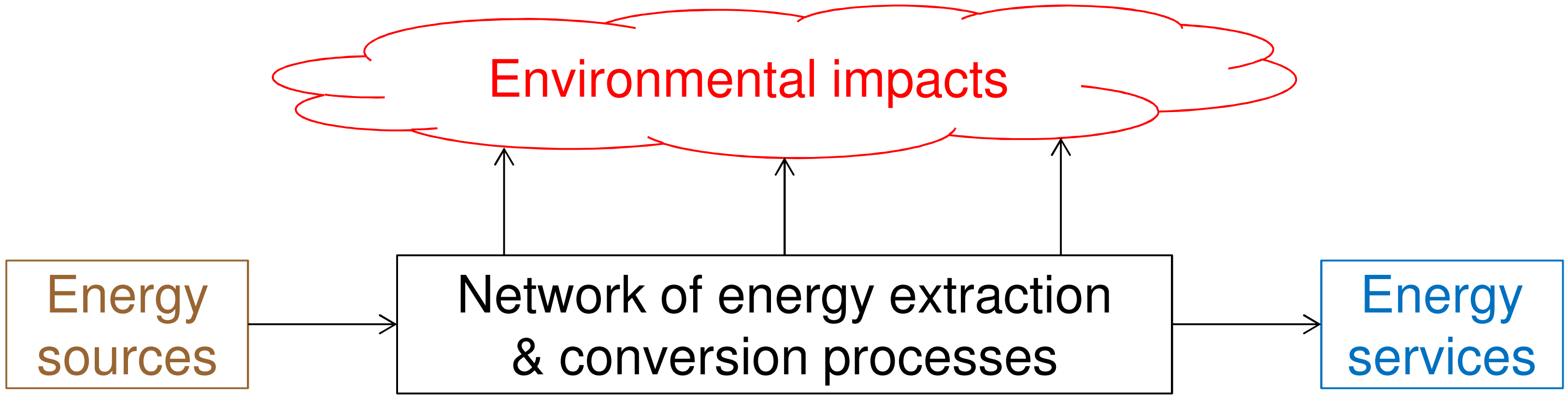
Going all solar: Displacing all fossil fuels with solar energy

Roland Geyer, Associate Professor

Bren School of Environmental Science and Management
University of California,
Santa Barbara, CA 93106, USA

The sustainability of fossil fuels is sink-constrained not source-constrained



We are not running out of reserves, but we cannot afford to use them

Fuel	Unit	Proved reserves				2012 Production	Reserves per production ratio (in years)
		end of 1991	end of 2001	end of 2011	end of 2012		
Oil	10^9 barrels	1033	1267	1654	1669	31.4	53
Gas	10^{12} m3	131	168	188	187	3.4	56
Coal	10^9 tonnes		985	861	861	7.8	109

Source: BP, Statistical Review of World Energy 2013

Combustion would result in an atmospheric CO_2 concentration of 559 ppm_v

Fossil Fuels are major contributors to many environmental impact categories

Pollutants

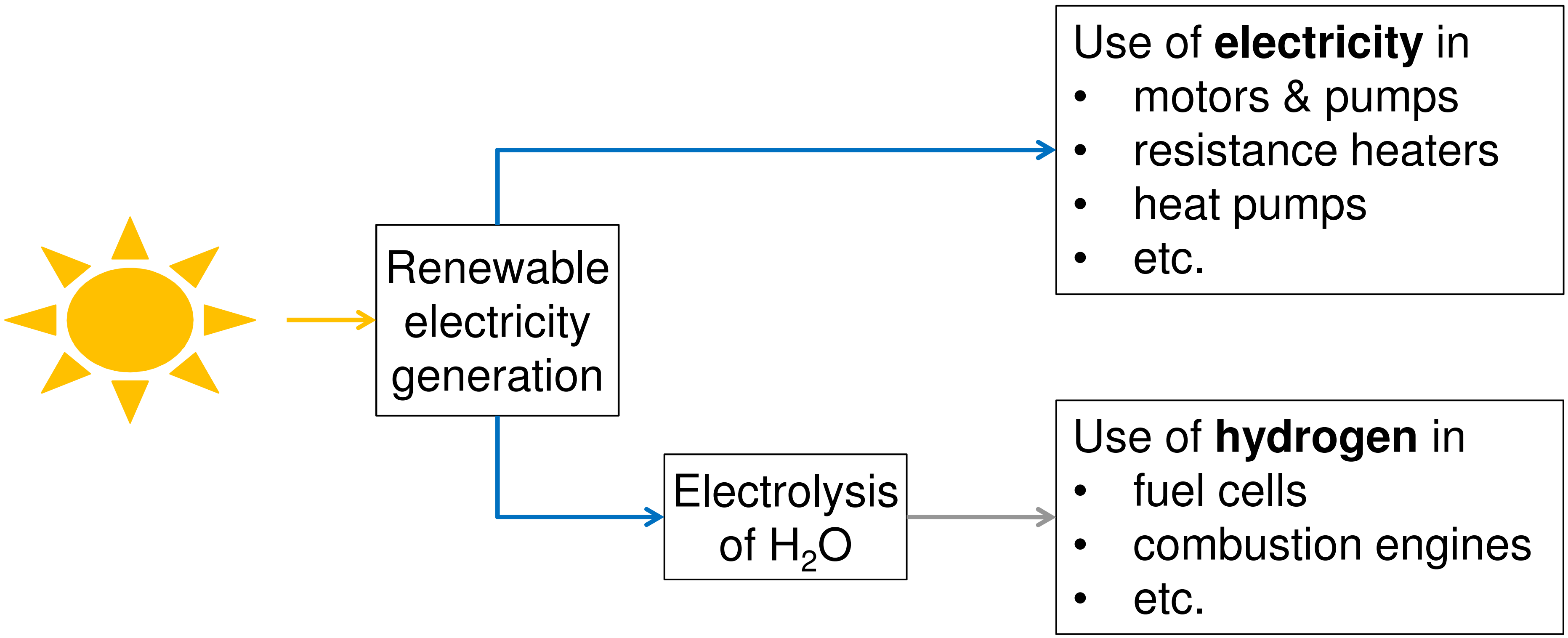
- Carbon Dioxide, CO_2
- Carbon Monoxide, CO, is the product of incomplete combustion
- Sulfur Oxides, SO_x, arise from the combustion of sulfur containing fuels
- Nitrogen Oxides, NO_x, arise when
  a) Nitrogen contained in the fuel is oxidized (fuel NO_x)
  b) Nitrogen contained in the ambient air is oxidized (thermal NO_x)
- Particulate matter, PM, from fossil fuels are soot and fly ash
- Heavy metals
- Methane, CH_4, leakage
- Spills, leaks, fugitive emissions of fuels

Environmental impacts

- Climate change (CO_2, CH_4)
- Acidification (SO_x, NO_x)
- Human toxicity (CO, SO_x, NO_x, PM, heavy metals)
- Ecotoxicity (CO, SO_x, NO_x, PM, heavy metals)
- Photochemical smog (VOC + NO_x + Sunlight = Ozone)
- Ecosystem pollution and disturbance (acid mine drainage, etc.)

Approach: Displace all fossil fuels with solar electricity

2 Solar Energy Pathways:



Displacing fossil fuels in the residential sector of the U.S.

$$1.08 \cdot [0.95 \cdot 0.82 + (1-0.95) \cdot 1.43] = 0.92$$

Residential Sector	Original Fuel in EJ	Electrified fraction	Electrified: electricity to fuel equivalence	Hydrogen: electricity to fuel equivalence	Electricity in EJ	Fraction of original fuel EJ_{el}/EJ_{fuel}
Liquids	1.08	0.95	0.82	1.43	0.92	85%
Natural Gas	4.49	0.95	0.82	1.43	3.84	85%
Coal	0.00	1	0.82	1.43	0.00	
Electricity *)	4.95	1	1.00		4.95	100%
Renewables	0.48	0.5	0.82	1.43	0.54	113%
Total	**10.99**				**10.25**	**93%**

*) electrical, not primary EJ

Source: EIA, Annual Energy Outlook 2014, Jacobson & Delucchi (2011) Energy Policy, 39, 1170-1190

Displacing fossil fuels in the commercial sector of the U.S.

Commercial Sector	Original Fuel in EJ	Electrified fraction	Electrified: electricity to fuel equivalence	Hydrogen: electricity to fuel equivalence	Electricity in EJ	Fraction of original fuel EJ_{el}/EJ_{fuel}
Liquids	0.67	0.9	0.82	1.43	0.59	89%
Natural Gas	3.13	0.9	0.82	1.43	2.77	89%
Coal	0.05	0.9	0.82	1.43	0.04	89%
Electricity	4.77	1	1.00		4.77	100%
Renewables	0.14	0.9	0.82	1.43	0.12	89%
Total	**8.75**				**8.29**	**95%**

*) electrical, not primary EJ

Source: EIA, Annual Energy Outlook 2014, Jacobson & Delucchi (2011) Energy Policy, 39, 1170-1190

Displacing fossil fuels in the industrial sector of the U.S.

Industrial Sector	Original Fuel in EJ	Electrified fraction	Electrified: electricity to fuel equivalence	Hydrogen: electricity to fuel equivalence	Upstream factor	Electricity in EJ	Fraction of original fuel EJ_{el}/EJ_{fuel}
Liquids	8.50	0.6	0.82	1.43	0.72	6.53	77%
Natural Gas	9.23	0.6	0.82	1.43	0.82	8.07	87%
Coal	1.57	0.6	0.82	1.43	0.73	1.22	78%
Electricity	3.53	1	1.00		0.93	3.28	93%
Renewables	2.11	0.9	0.82	1.43	1	1.87	89%
Total	**24.93**					**20.96**	**84%**

*) electrical, not primary EJ

Source: EIA, Annual Energy Outlook 2014, Jacobson & Delucchi (2011) Energy Policy, 39, 1170-1190

Displacing fossil fuels in the transportation sector of the U.S.

Transportation Sector	Original Fuel in EJ	Electrified fraction	Electrified: electricity to fuel equivalence	Hydrogen: electricity to fuel equivalence	Upstream factor	Electricity in EJ	Fraction of original fuel EJ_{el}/EJ_{fuel}
Liquids	27.35	0.73	0.19	0.64	1.18	10.06	37%
Natural Gas	0.82	0.9	0.82	1.43	1	0.72	89%
Coal	0.00	0.9	0.82	1.43	1	0.00	
Electricity	0.02	1	1.00		1	0.02	100%
Renewables	0.00						
Total	**28.19**					**10.81**	

*) electrical, not primary EJ

Source: EIA, Annual Energy Outlook 2014, Jacobson & Delucchi (2011) Energy Policy, 39, 1170-1190

Displacing all fossil fuels in all U.S. sectors

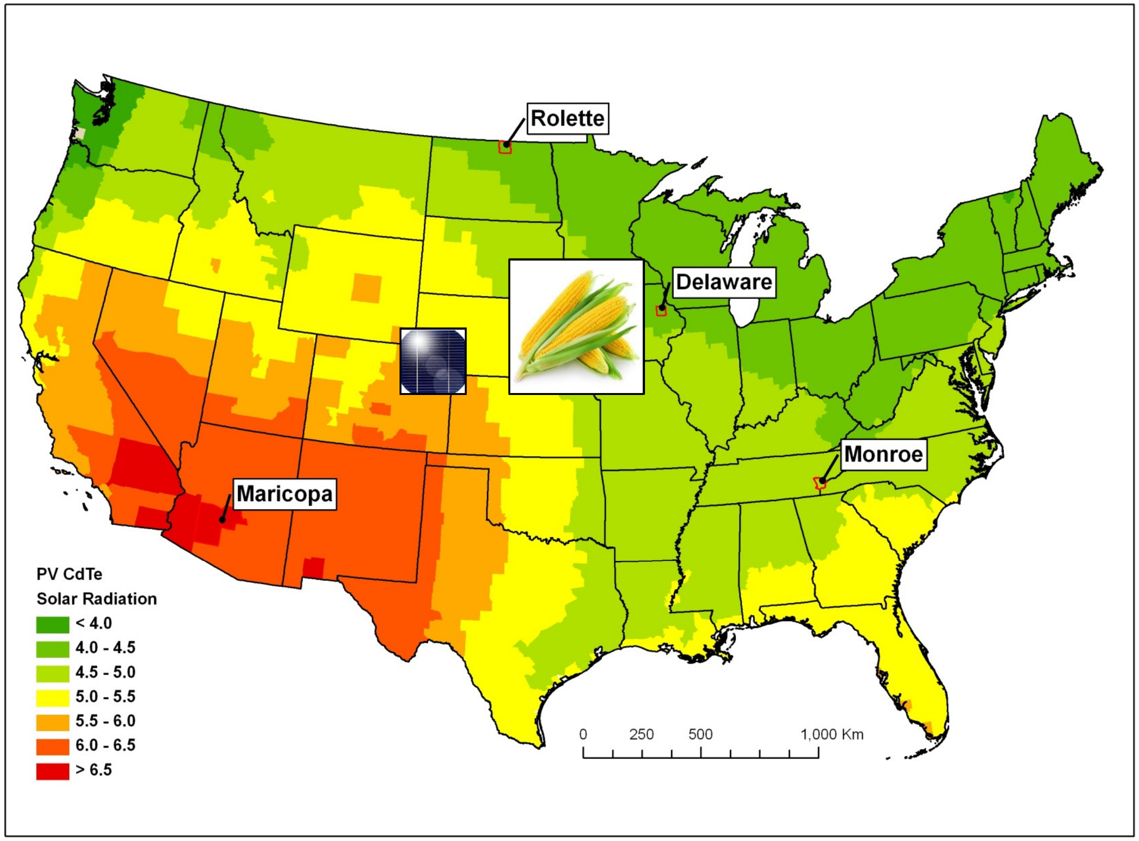
Total U.S. Energy Consumption in 2012	Original Fuel in EJ	Equivalent Electricity in EJ
Liquids	37.60	18.10
Natural Gas	17.66	15.40
Coal	1.61	1.26
Electricity	13.27	13.02
Renewables	2.72	2.53
Total	**72.87**	**50.31**

Could be much lower, since it does not include energy efficiency measures. Dave Auston will talk about that.

How much land is required for 50 EJ of PV electricity per year?

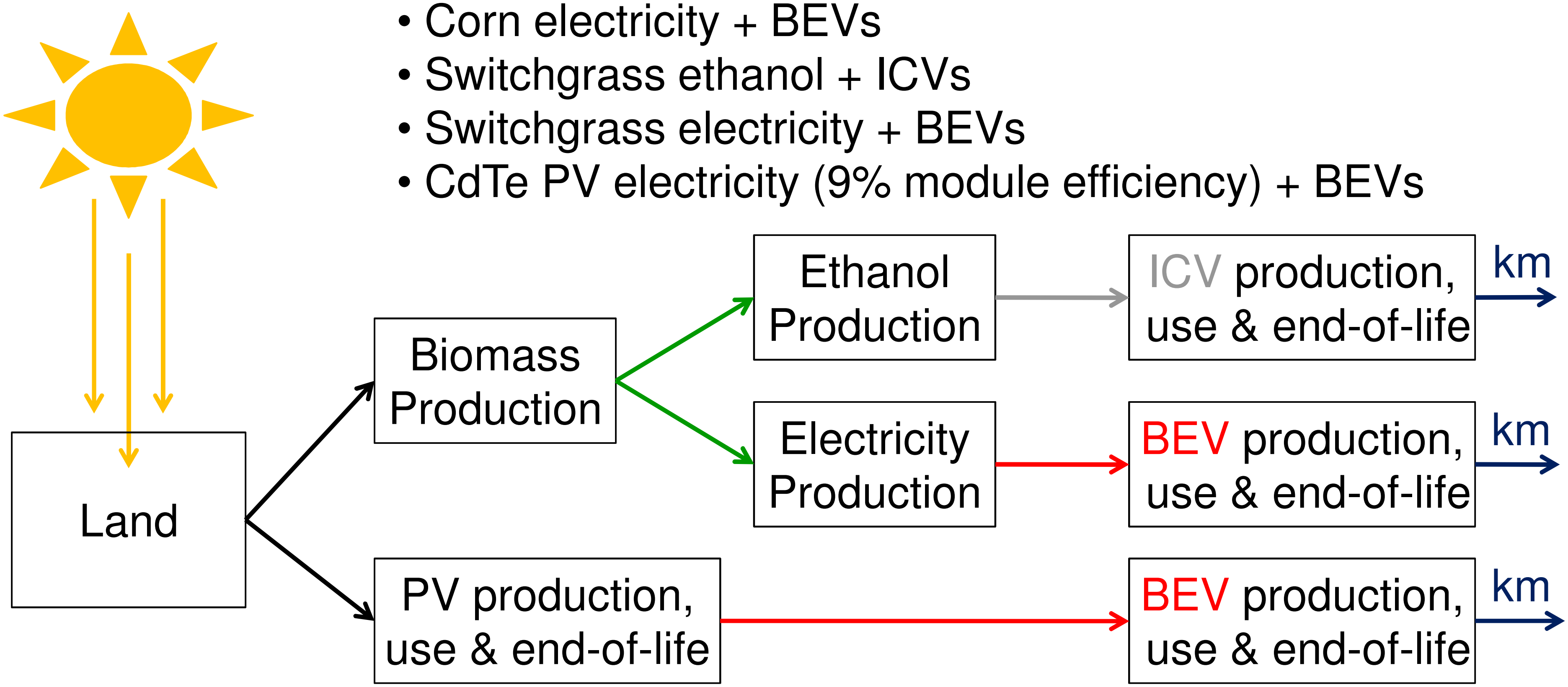
Inputs:
5.055 kWh/m^{2}day avg. U.S. solar insolation
15%   PV module conversion efficiency
0.684 avg. lifetime performance ratio

Results:
7.3 million hectares
>1% of land area of the contiguous U.S.
23% of harvested corn fields (2005-2009 avg.)



Case Study: 5 Sun-to-Wheels Transportation Pathways

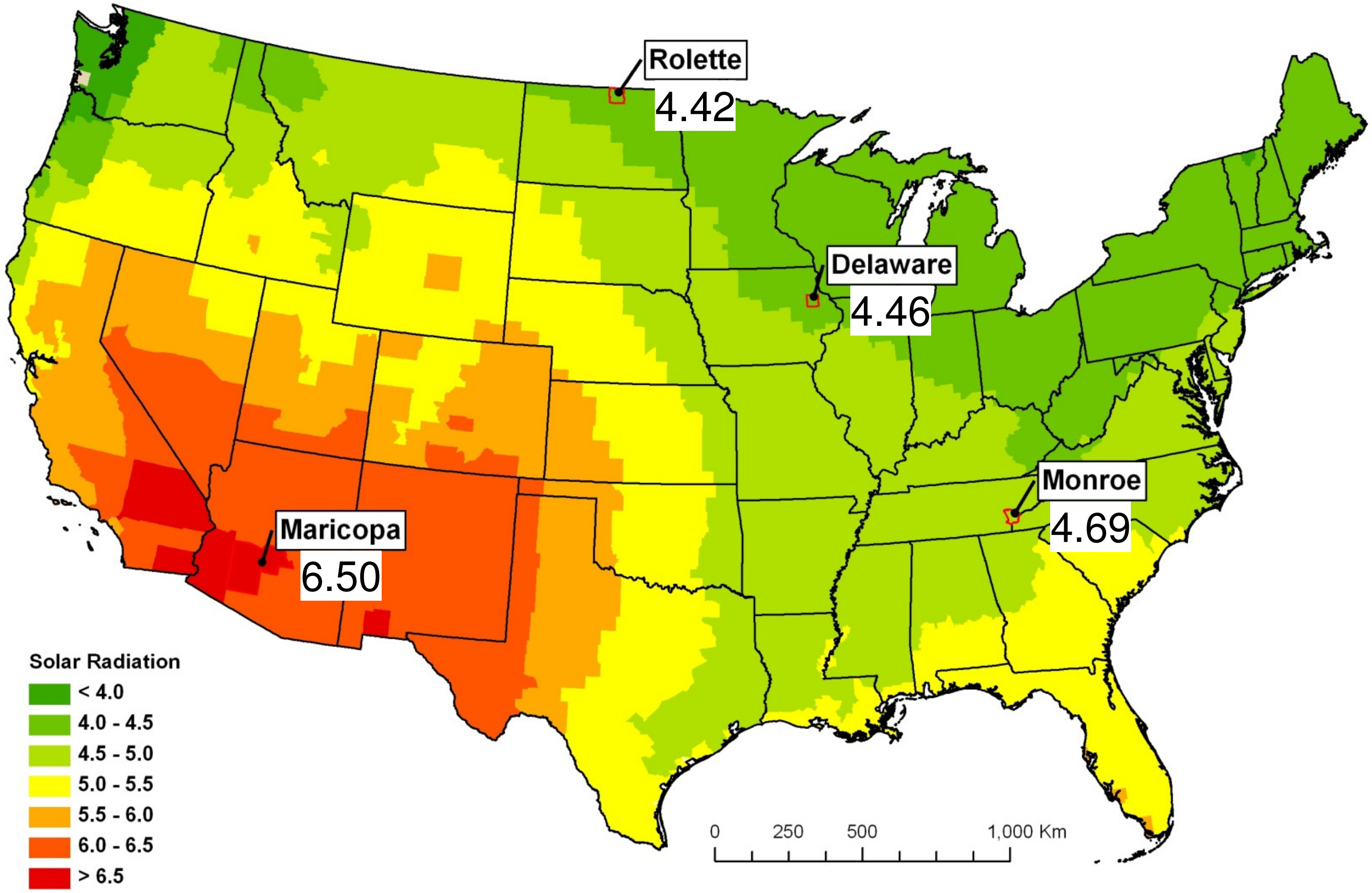
- Corn ethanol + ICVs
- Corn electricity + BEVs
- Switchgrass ethanol + ICVs
- Switchgrass electricity + BEVs
- CdTe PV electricity (9% module efficiency) + BEVs



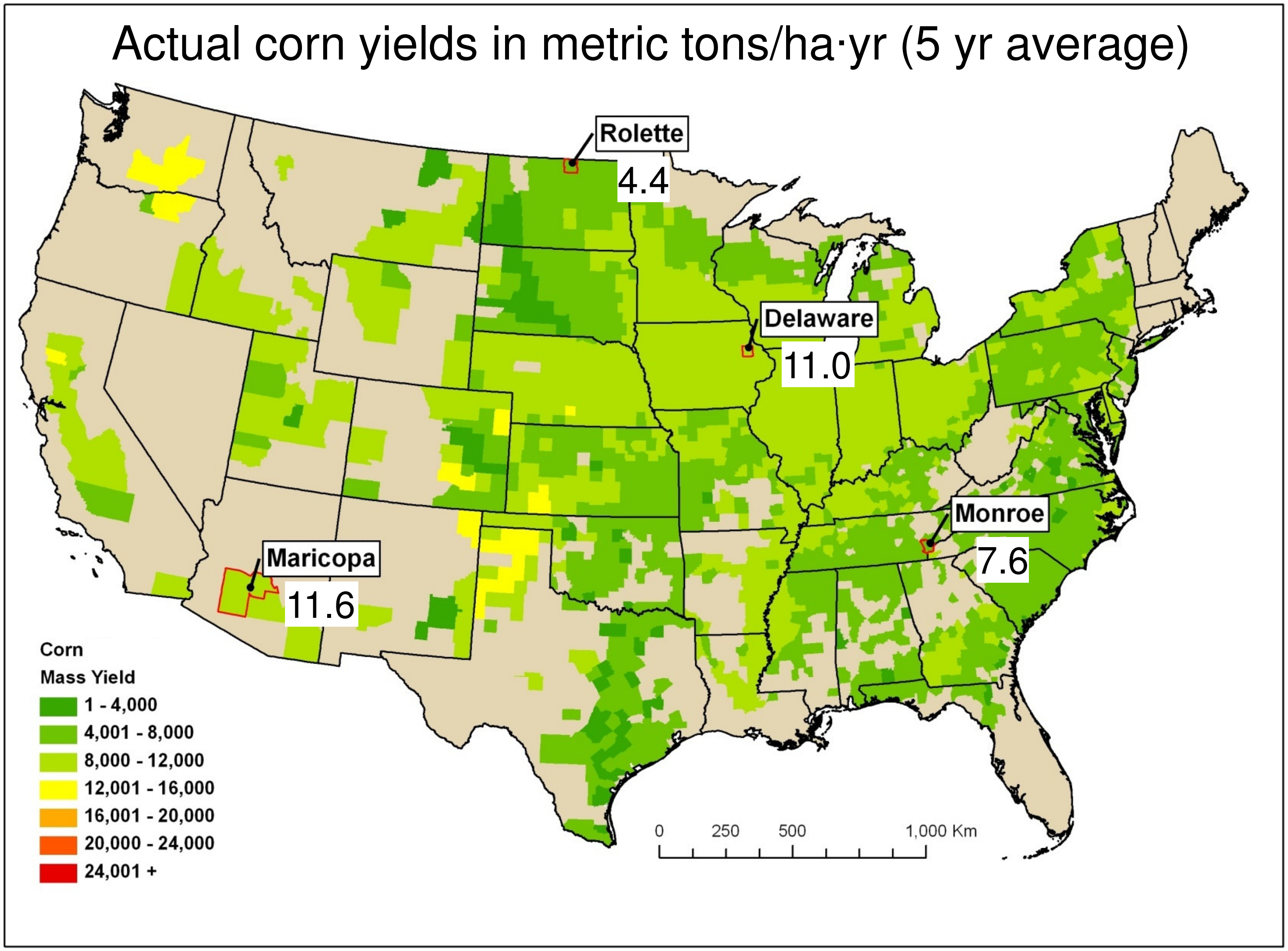
Geyer, Stoms, Kallaos (2013)
Environmental Science and Technology, 47(2), 1170-1176
NSF CBET-0932369

CdTe: Cadmium telluride
ICV: Internal combustion vehicle
BEV: Battery electric vehicle

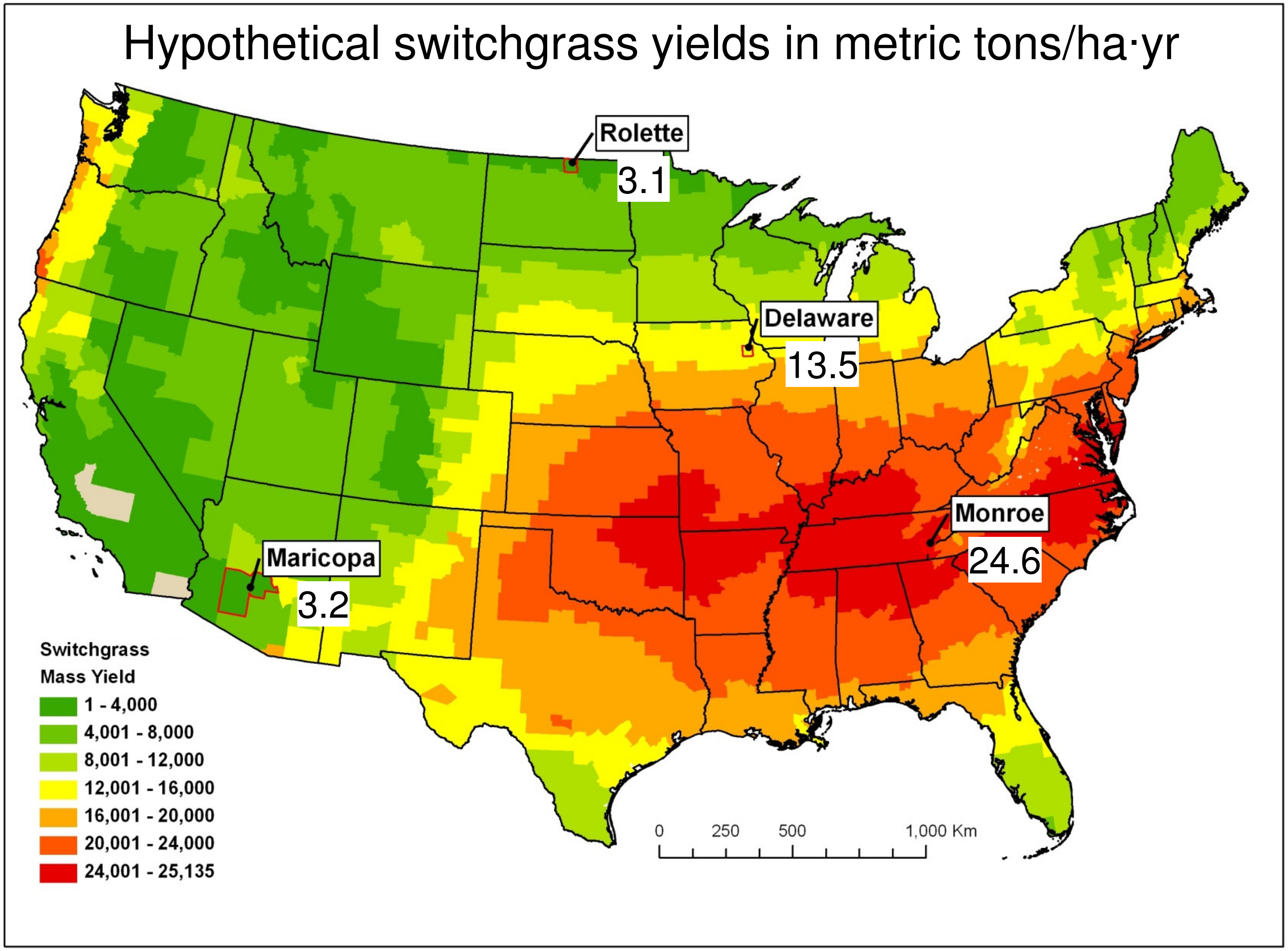
Ground-level solar radiation in kWh/m^2·day



Source: NREL

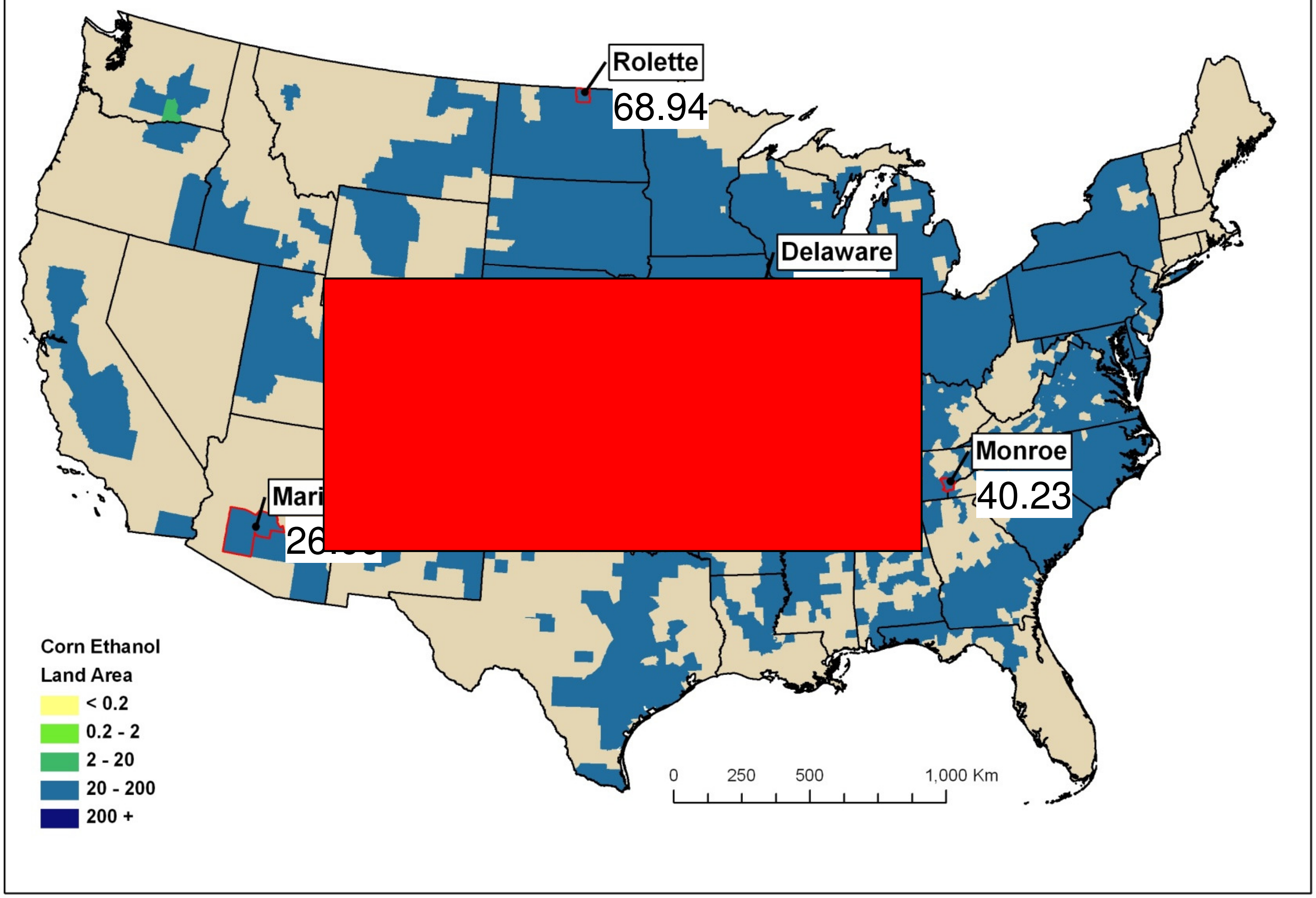


Source: USDA NASS


Hypothetical switchgrass yields in metric tons/ha·yr
Rolette
3.1
Delaware
13.5
Monroe
24.6
Maricopa
3.2
Switchgrass
Mass Yield
1 - 4,000
4,001 - 8,000
8,001 - 12,000
12,001 - 16,000
16,001 - 20,000
20,001 - 24,000
24,001 - 25,135
0
250
500
1,000 Km

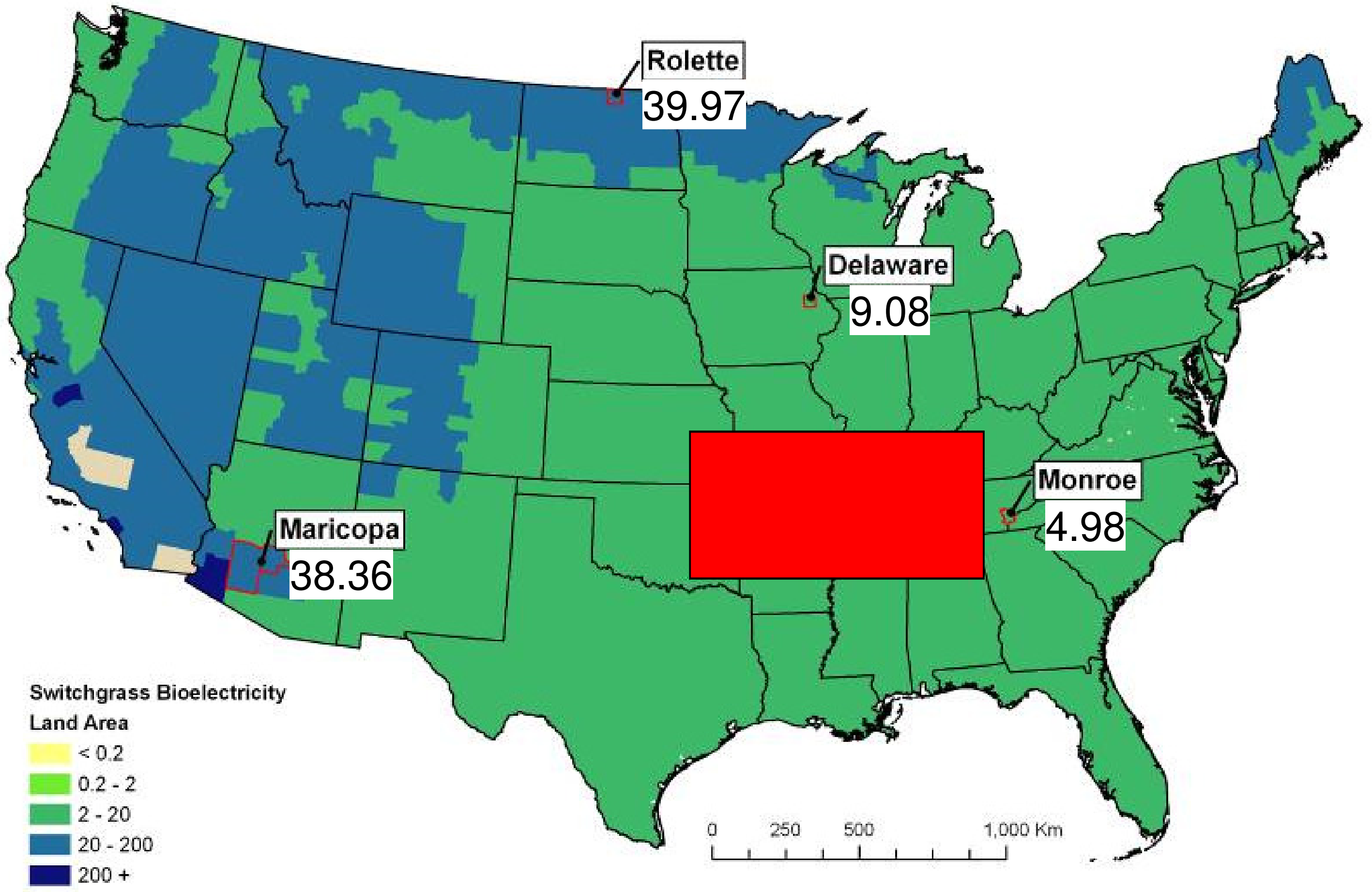
Source: ORNL

Direct land use for corn ethanol in m^2/100km

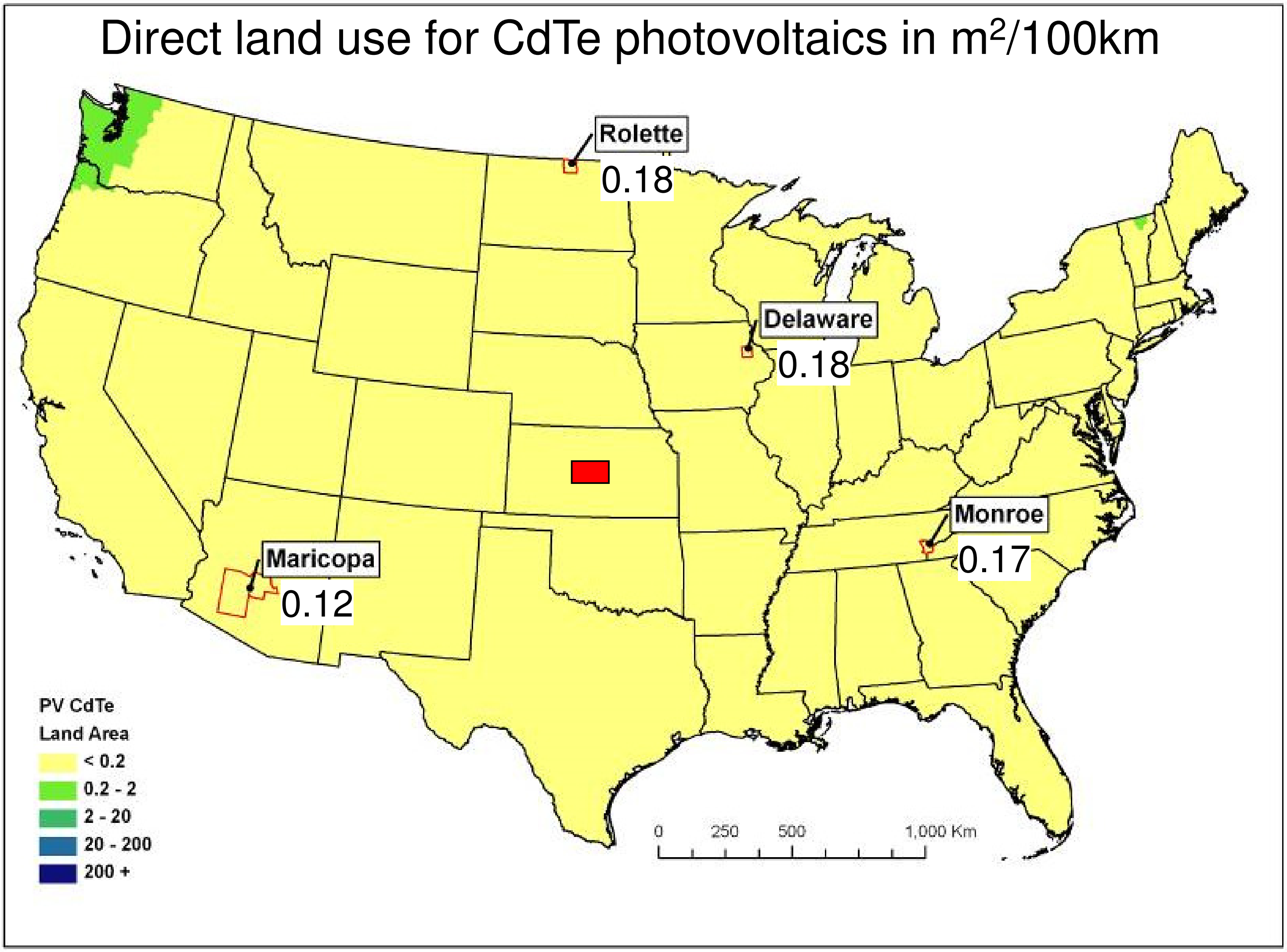


Displacing all gasoline used in transportation in the U.S. in 2009 (18EJ), would require $220 \cdot 10^6$ ha of land (using the average U.S. corn yield of 9,616 kg/ha·yr).

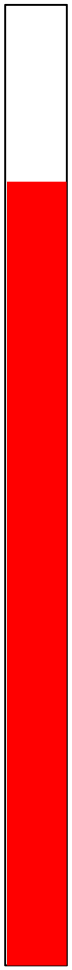
Direct land use for switchgrass bioelectricity in $m^2/100km$



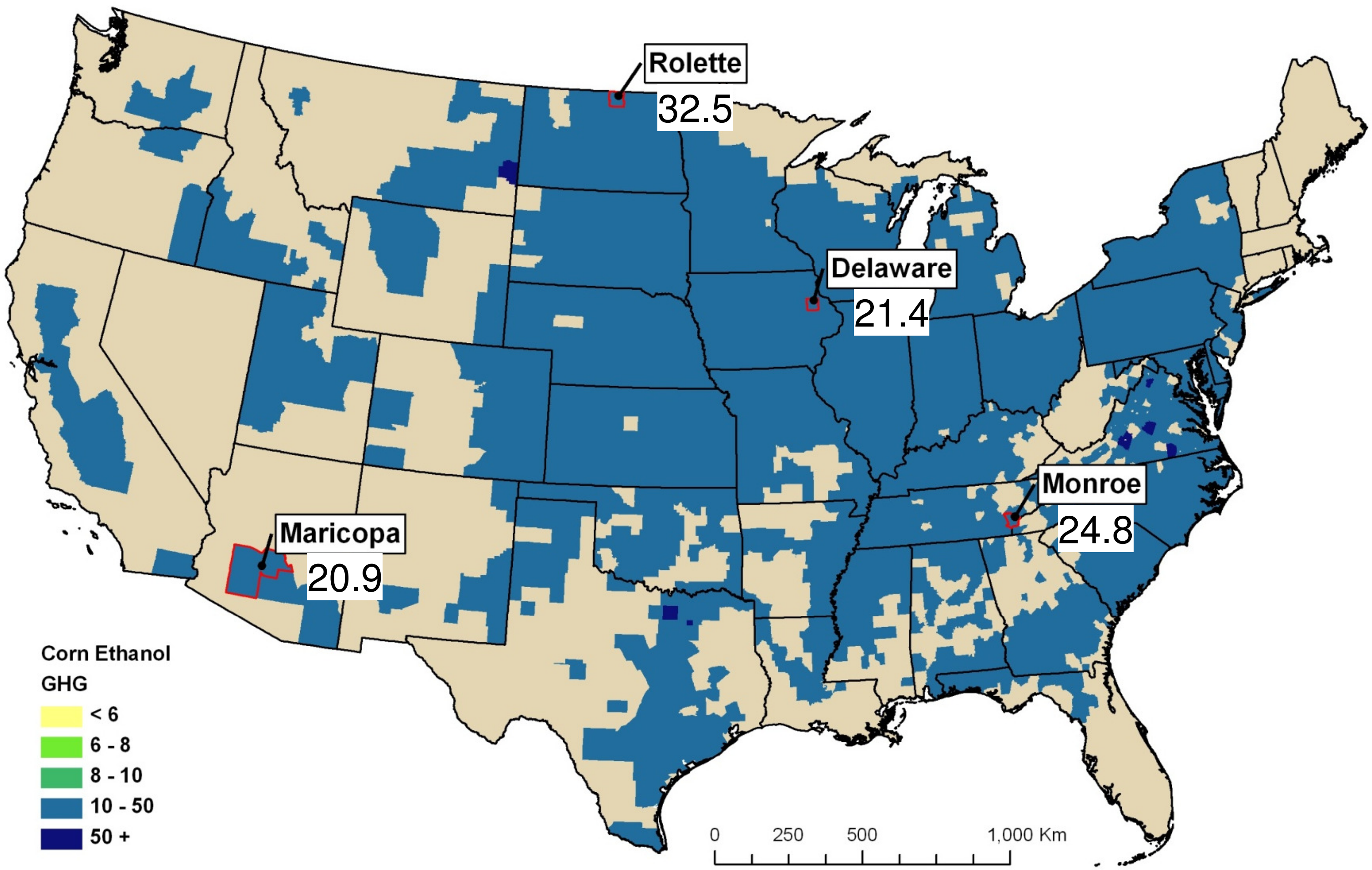
Displacing all U.S. transportation gasoline used in 2009 (18 EJ), would require $48 \cdot 10^6$ ha of land (using a hypothetical switchgrass yield of 17,757 kg/ha·yr).



Displacing all gasoline used in transportation in the U.S. in 2009 (18 EJ), would require $1.1 \cdot 10^6$ ha of land (using an average insolation of 5.055 $KWh/m^2 \cdot day$).

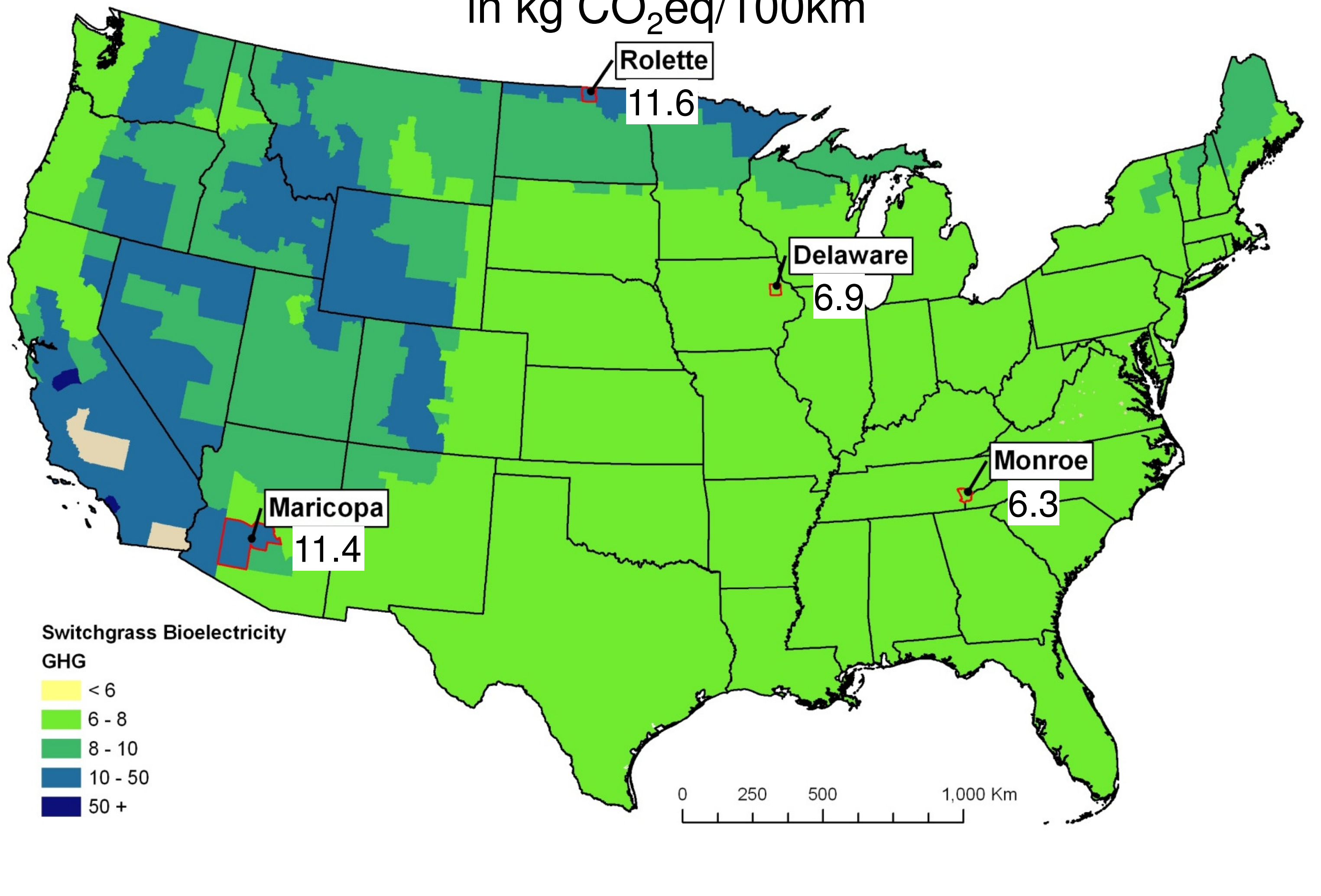


GHG emissions of corn ethanol and ICVs in kg CO_2eq/100km

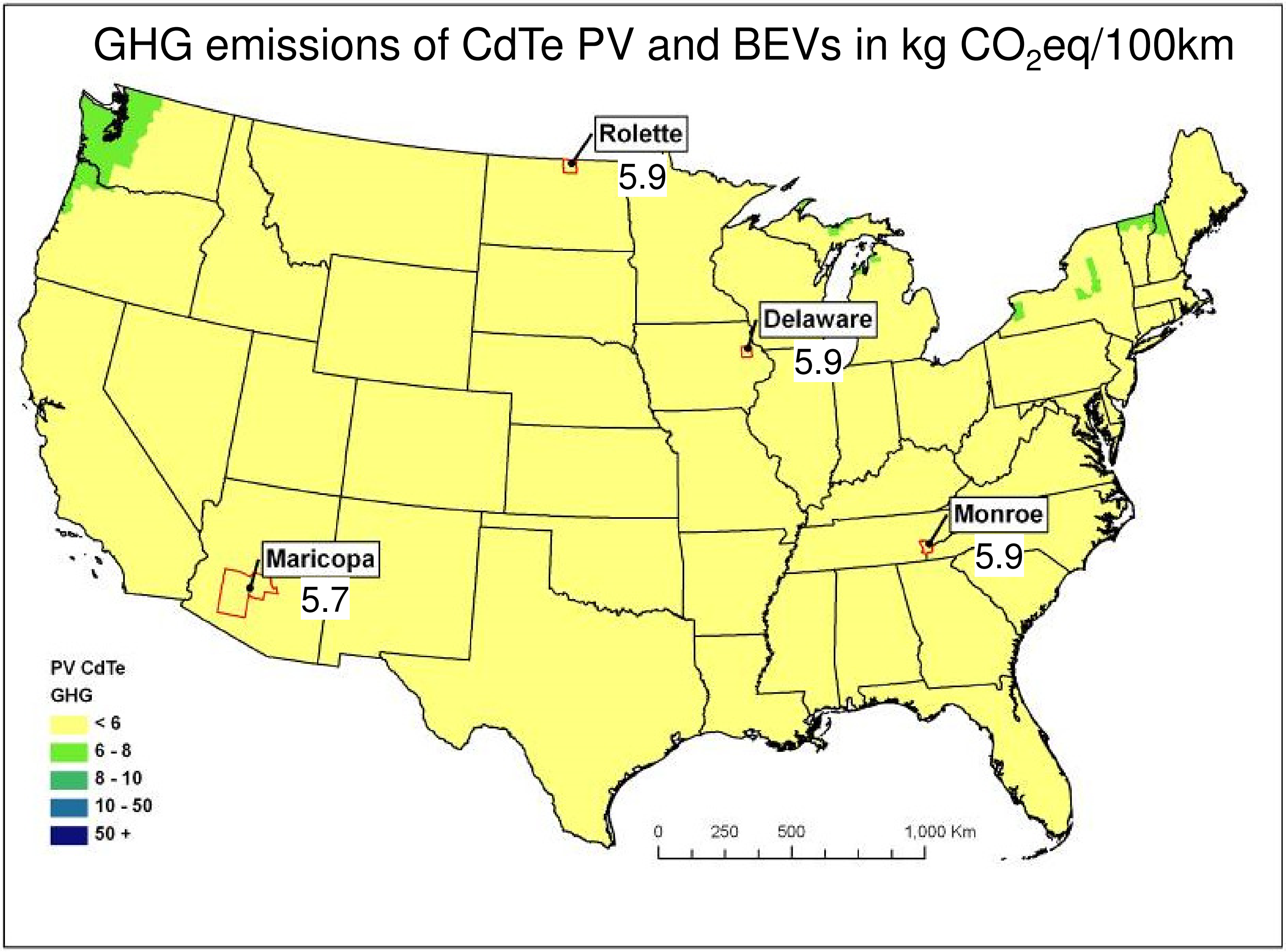


Displacing all gasoline used in U.S. transportation in 2009, would reduce direct GHG emissions by 18.5% (average U.S. corn yield of 9,616 kg/ha·yr).

GHG emissions of switchgrass electricity and BEVs in kg CO_2eq/100km

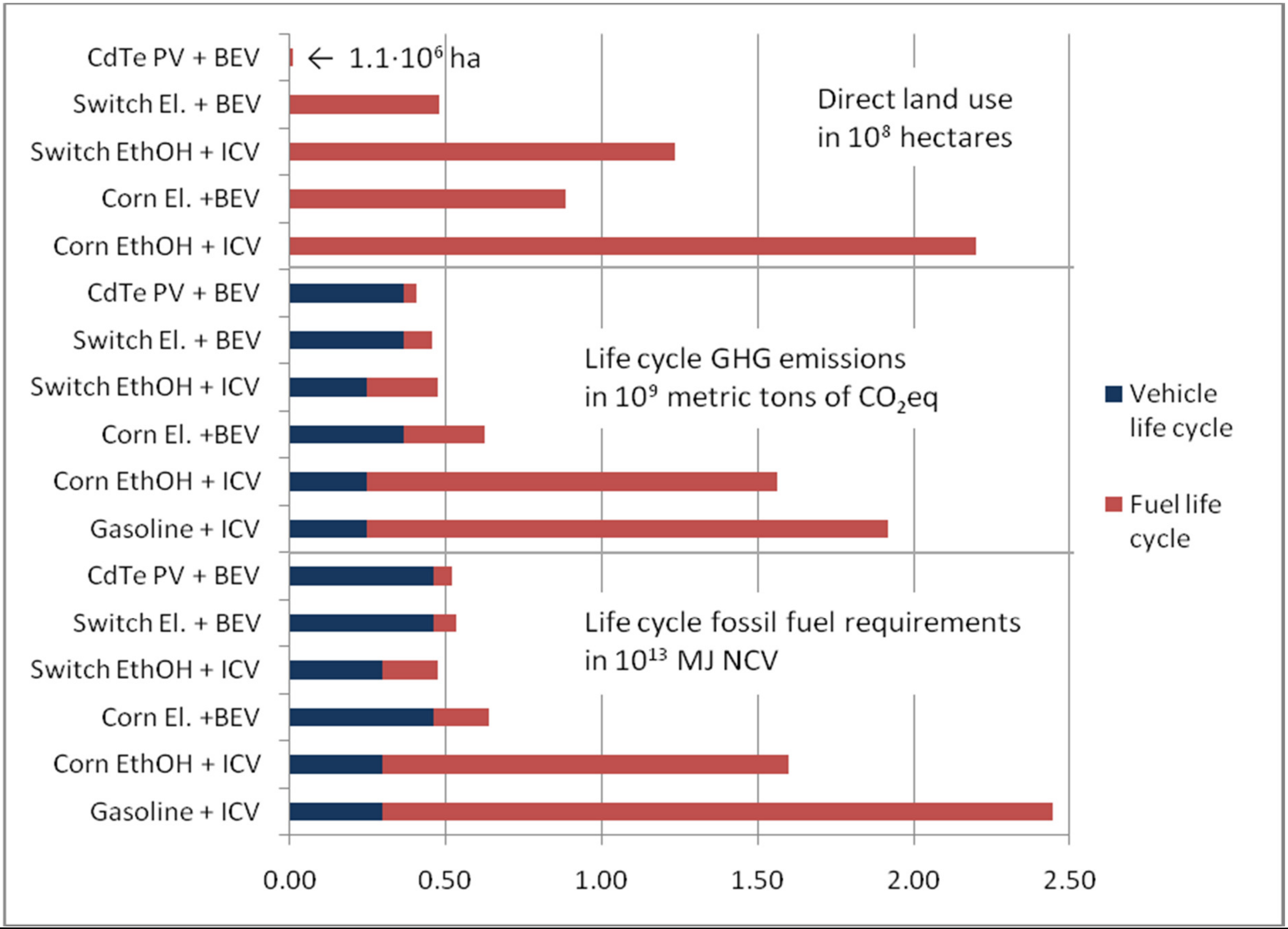


Displacing all gasoline used in U.S. transportation in 2009, would reduce direct GHG emissions by 76% (hypothetical switchgrass yield of 17,757 kg/ha·yr).



Displacing all gasoline used in U.S. transportation in 2009, would reduce GHG emissions by 79% (using an average insolation of 5.055 KWh/m2·day).

Summary


CdTe PV + BEV
Switch El. + BEV
Switch EthOH + ICV
Corn El. +BEV
Corn EthOH + ICV
← 1.1·10⁶ ha
Direct land use
in 10⁸ hectares
CdTe PV + BEV
Switch El. + BEV
Switch EthOH + ICV
Corn El. +BEV
Corn EthOH + ICV
Gasoline + ICV
Life cycle GHG emissions
in 10⁹ metric tons of CO₂eq
CdTe PV + BEV
Switch El. + BEV
Switch EthOH + ICV
Corn El. +BEV
Corn EthOH + ICV
Gasoline + ICV
Life cycle fossil fuel requirements
in 10¹³ MJ NCV
0.00
0.50
1.00
1.50
2.00
2.50
Vehicle life cycle
Fuel life cycle

What's the problem with biofuels?

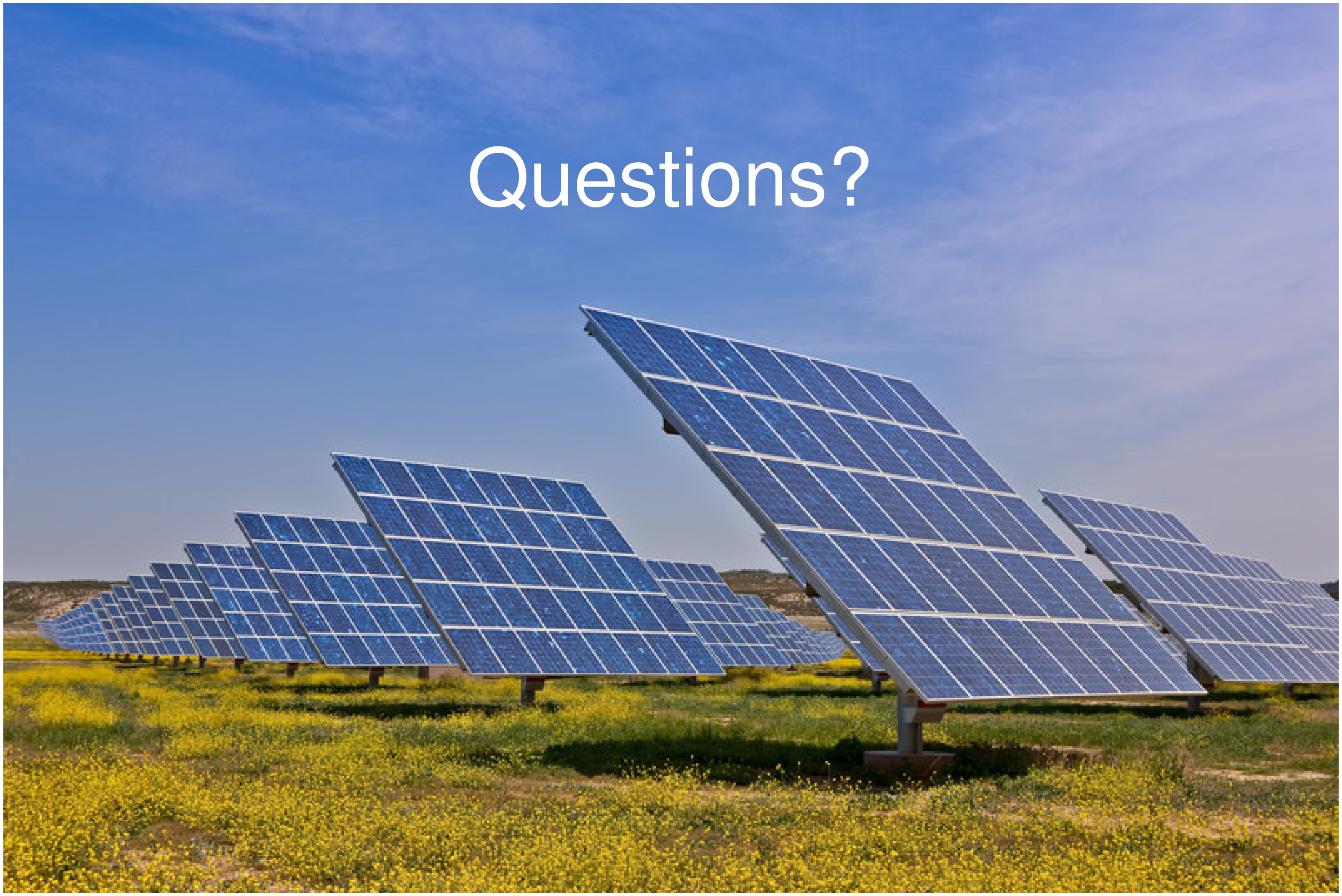
- ~ 20% of solar radiation is hitting the leaves
- ~ 12% of this radiation is absorbed by the leaves
- ~ 60% of this is used for biomass production and ~ 40% for respiration

- 8 photons of ~1.8 eV are required to fix one carbon storing ~4.8eV (4.8/14.4 = ~33%)

Resulting overall sun-to-biomass conversion efficiency:

$$0.2 \cdot 0.12 \cdot 0.6 \cdot 0.33 \approx 0.5$$

Source: Andrews & Jelley (2007) Energy Science, Oxford University Press


Questions?