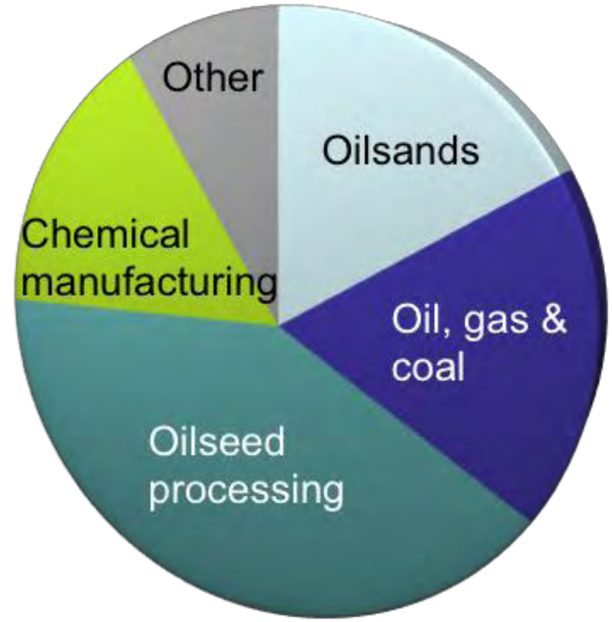
- no flammability
- low insurance costs
- no vapour losses
- no smog formation
- no inhalation hazards

SWITCHABLE-HYDROPHILICITY SOLVENTS

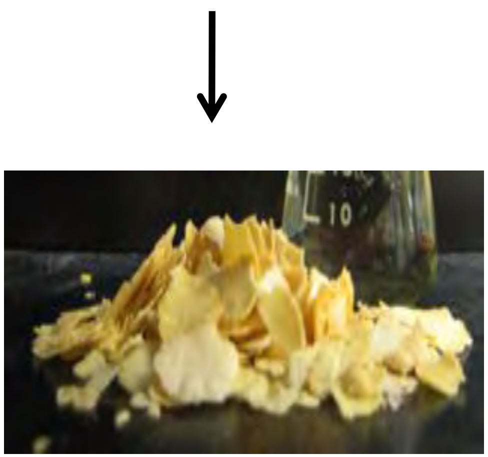


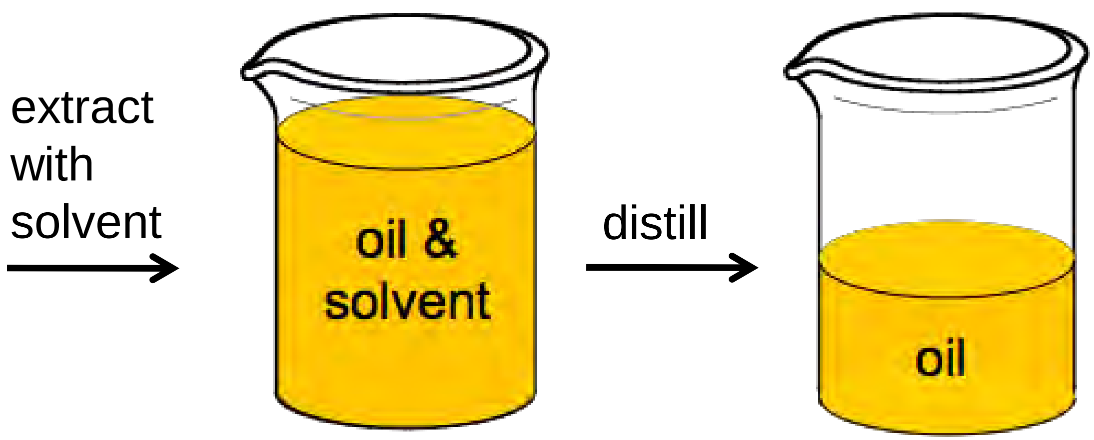
Green Chem (2010) *12*, 809
Green Chem (2011) *13*, 619

A REAL WORLD PROBLEM



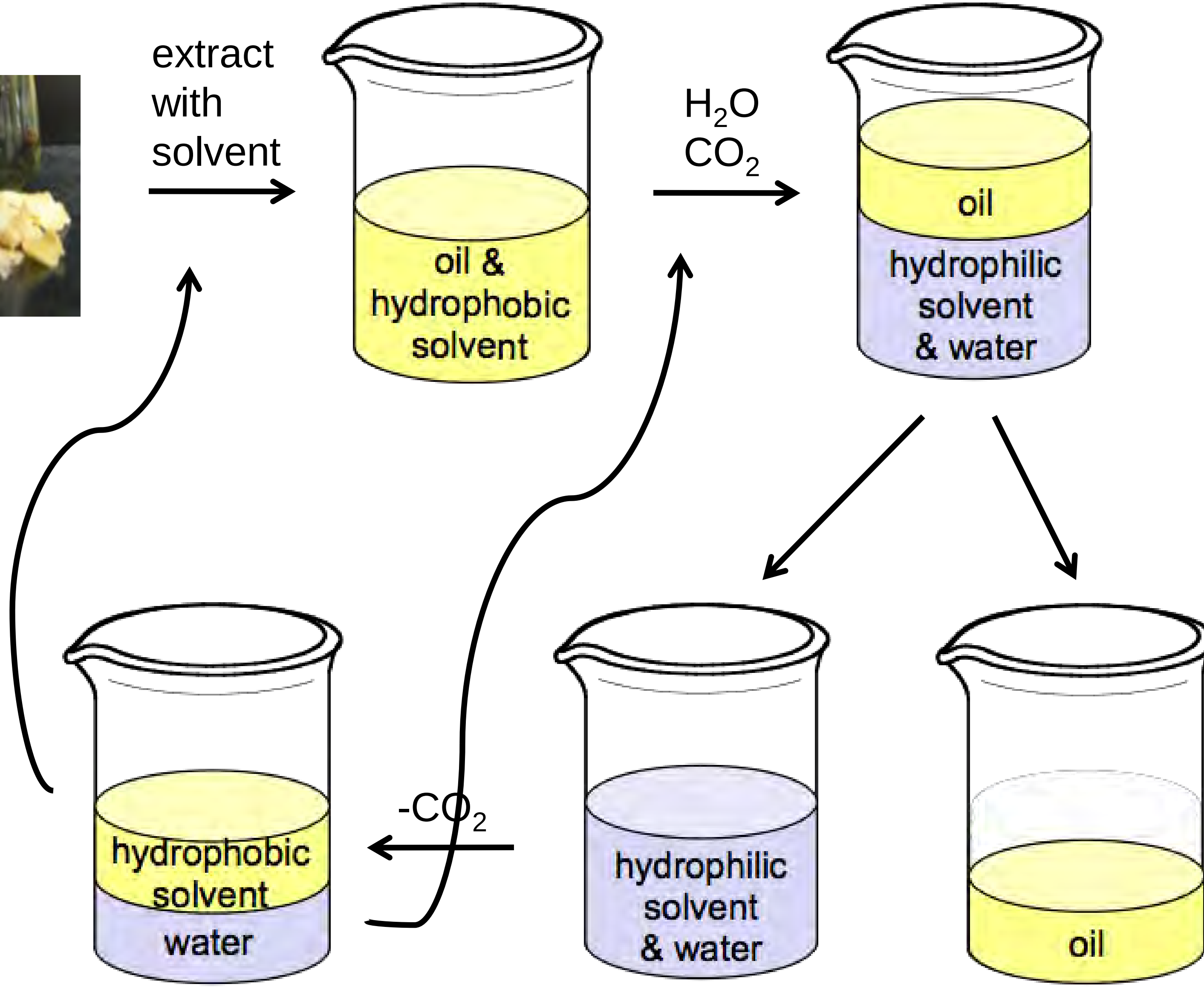
hexane emissions to air in Canada (NPRI, 2007)





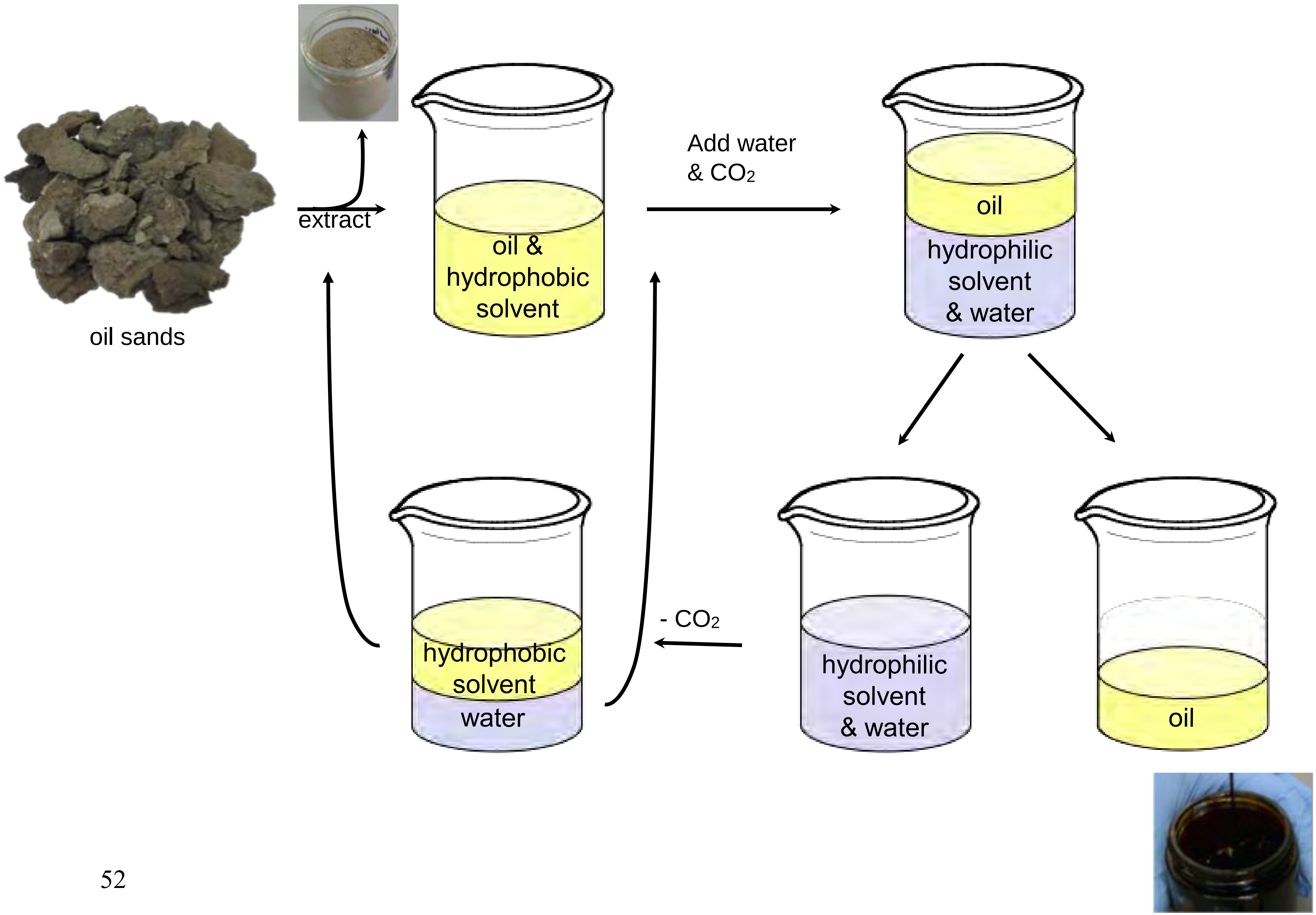
Green Chem (2010) *12*, 809

SOY EXTRACTION WITHOUT DISTILLATION

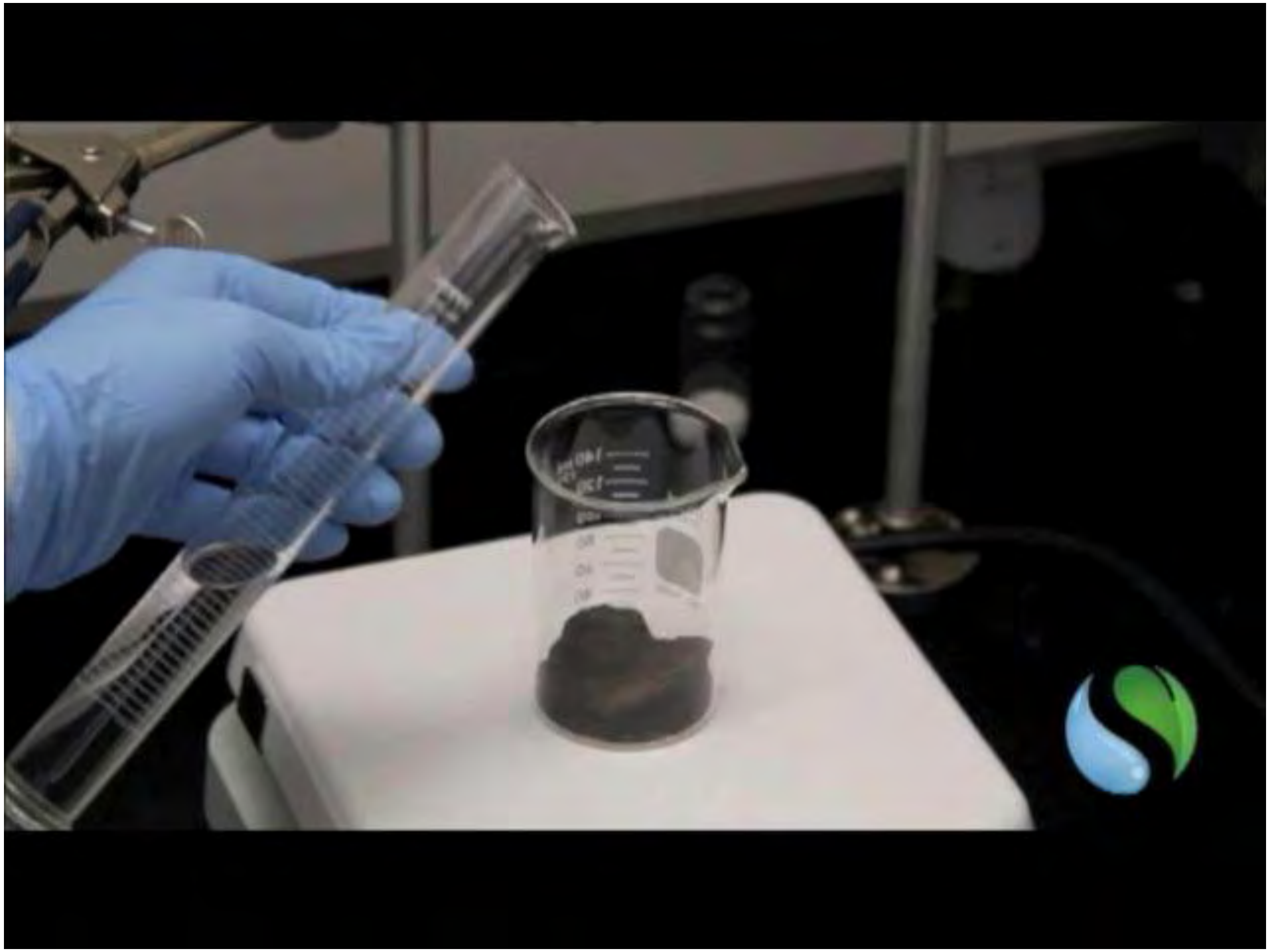


Green Chem (2010) *12*, 809
Green Chem (2011) *13*, 619

USING A SWITCHABLE-HYDROPHILICITY SOLVENT



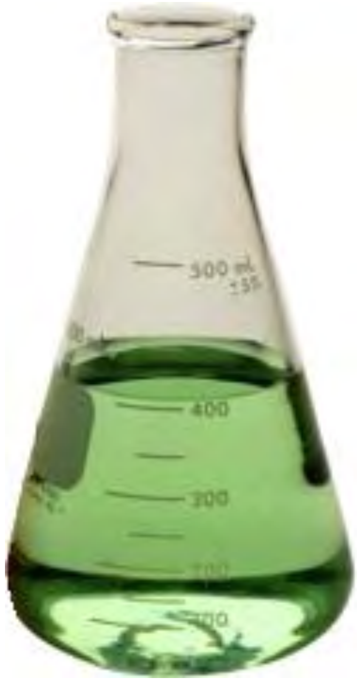
OIL SANDS



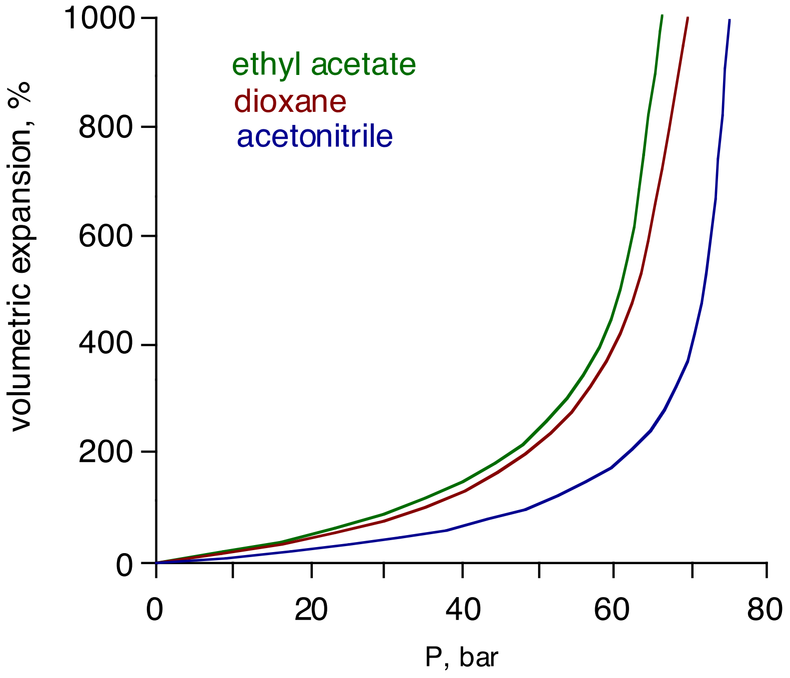

DISTILLATION
DISTILLATION
CARBONATED WATER
EXTRACTION

OUTLINE

1. Reducing the Impact of Solvents
2. Solvent Properties
3. Greener Conventional Solvents
4. Unconventional Solvents
    - Ionic Liquids
    - Liquid Polymers
    - Switchable Solvents
    - Gas-Expanded Liquids
    - Supercritical Fluids
5. Conclusions



EXPANSION OF LIQUIDS BY CO_2



Volumetric expansion of aprotic solvents by CO_2 at 40˚C (Kordikowski, 1995)

CO_2-expanded NEt_3 (Jessop, 1996)

Characteristics:

- tunable polarity
- tunable solvent properties
- lowered melting point
- improved mass transfer rates
- improved solubility of reagent gases

EFFECT OF SOLVENT CHOICE

Expansion with CO_2 increases in the order:

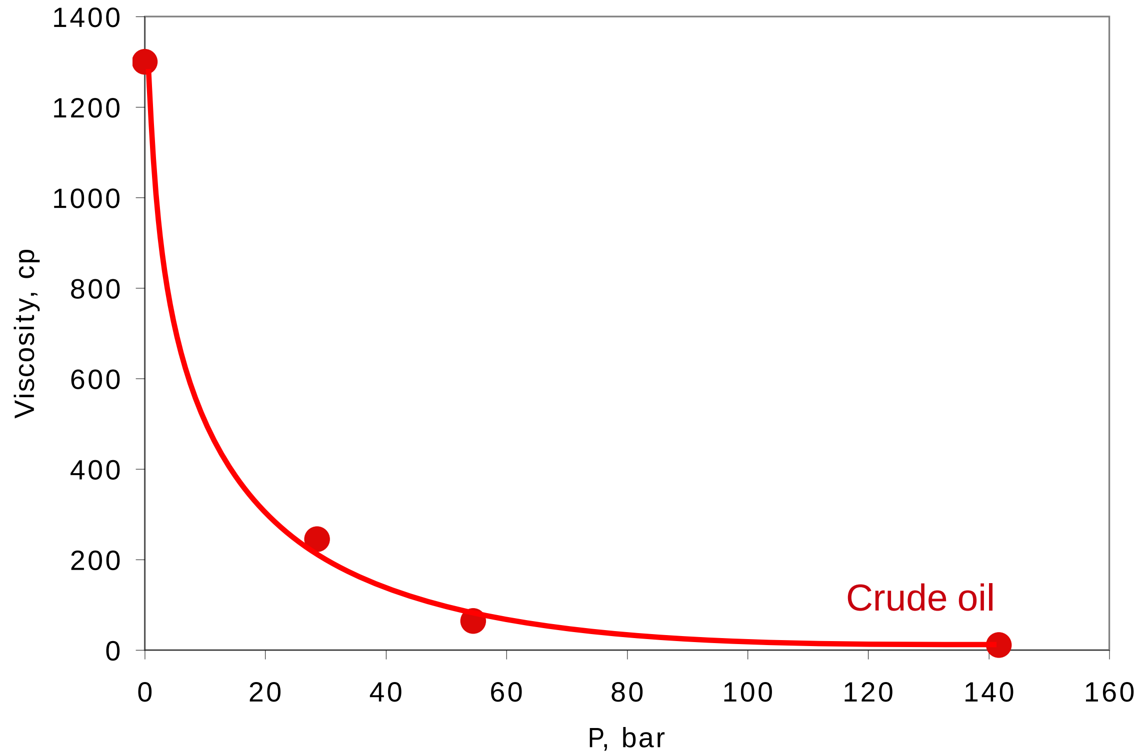
water < ionic liquid liquid polymer < protic polar < aprotic polar < nonpolar

Class	Examples	Volumetric change	Properties that change	Properties that don't change
I	Water Glycerol	Very small	Acidity	Most
II	Hexane Methanol DMF	Very large	All	None
III	Ionic liquids Liquid polymers Crude oil	Moderate	Viscosity Phase behaviour	Polarity

review paper: Jessop & Subramaniam, *Chem. Rev.* (2007) *107*, 2666

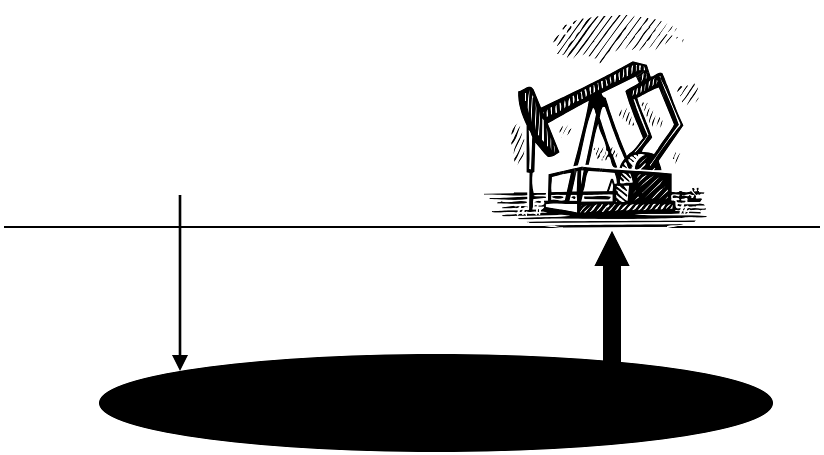
VISCOSITY

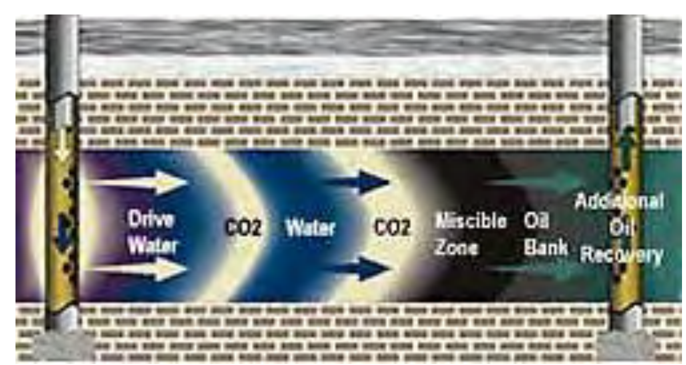
Solvent	viscosity (cP)
CO_2 (1 atm)	0.015
pentane	0.22
benzene	0.60
water	0.89
cyclohexane	0.90
CCl_4	0.91
mercury	1.53
[bmim]PF_6	450
shampoo	1000



Viscosity of CO_2-expanded crude oil at 49 ˚C

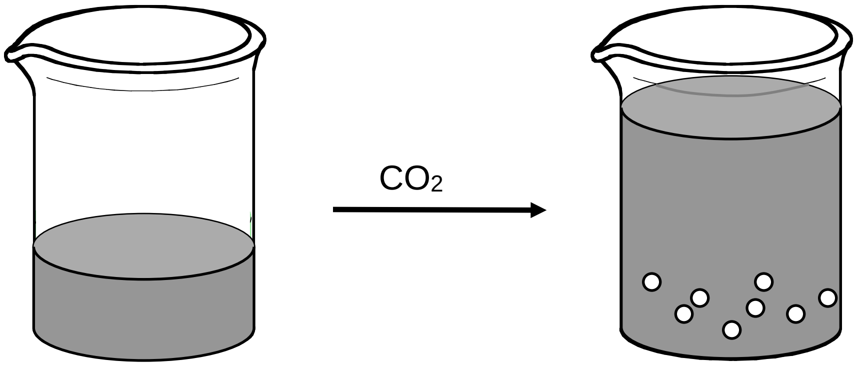
Simon & Graue, J. Petrol. Technol. (1965) 102.



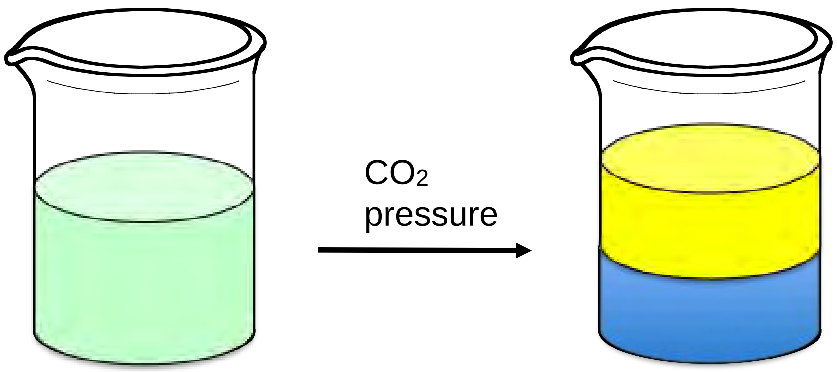


CO_2 CAN TRIGGER *INSOLUBILITY AND IMMISCIBILITY*

Polar solids are precipitated from solution when the solvent is expanded with CO_2



Some miscible liquids become immiscible when expanded with CO_2



Solvent A	Solvent B	P, bar
water	methanol	80
water	1-propanol	68
water	acetic acid	75
water	acetone	26
water	THF	<10
water	1,4-dioxane	<28
water	MeCN	<19

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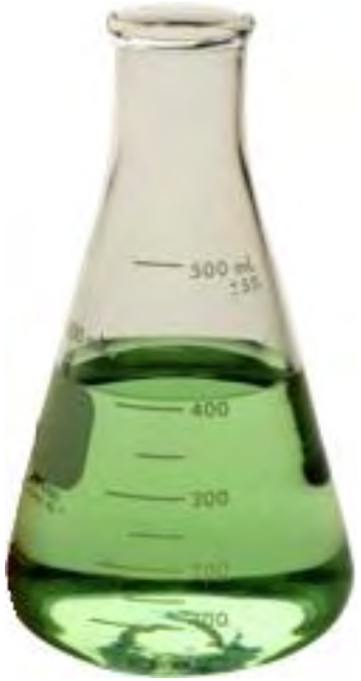
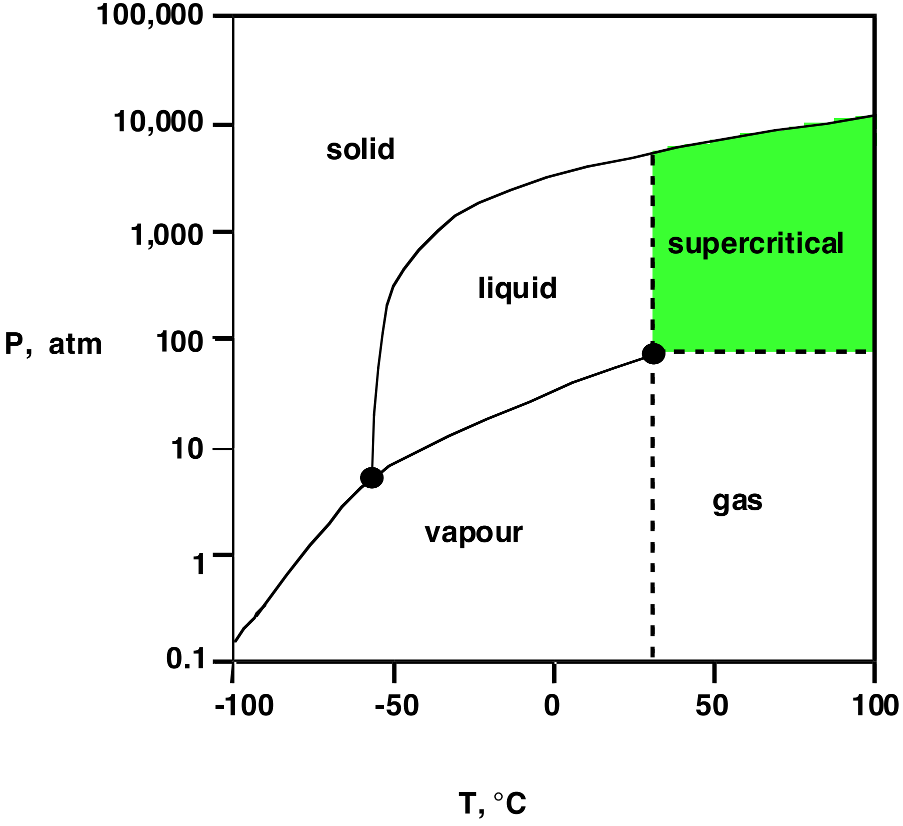
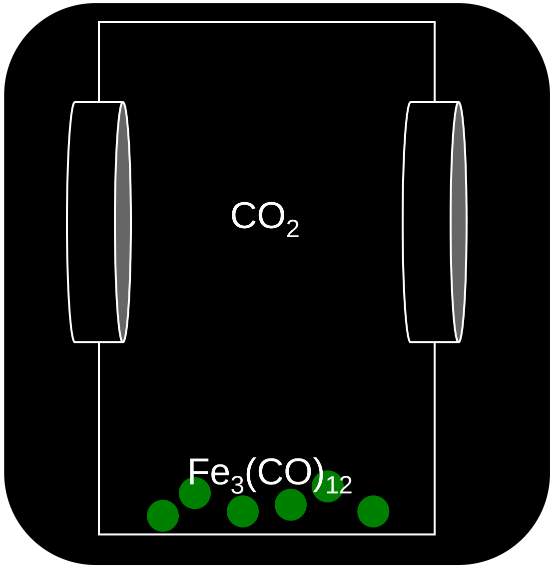


SUPERCRITICAL CO_2





CO_2
$Fe_3(CO)_{12}$

TC 02:10:43:20

CO_2 AS A SOLVENT

Natex CO_2 decaffeination plant

DuPont fluoropolymer plant, N.C

Prep SFC (Novasep)

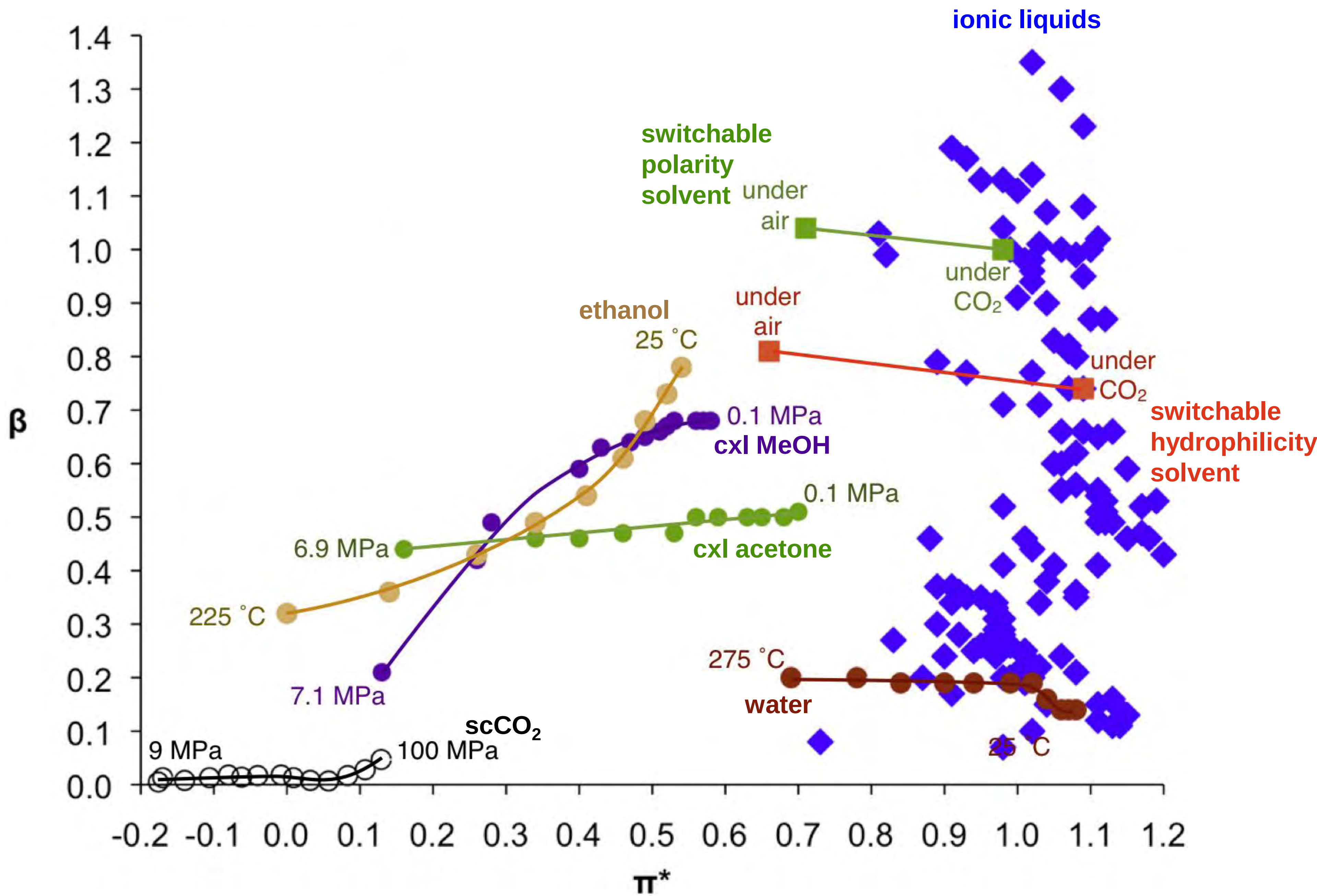
CO_2 dry cleaning

http://www.natex.at/album/index.htm
http://www.metropolitanmachinery.com/sail_star.htm
http://www.pharmaceutical-technology.com/contractors/purification/novasep/novasep3.html

$scCO_2$ AS A SOLVENT

	ADVANTAGES	DISADVANTAGES
Safety	Nonflammable Nontoxic In-situ fire/explosion suppression	Pressure
Economics	Free	Pressure
Environment	Recycled material No smog, ozone contribution Naturally occurring	
Process benefits	Rapid mass transfer High solubility of reagent gases Controllable solubilizing power Easy to separate	Pressure Low solubility of some reagents

OVERVIEW OF UNCONVENTIONAL GREEN SOLVENTS

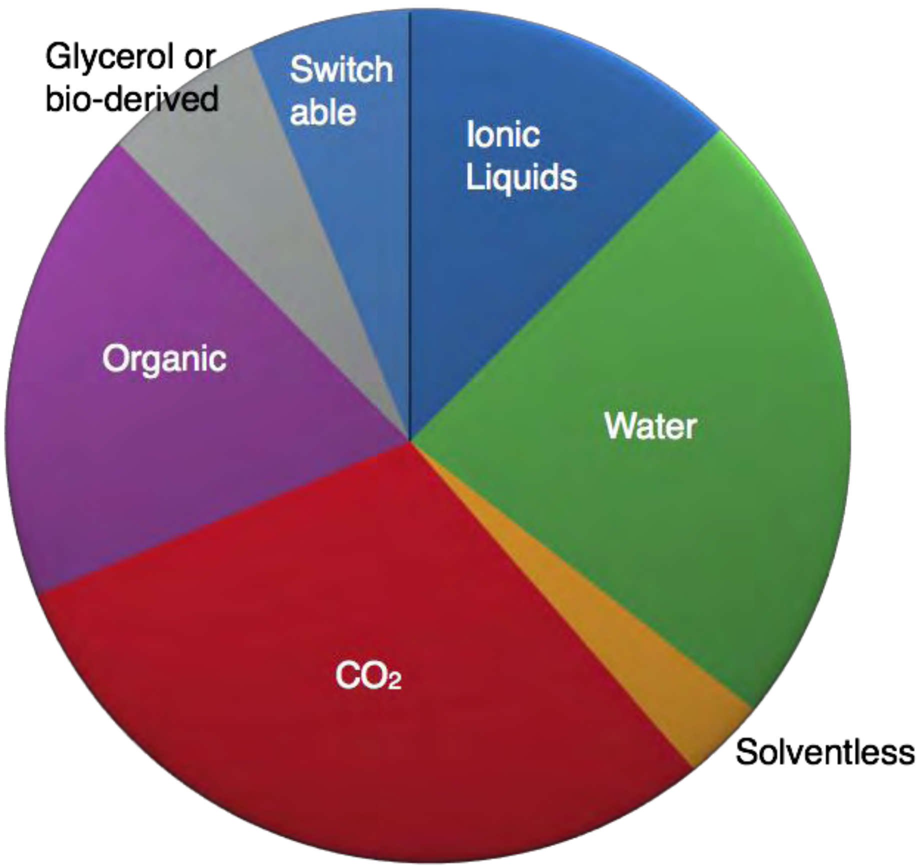


SURVEY

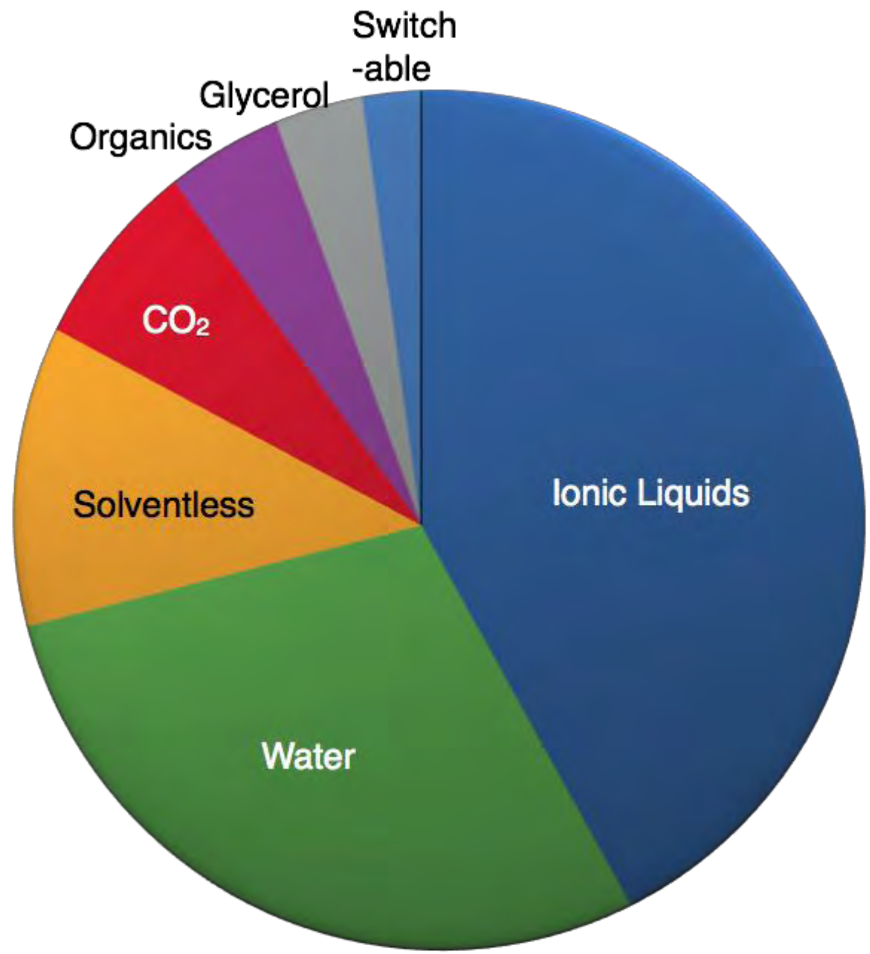
If the adoption of greener solvents over the next 20-30 years will reduce environmental damage from human activities, then the adoption of what class of solvents will be responsible for the greatest reduction in environmental damage?

- *Bioderived solvents (glycerol, 2-methylTHF, valerolactone, etc.)*
- *CO_2 (liquid, supercritical, expanded liquid)*
- *Conventional organic solvents (carefully selected)*
- *Ionic liquids*
- *Switchable solvents*
- *Solvent-free conditions*
- *Water (including liquid, superheated, supercritical, on-water)*

SURVEY

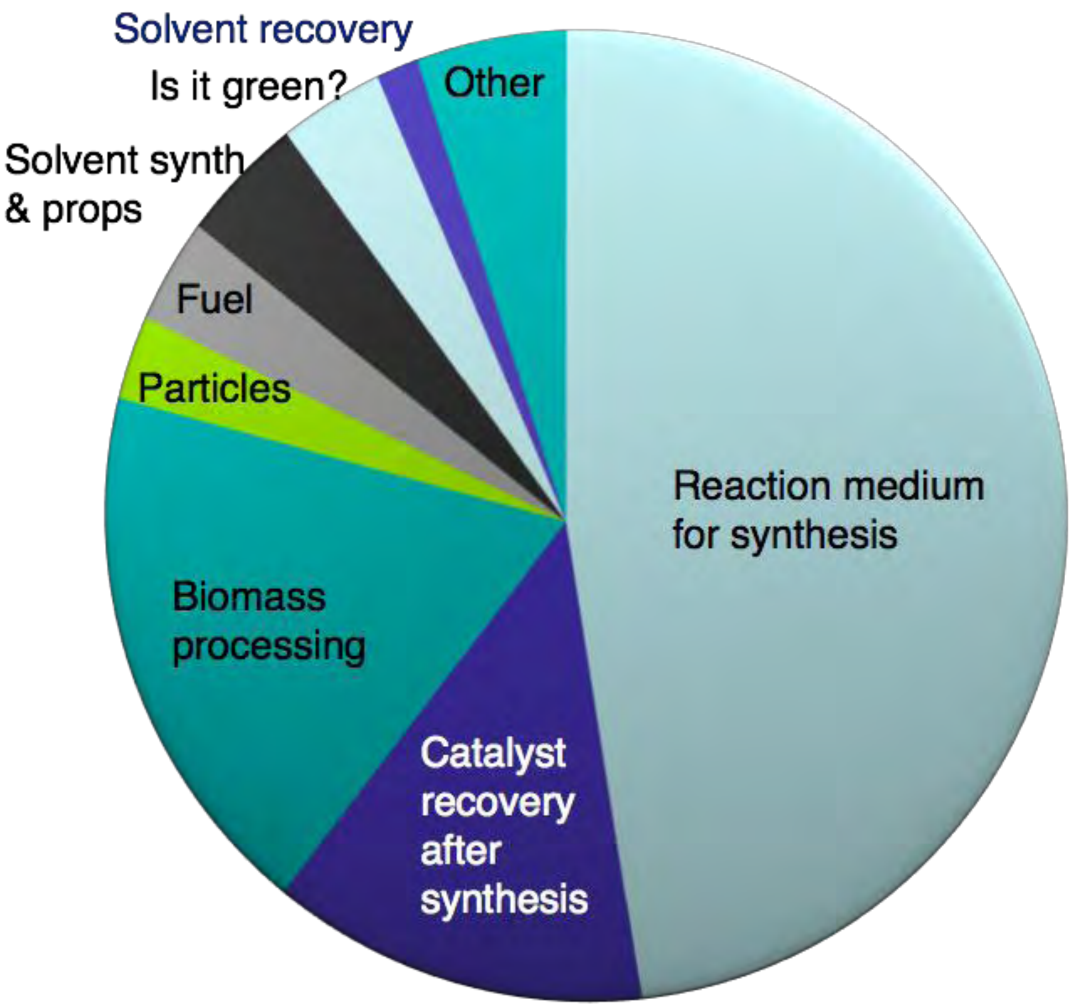


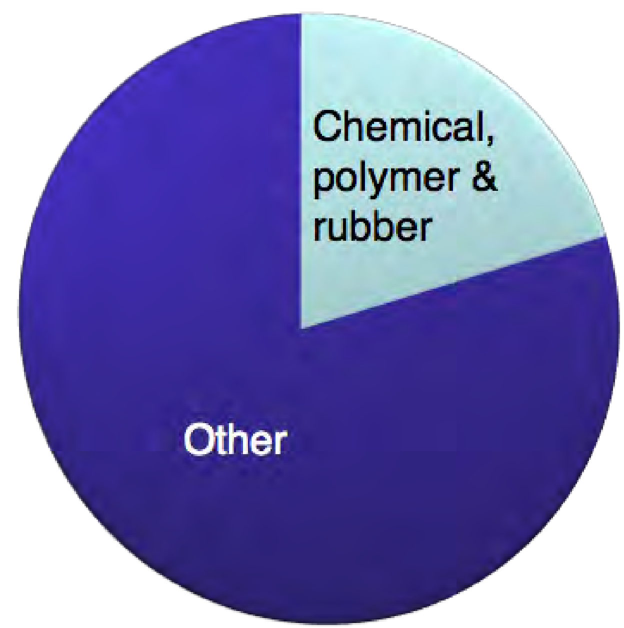
survey results



solvents described in related papers in Green Chemistry in 2010

WHAT DO WE CHOOSE TO STUDY?





Uses of CH_2Cl_2

CONCLUSIONS

No solvent is perfectly green.

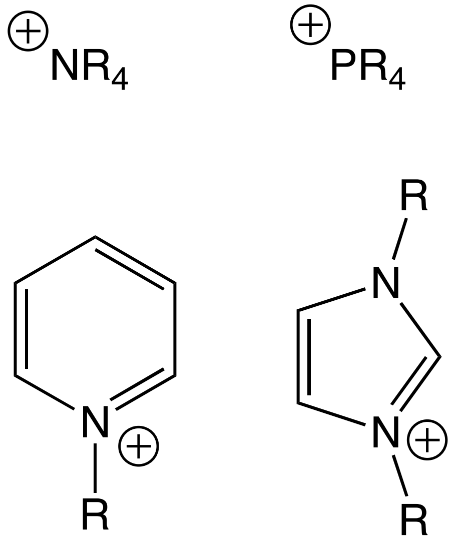
The nonconventional solvents are more exciting, but it’s the conventional ones that are greening the industry.

We’re making progress populating the map with green solvents.

Is it really green? Consider the solvent’s synthesis and its effect on the entire process.

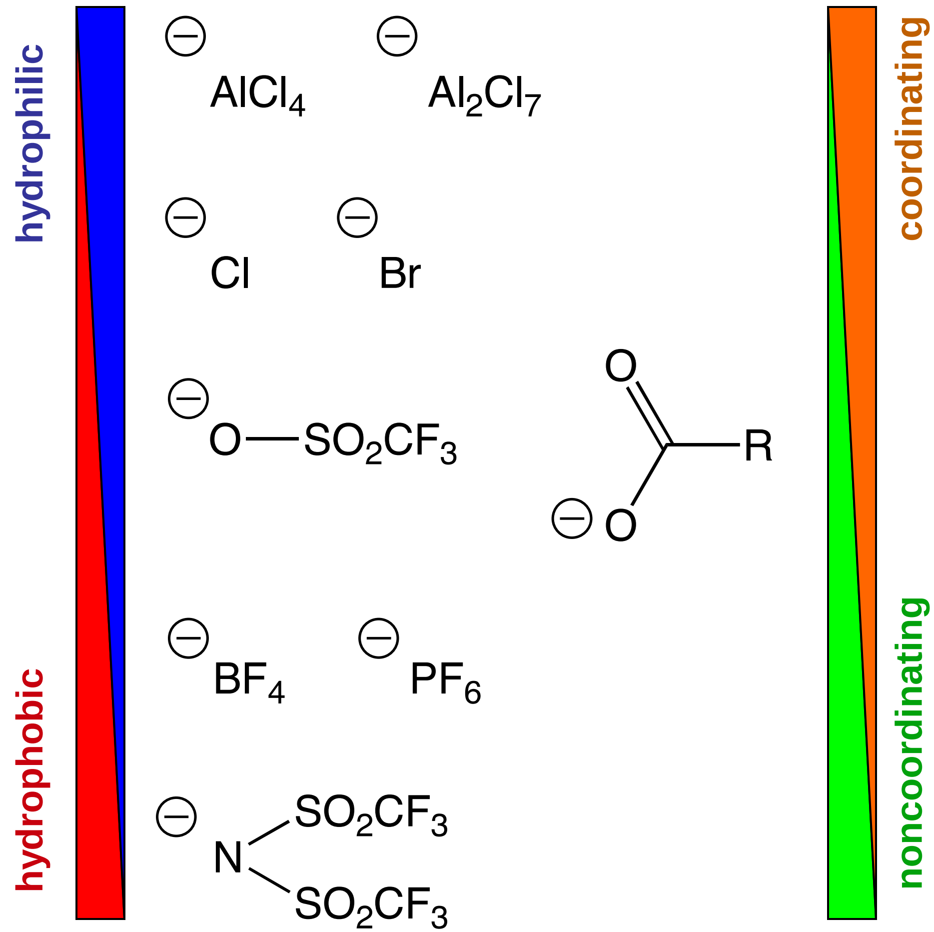
CATIONS AND ANIONS

Cations

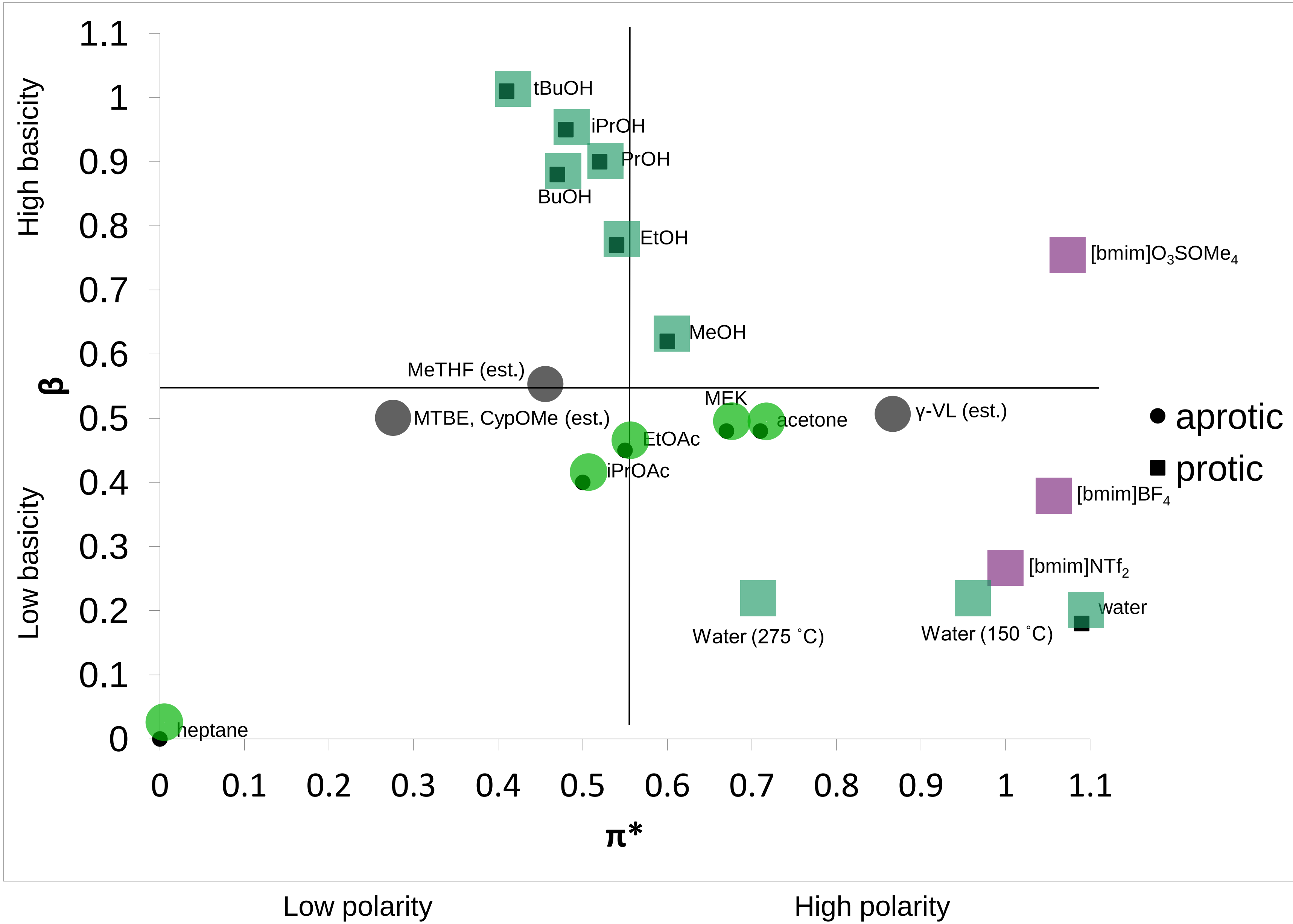


emim
bmim
hmim

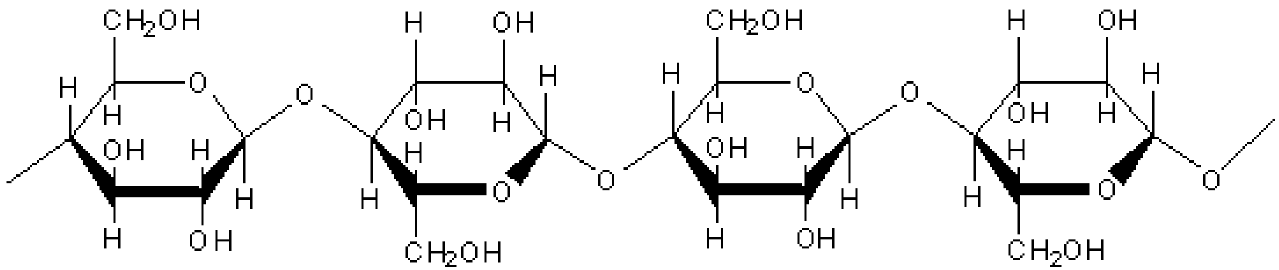
Anions



GREEN SOLVENTS



DISSOLVING CELLULOSE



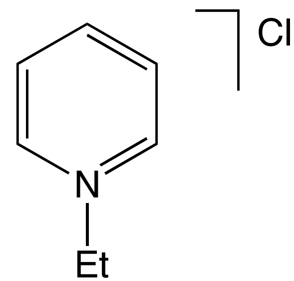
Solvents known to dissolve cellulose:

Strong alkali & CS_2

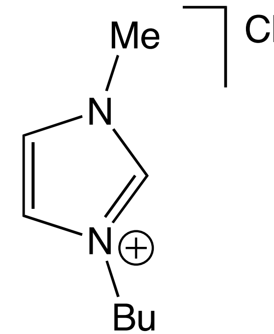
Cellosolve ($EtOCH_2CH_2OH$)

$ZnCl_2$ solution

DMA / LiCl



Graenacher, US Pat. 1943176, 1934



Rogers, JACS (2002) 124, 4974

Uses of IL cellulose solutions
- separation from lignin
- prep of cellulose for conversion to EtOH
- derivatization of cellulose

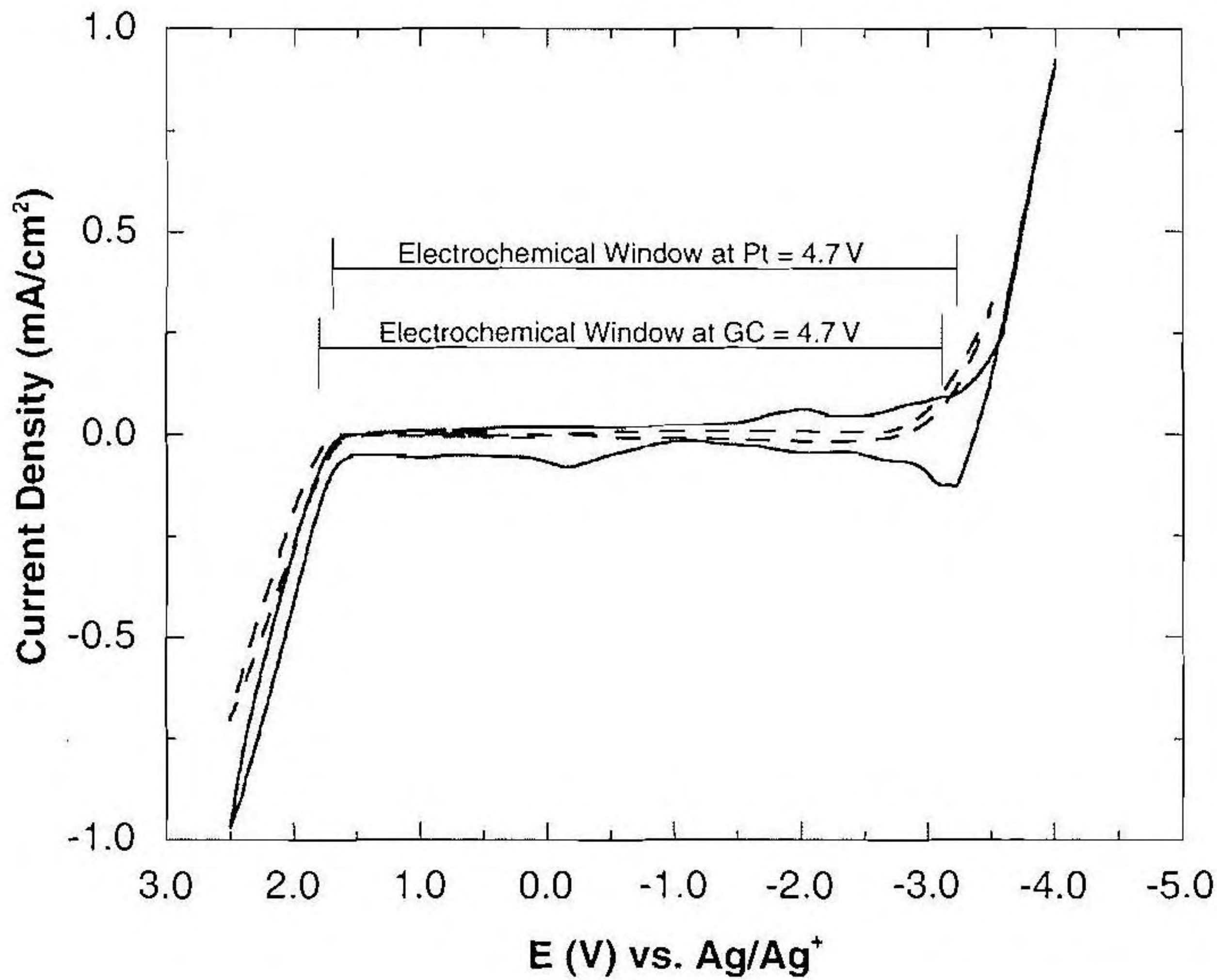
Review: ***Green Chem.***, 2006, 8, (4), 325-327

ELECTROCHEMISTRY AND ELECTRODEPOSITION

$MCl_3 + 3e^-$

↓

$M + 3Cl^-$



Trulove & Mantz, in *Ionic Liquids in Synthesis*