AAPT PHYSICS EDUCATION® 2020 VIRTUAL SUMMER MEETING July 19-22

The Physics of Green Energy

Wolfgang Bauer

MSU

MICHIGAN STATE UNIVERSITY

Contents

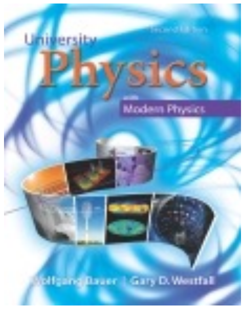
- What we need to teach
  - Global Warming
  - Renewable Energy Resources
- What we can study
  - Improving solar, wind, geothermal, biomass
  - Enhancing energy efficiency
- What we should do
  - Example Michigan State University
    Energy Transition Plan

Humans who are alive today have added more greenhouse gases to the atmosphere than all humans who have ever lived before us in the entire history of mankind.

A History of CO_2

- Human activity measurably increased CO_2 in the atmosphere since the beginning of the industrial age, ~1750
- CO_2 concentration in atmosphere measured in air samples since 1867
  - Thorpe, T. E. (1867). On the Amount of Carbonic Acid Contained in Sea-Air, *J. Chem. Soc.* 20, pp. 189-199.
- Worries that increase in CO_2 may cause global warming since 1896
  - Arrhenius, S. (1896). On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, *Philosophical Magazine* 41 (251), pp. 237-276.

Atmospheric CO_2



- Concentration between 190 ppm and 290 ppm during the last half million years (ice core samples)
- Near exponential rise from burning fossil fuels since the beginning of the industrial revolution (hockey stick graph)
- 6-7 ppm seasonal oscillations from plant growth and decay (Mauna Loa, 'Keeling curve')
- Net addition of ~2 ppm/year from human activity

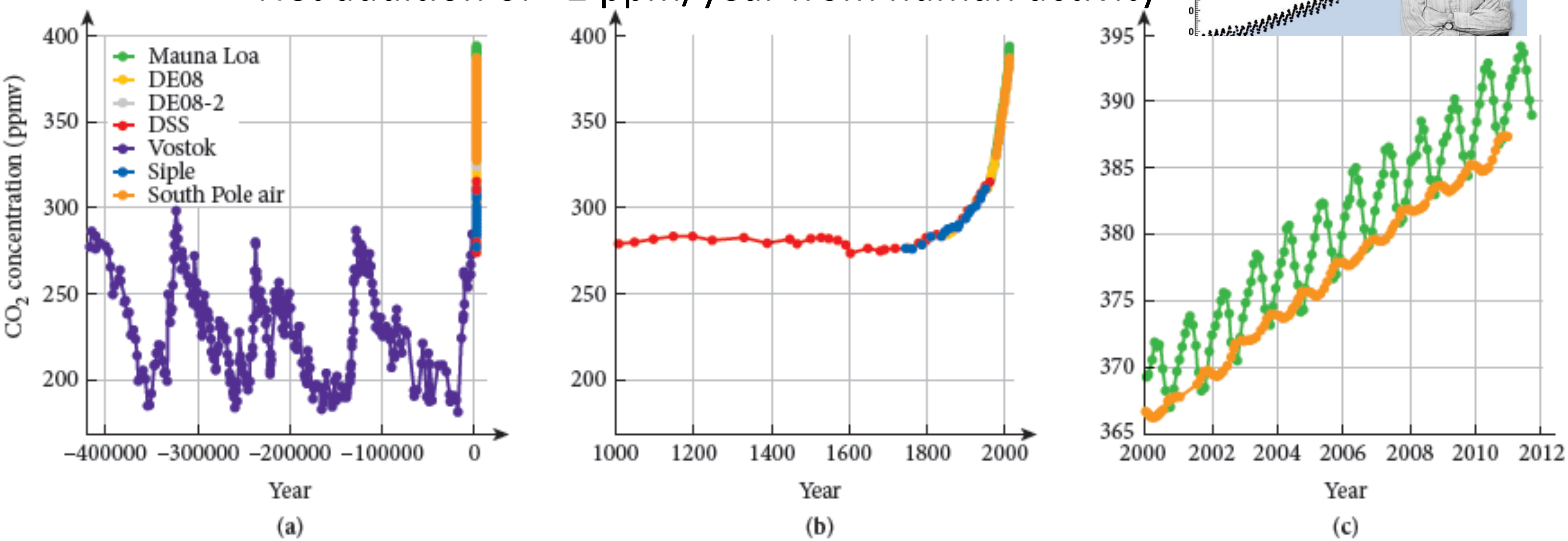
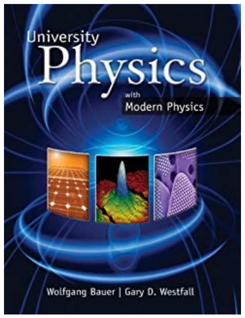
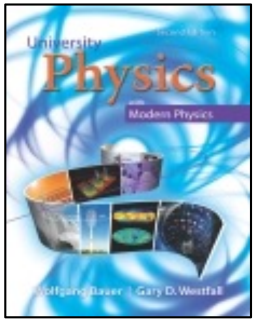


FIGURE 18.28 Concentration of carbon dioxide (CO_2) in the Earth's atmosphere in parts per million by volume (ppmv). (a) Concentration of carbon dioxide in the atmosphere during the last 420,000 years. The measurements shown are from air samples at Mauna Loa in Hawaii (green) and the South Pole (orange) and various ice core samples from Antarctica. (b) Display of the same data as in part (a), but only from 1000 AD to the present. (c) Display of the same data as in part (b), but only from 2000 to 2012.

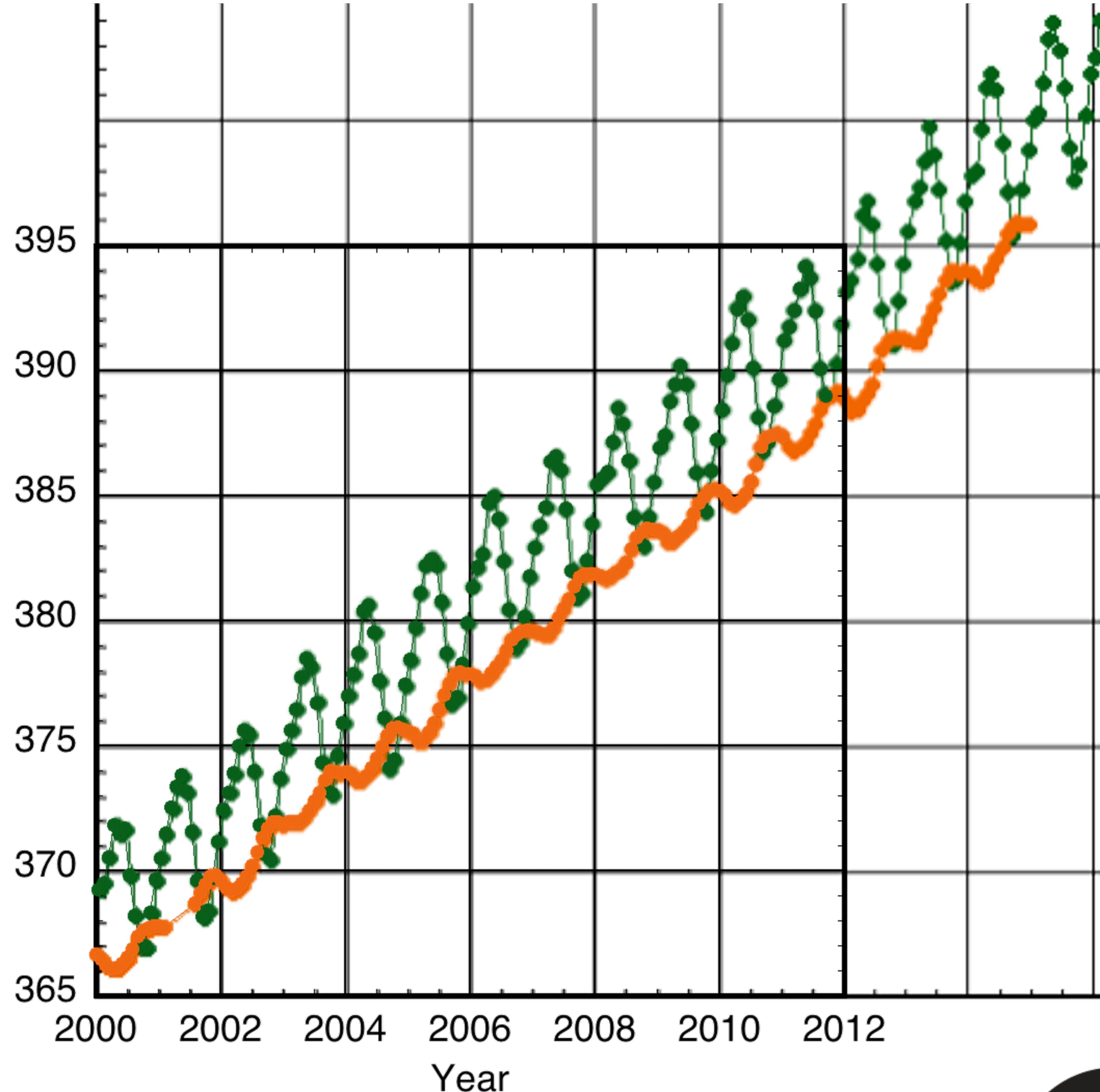
Atmospheric CO_2





Net addition of 2 ppm/year of CO_2 to atmosphere
= 16 billion metric tons / year!
= 35 times the weight of all humans on the planet

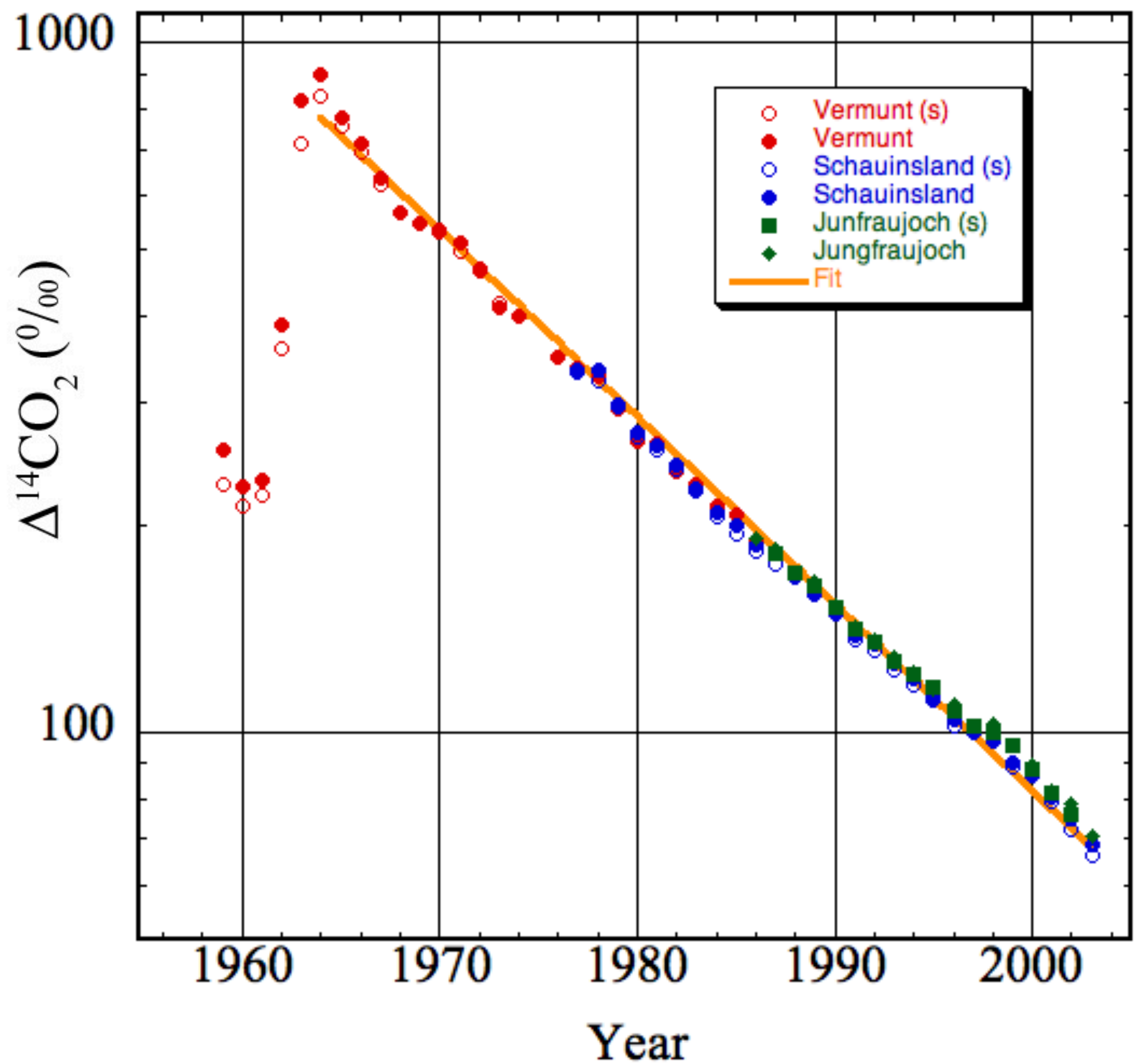
https://scripps.ucsd.edu/programs/keelingcurve/
Latest CO_2 reading: 413.40 ppm



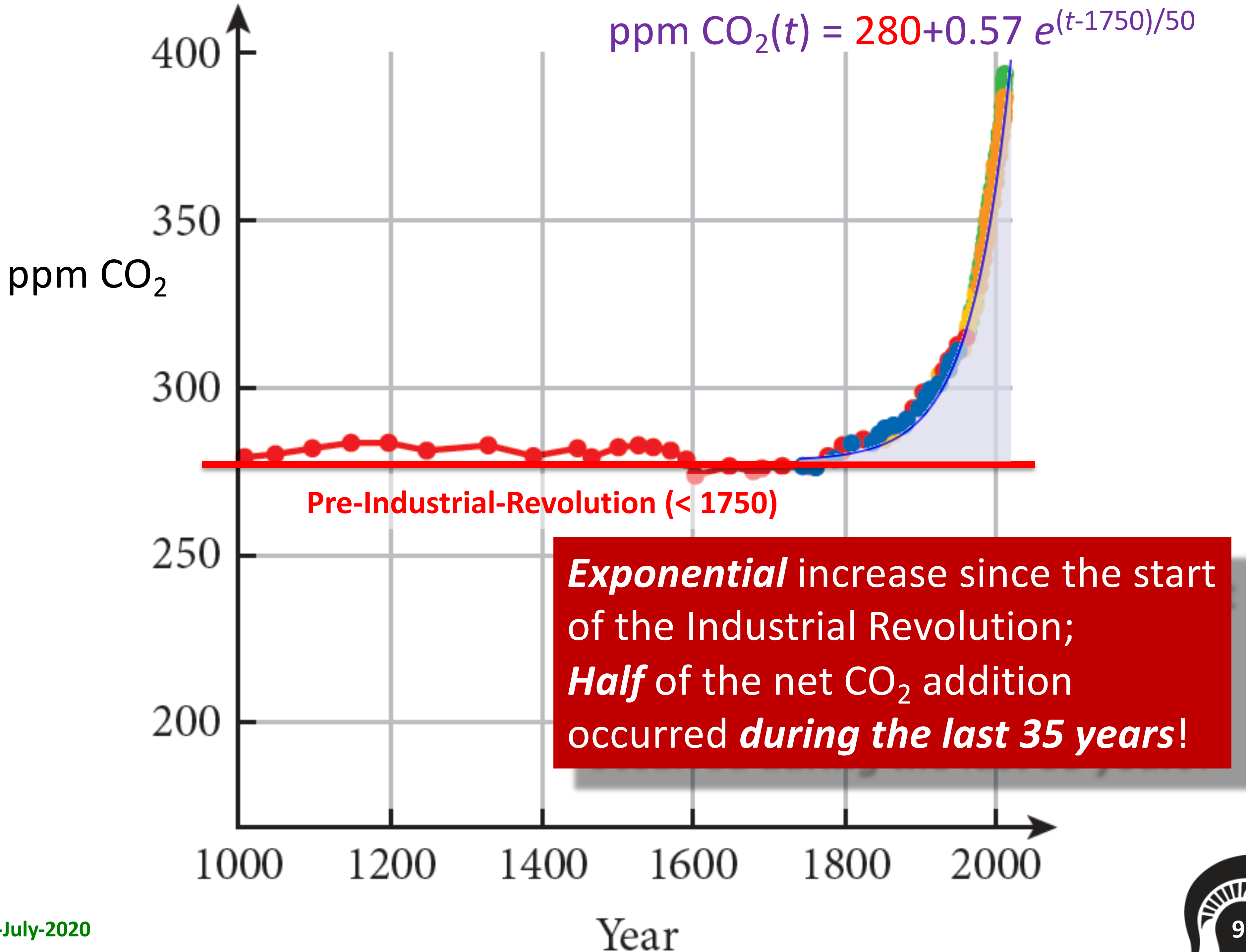
CO_2 Lingers For Decades

- Atmospheric nuclear weapons tests in 1950s increased ^{14}C until test ban treaty in 1963
- Exponential decay since then
- Fit line: CO_2 half life of 16 years in atmosphere
- *Note*: $T_{1/2}(^{14}C) = 5730$ years

W. Bauer (2019)



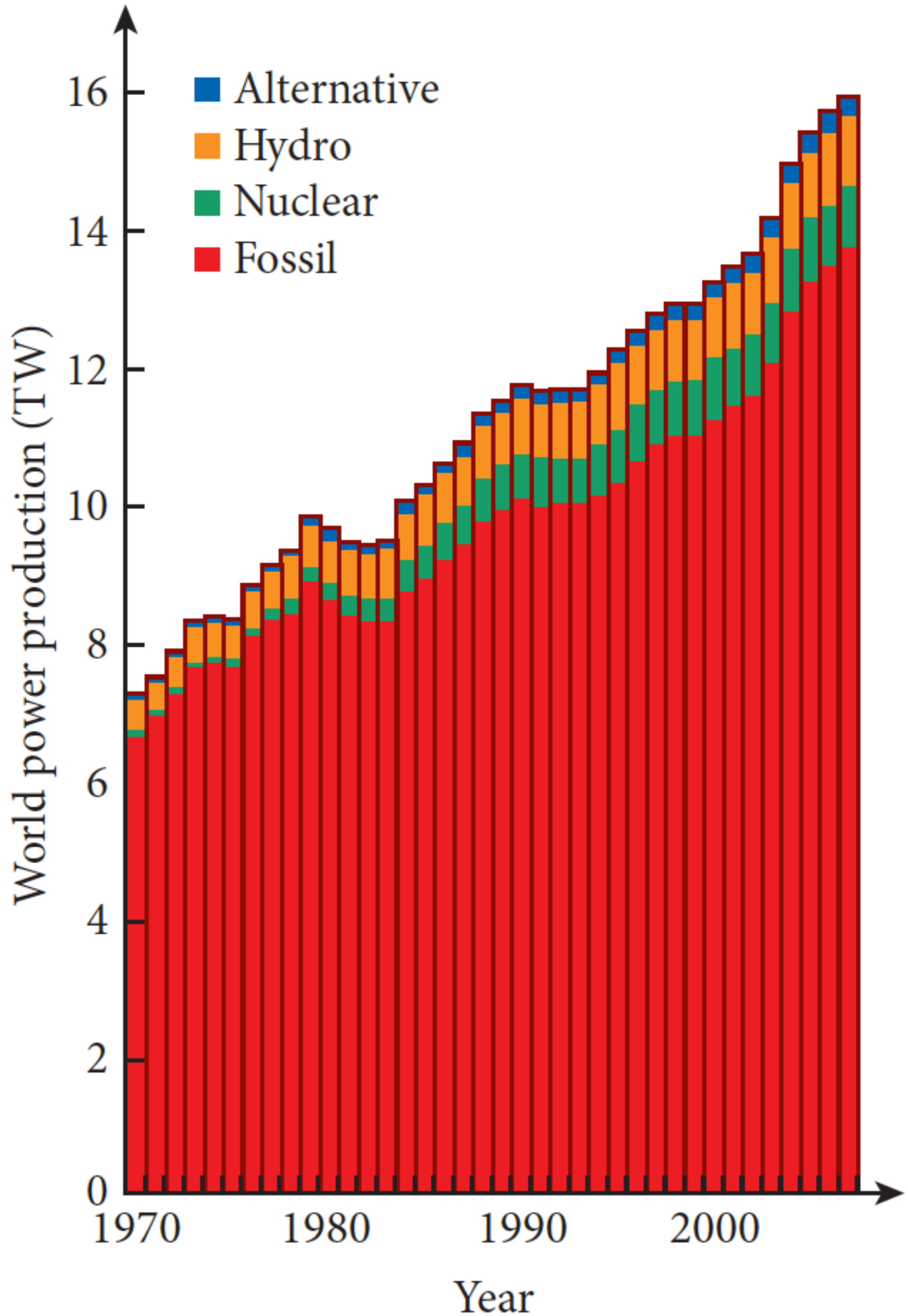
Humans who are alive today have added more greenhouse gases to the atmosphere than all humans who have ever lived before us in the entire history of mankind.



ppm $CO_2(t) = 280+0.57\, e^{(t-1750)/50}$
400
350
300
250
200
ppm CO_2
1000
1200
1400
1600
1800
2000
Year
Pre-Industrial-Revolution (< 1750)
Exponential increase since the start of the Industrial Revolution;
Half of the net CO_2 addition occurred ***during the last 35 years***!

Why are we doing this to our planet?

Global Power Production

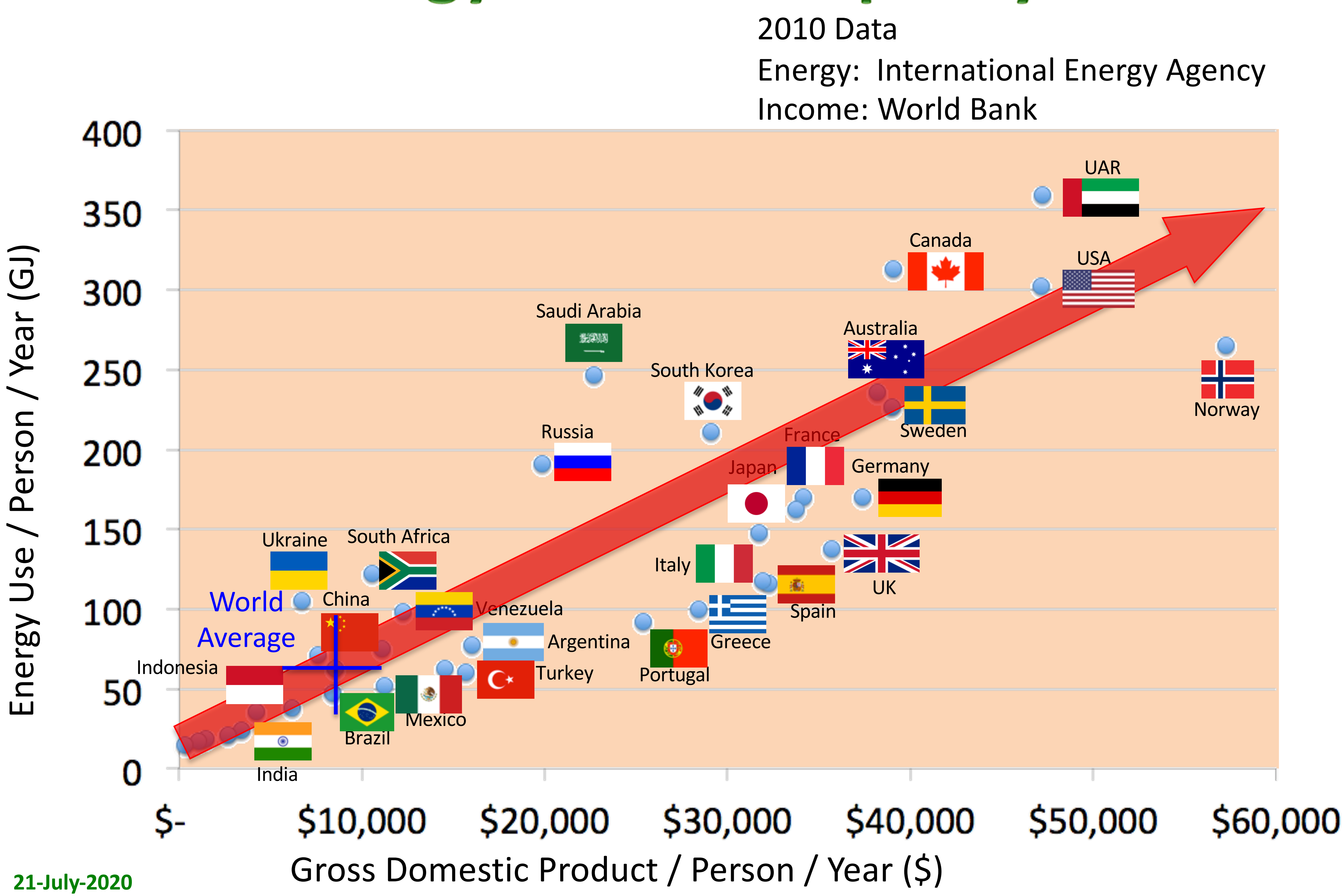


Bauer & Westfall, 2nd edition
Data: US DOE EIA

Main Take-Home Message

$$E = \$$$

Energy Use & Prosperity



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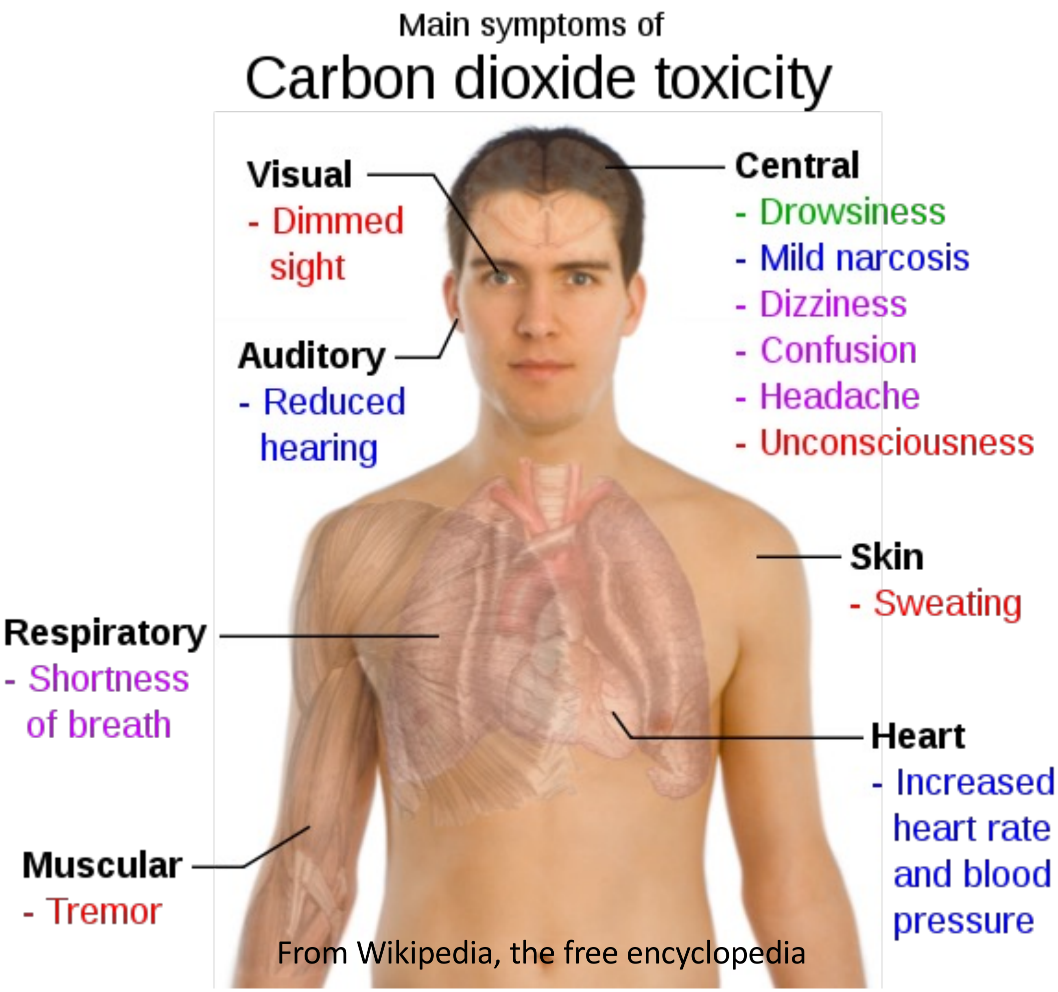
Good news: we can still breathe!



From Wikipedia, the free encyclopedia

Volume % in air

- 1% = 10000 ppm
- 3% = 30000 ppm
- 5% = 50000 ppm
- 8% = 80000 ppm

CO_2 level in atmosphere still a factor of ~20 below danger level

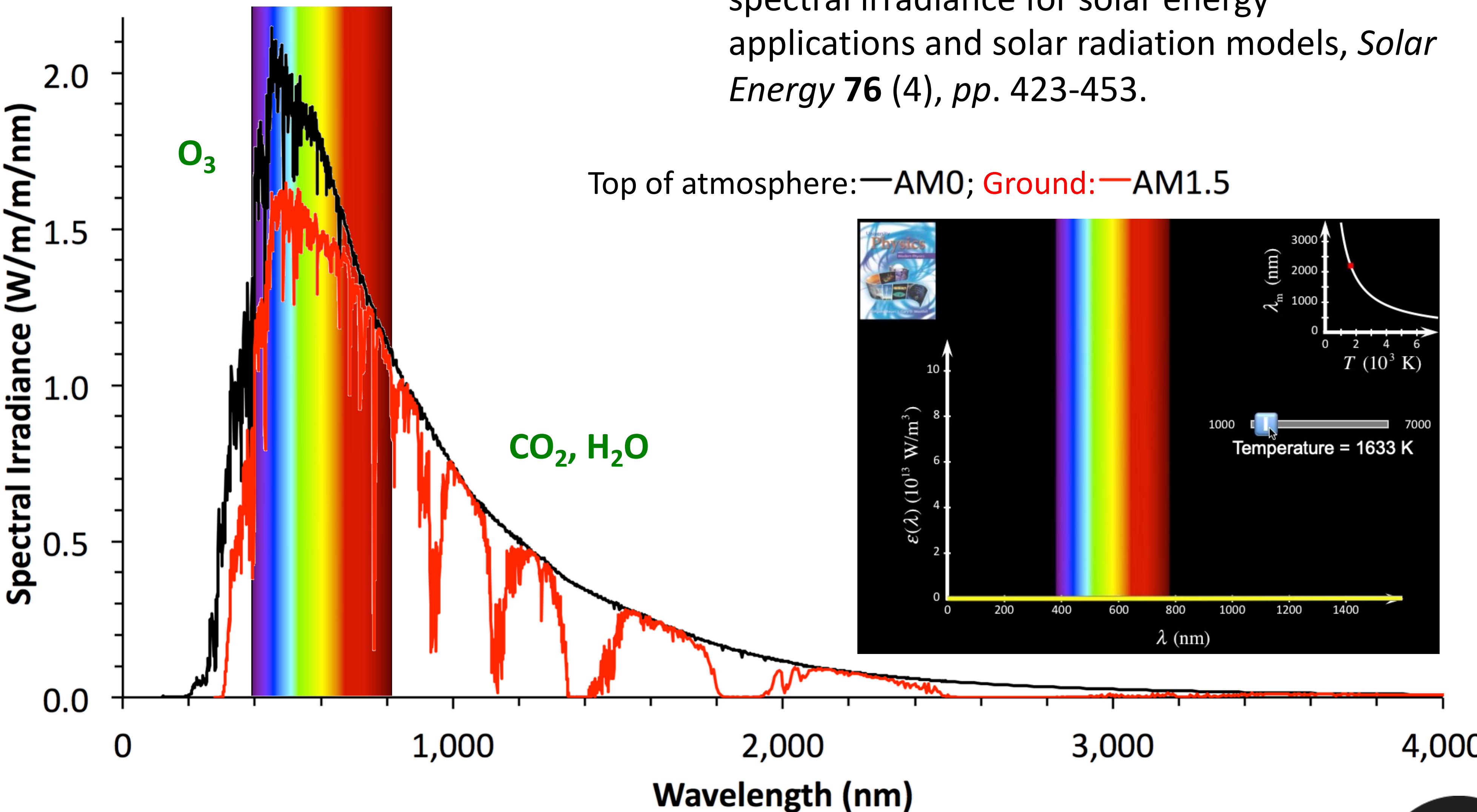
Interesting fact / good 'order of magnitude estimation' problem:

Humans breathe out ~ $3{\cdot}10^9$ tons of CO_2 (~ 0.4 ppm) per year

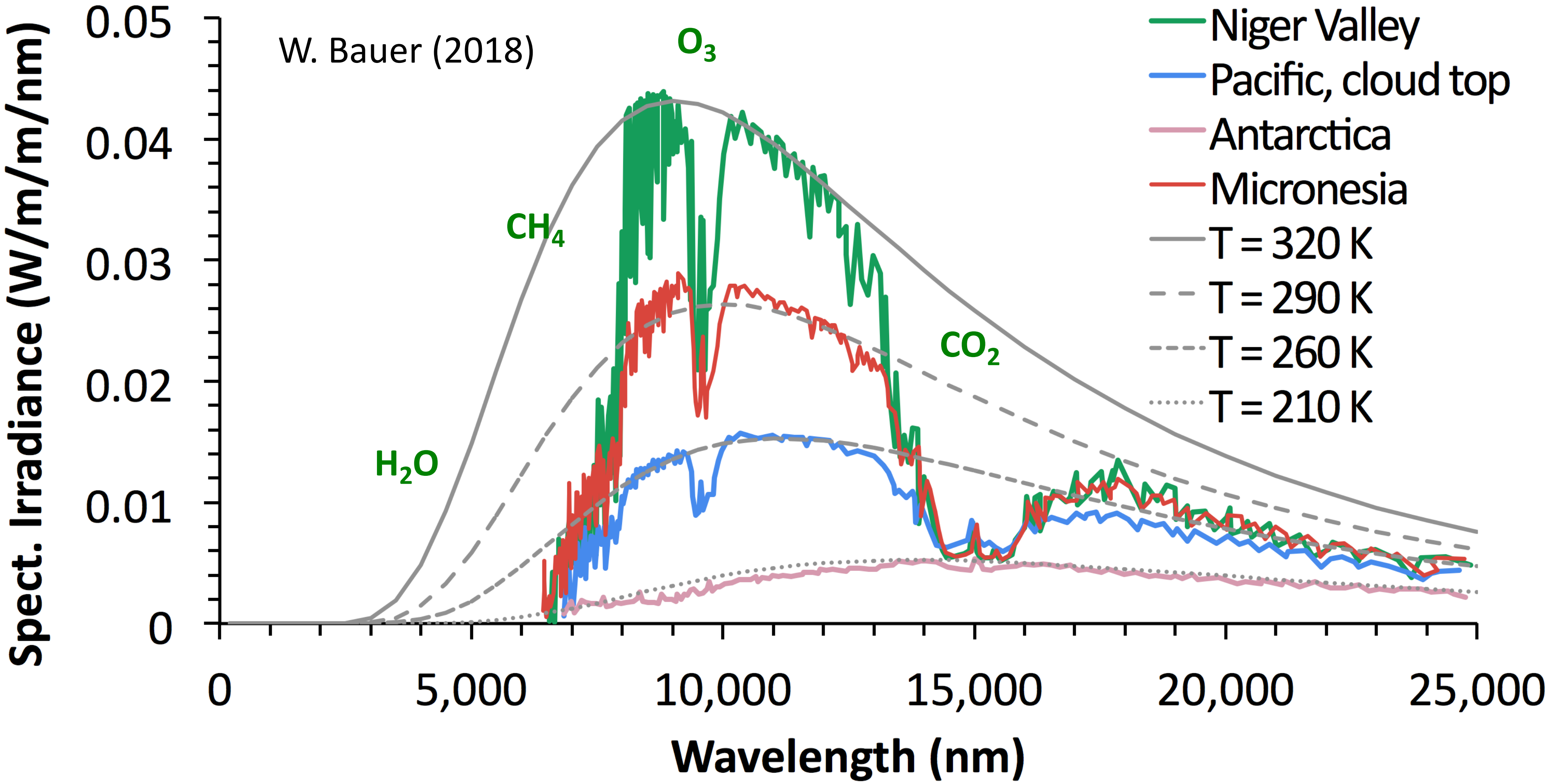
Global Warming

Solar radiation: 5800 K Blackbody

Gueymard, C. (2004). The sun's total and spectral irradiance for solar energy applications and solar radiation models, *Solar Energy* **76** (4), *pp*. 423-453.

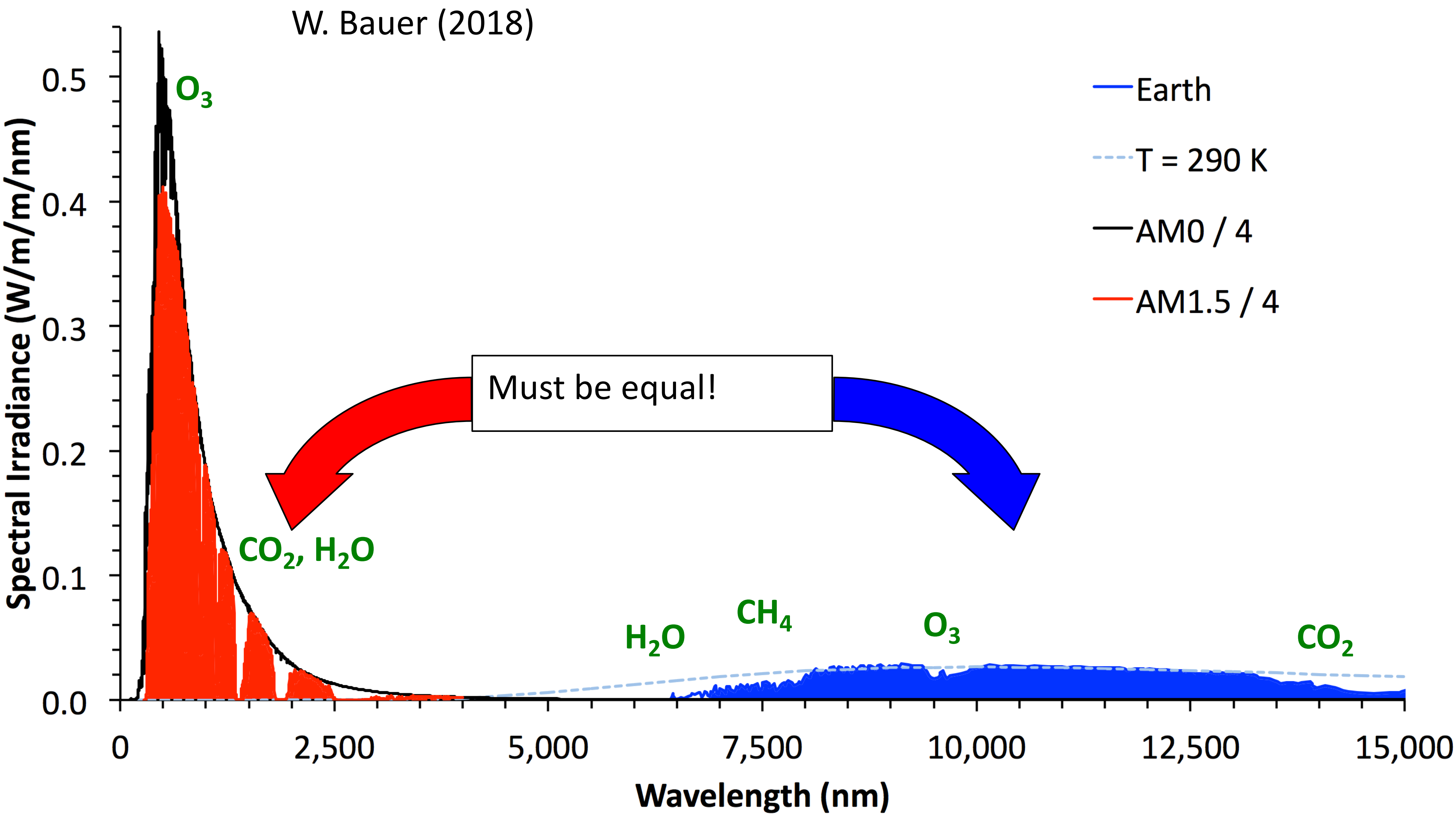


Earth radiation

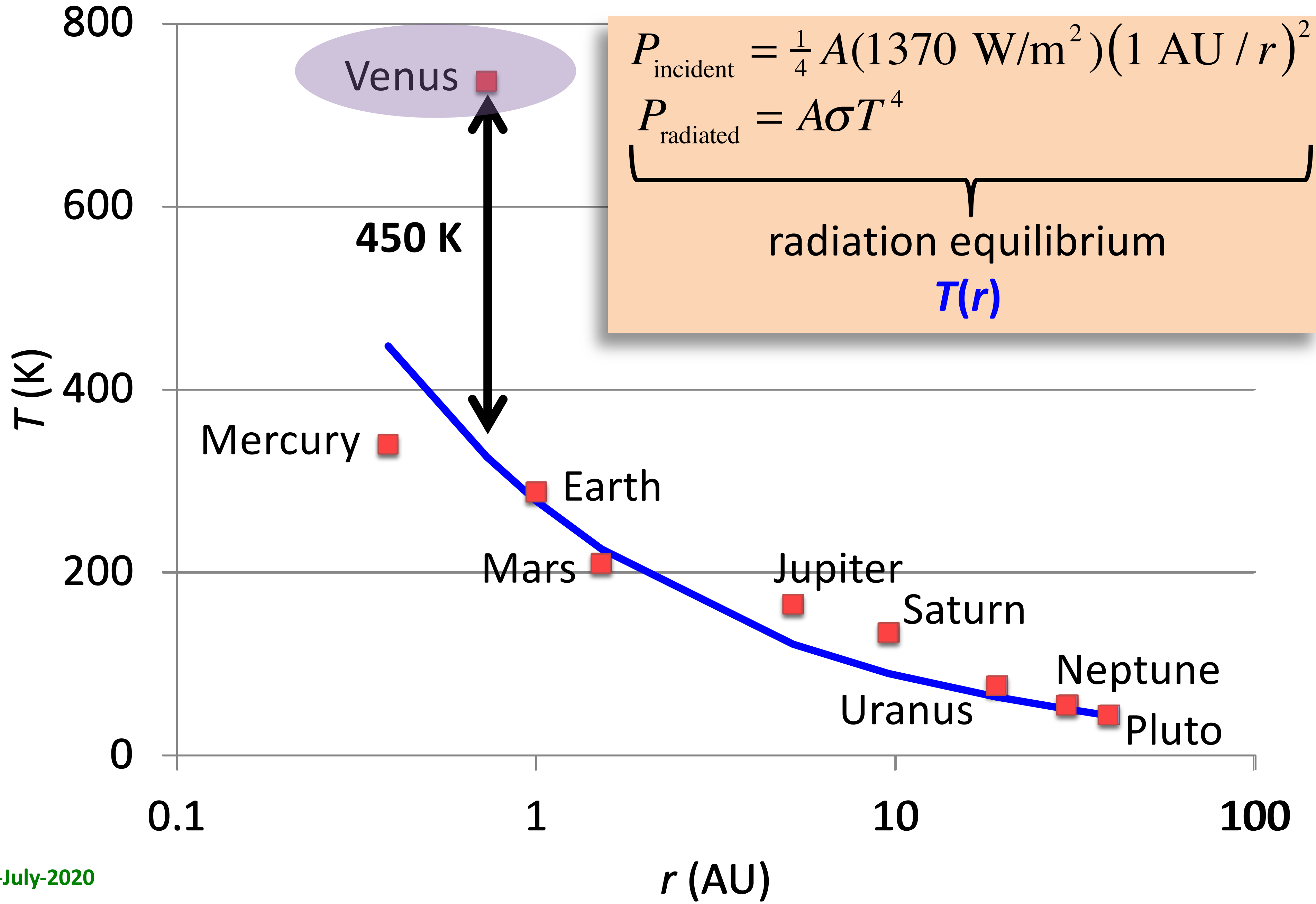


Data from: Hanel, R. A., Conrath, B. J., Kunde, V. G., Prabhakara, C., Revah, I., Solomonson, V. V., and Wolfrod, G. (1972). The Nimbus 4 Infrared Spectroscopy Experiment, 1. Calibrated Thermal Emission Spectra, *Journal of Geophysical Research* **77**, *pp*. 2629-2641.

Radiation balance



Planetary Surface Temperatures



Venus Runaway Greenhouse Effect

- Early Venus may have had liquid water oceans
- High greenhouse gas concentration led to warming of planet and subsequent boiling and evaporation of its oceans
- **Can Earth encounter the same fate?**

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL069790

Was Venus the first habitable world of our solar system?

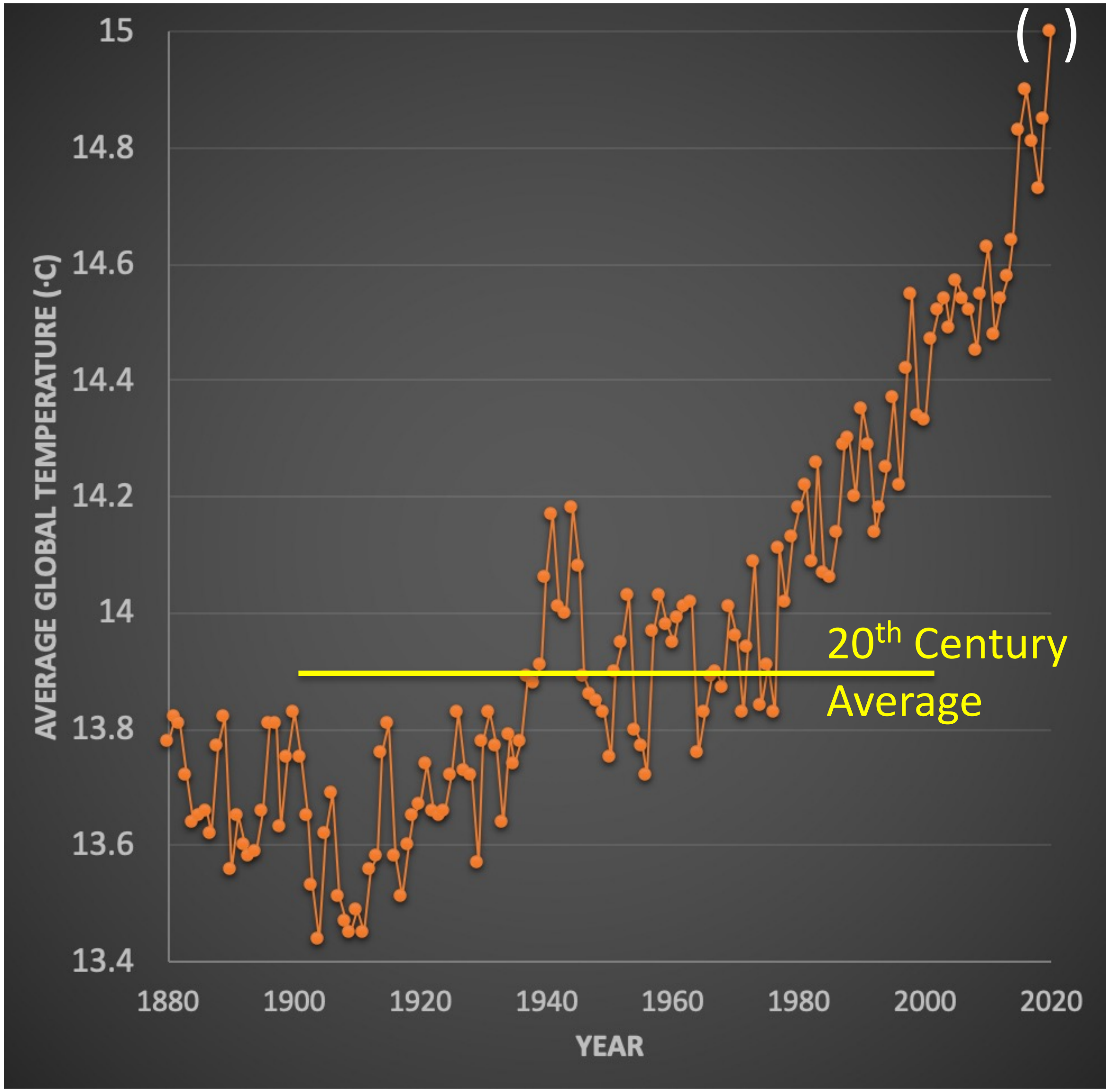
M. J. Way[1,2], Anthony D. Del Genio[1], Nancy Y. Kiang[1], Linda E. Sohl[1,3], David H. Grinspoon[4], Igor Aleinov[1,3], Maxwell Kelley[1], and Thomas Clune[5]

[1]NASA Goddard Institute for Space Studies, New York, New York, USA, [2]Department of Astronomy and Space Physics, Uppsala University, Uppsala, Sweden, [3]Center for Climate Systems Research, Columbia University, New York, New York, USA, [4]Planetary Science Institute, Tucson, Arizona, USA, [5]Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

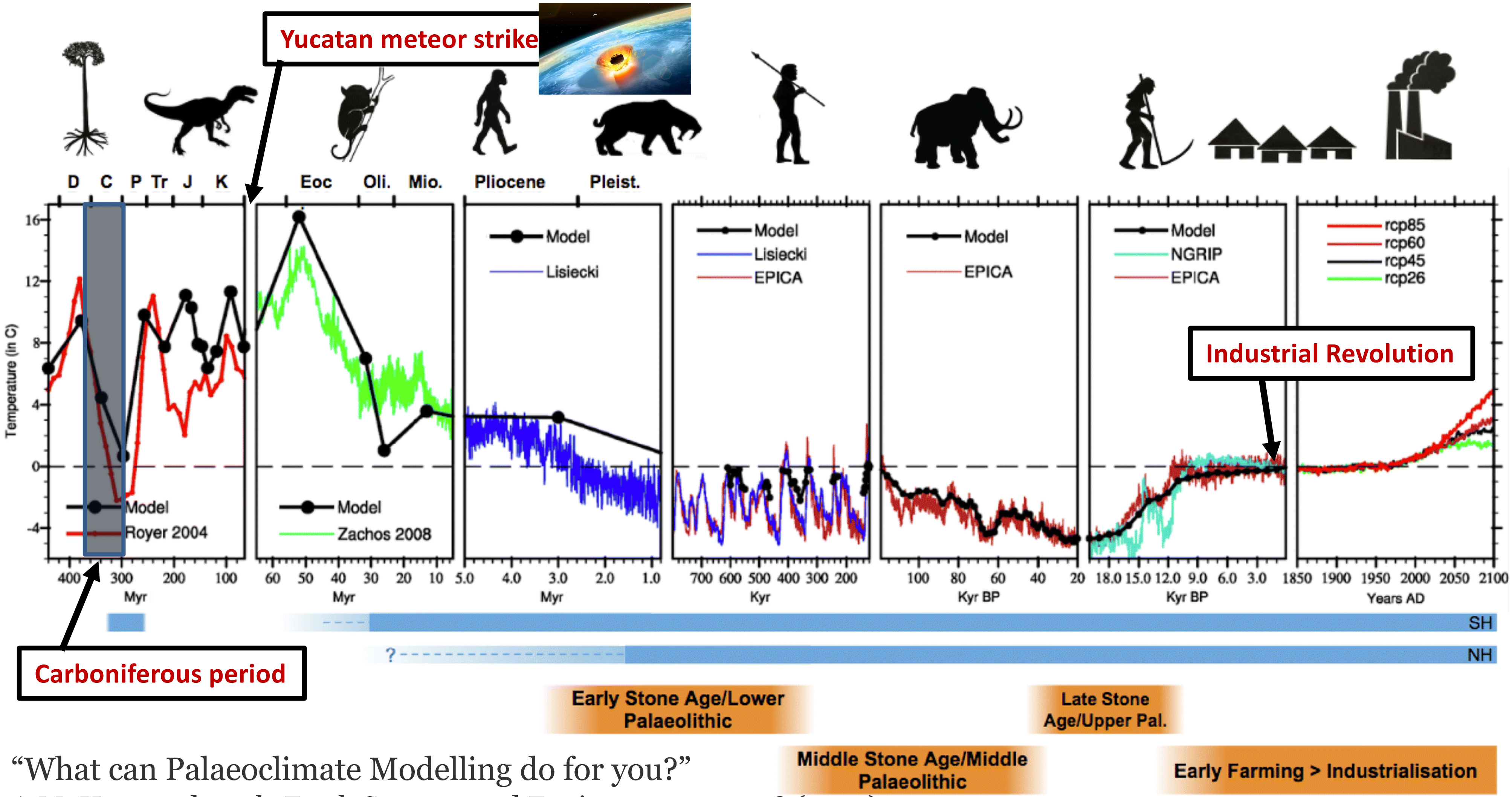
Key Points:
- Venus may have had a climate with liquid water on its surface for approximately two billion years
- The rotation rate and topography of Venus play crucial roles in its surface temperature and moisture
- Young Venus-like exoplanets may be considered candidates for the search for life beyond Earth

Global Average Temperature

https://www.ncdc.noaa.gov/cag/global/time-series/globe/land_ocean/ytd/12/1880-2020



2020 incomplete



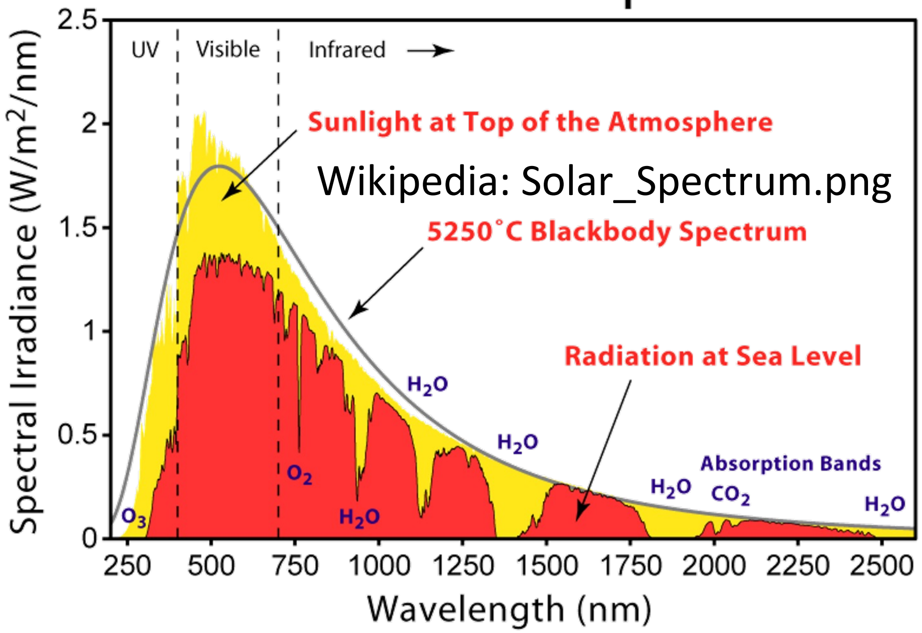
"What can Palaeoclimate Modelling do for you?"
A.M. Haywood *et al.*, Earth Systems and Environment **3**, 1-18 (2019)
https://link.springer.com/article/10.1007/s41748-019-00093-1?shared-article-renderer

Let’s Teach Renewables: Solar

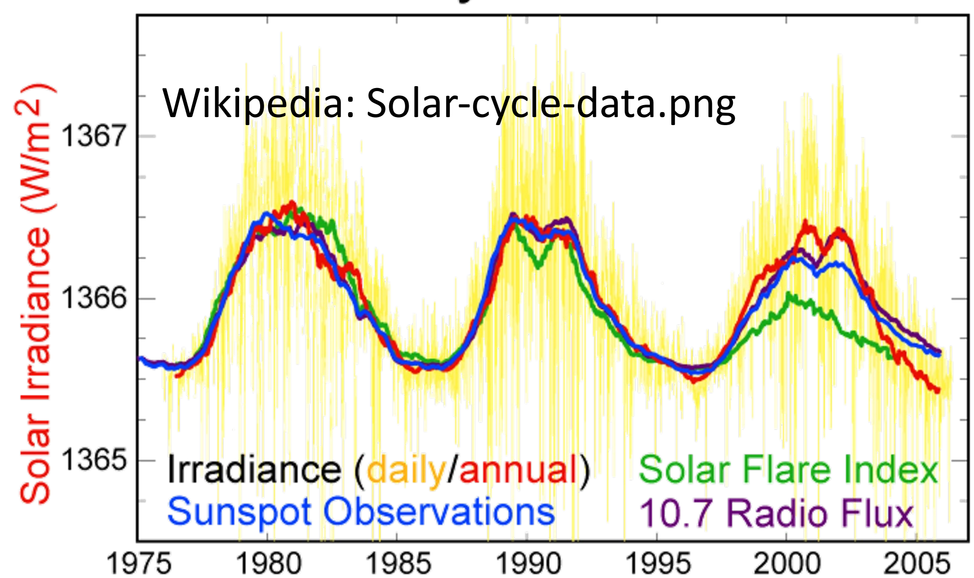
Power from the Sun

- Solar "constant" = 1.366 kW/m^2
(1.41 kW/m^2 in Jan., 1.31 kW/m^2 in July)
- Average radiation hitting any point on the ground **200 W/m^2** (= 55% of 1.366 kW/m^2/4)
- Total: **~100,000 TW** (> 5,000x humanity's demand)

Solar Radiation Spectrum

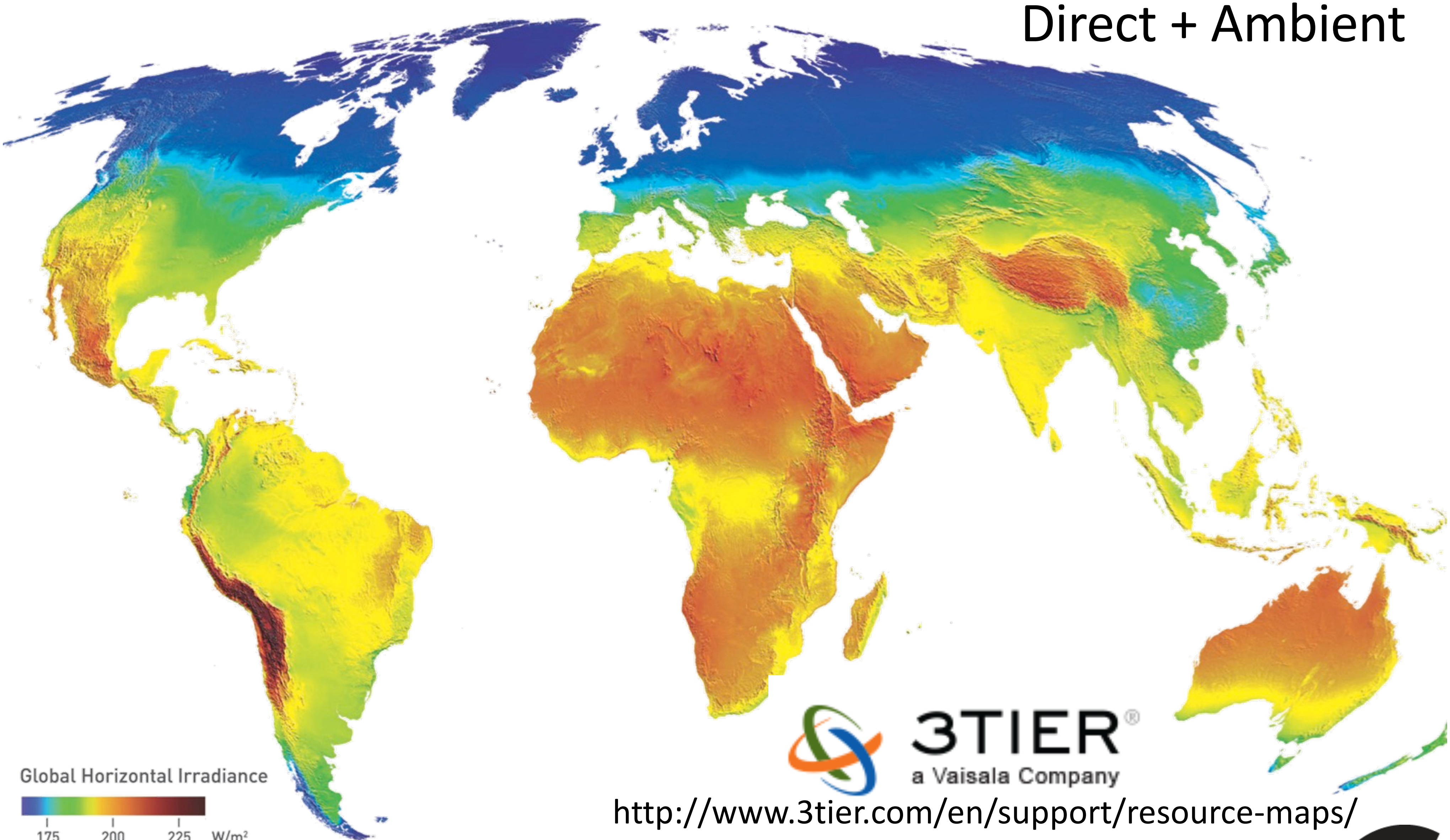


Solar Cycle Variations



Usable Solar Radiation

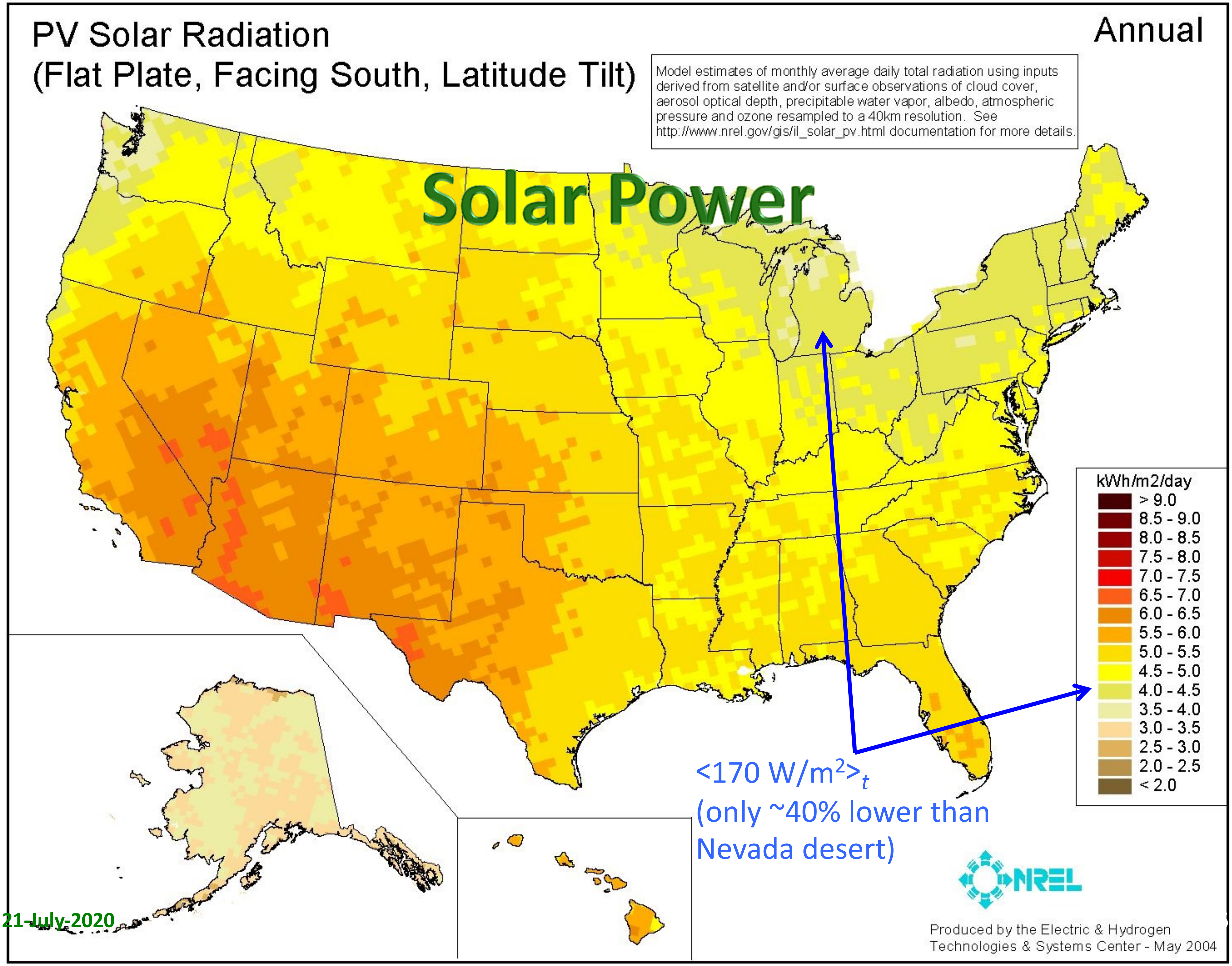
Direct + Ambient



3TIER®
a Vaisala Company

http://www.3tier.com/en/support/resource-maps/

Solar Power

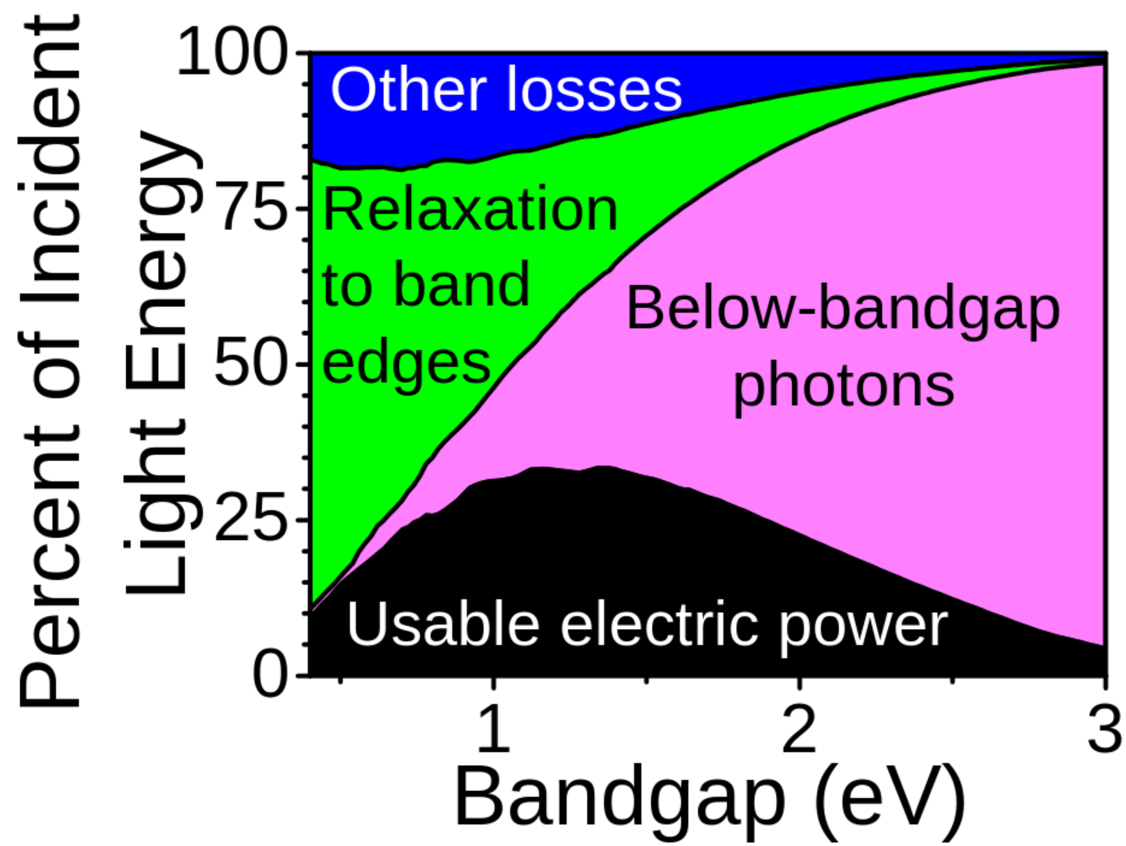


$<170\ \mathrm{W/m^2}>_t$
(only ~40% lower than Nevada desert)

Efficiency vs. Band Gap

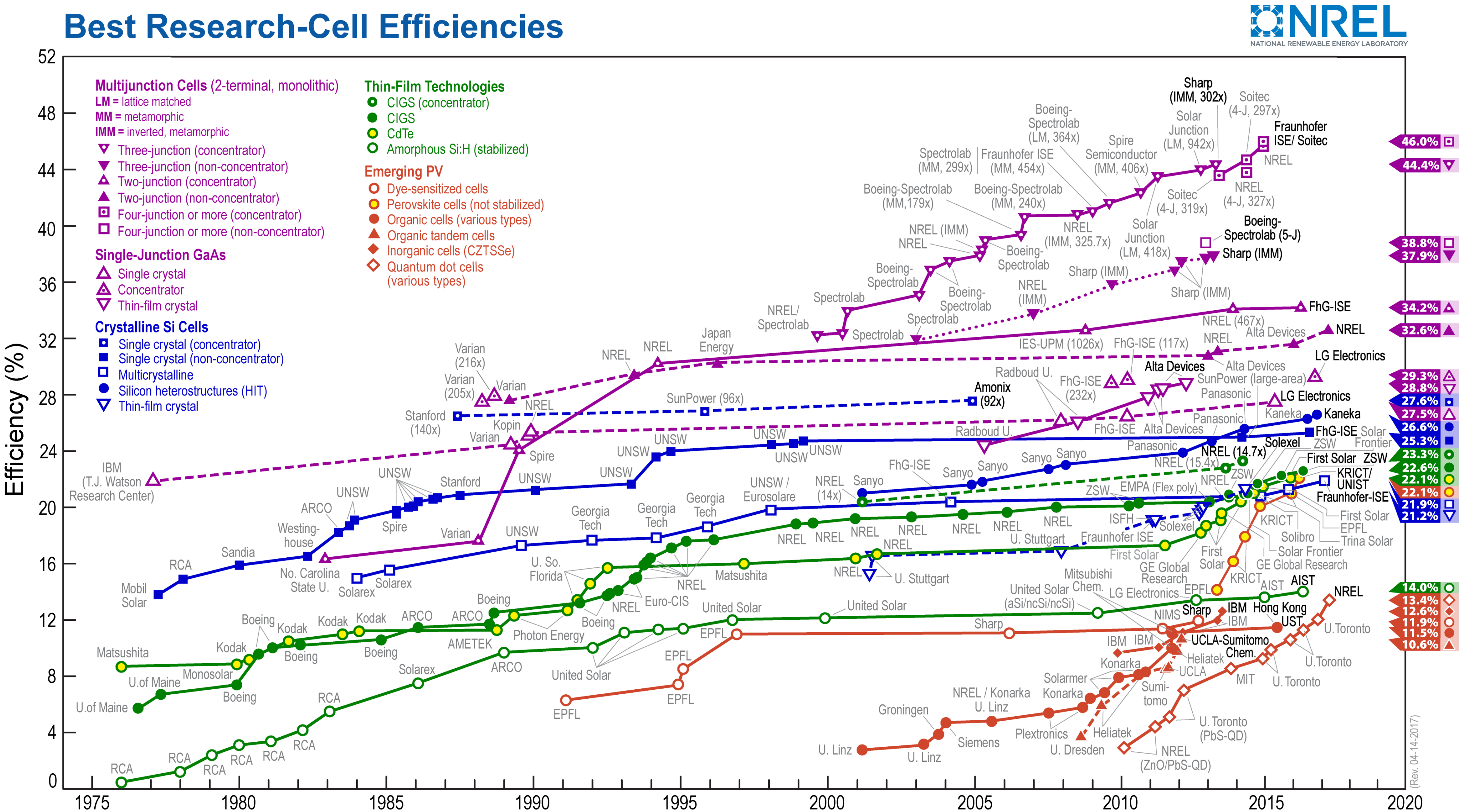
- Monocrystalline cells with single p-n junction
- 33.7% for band gap of 1.34 eV optimal (with AM 1.5 solar spectrum)
- Si: 1.1 eV band gap; max 24% efficiency

https://en.wikipedia.org/wiki/Shockley–Queisser_limit#/media/File:ShockleyQueisserBreakdown2.svg



William Shockley and Hans J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", Journal of Applied Physics, Volume 32 (March 1961), pp. 510-519

PV Cells are Getting More Efficient



https://www.nrel.gov/pv/assets/images/efficiency-chart.png

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UNIVERSITY

MICHIGAN STATE UNIVERSITY | Center of Research Excellence in Complex Materials

CORE-CM

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Faculty leads

Funded groups

Industry programs

Training programs

Center facilities

Staff

Calendar

Featured publications

Affiliated center and large group activities

1. *Revolutionary Materials for Solid State Energy Conversion.* **DOE-EFRC. MSU Faculty:** Don Morelli (PI), Eldon Case, Tim Hogan, Bhanu Mahanti, Jeff Sakamoto, Harold Schock.

2. *Design and Development of Efficient Solid-State Dye-Sensitized Solar Cells.* **NSF-Solar. MSU Faculty:** Jim McCusker (PI), Greg Baker, Andrew Christlieb, Larry Drzal, Keith Promislow.

3. *Developing the next generation of advanced battery technology.* **DoD. MSU Faculty:** Larry Drzal (PI), Greg Baker, Jeff Sakamoto, Martin Hawley, Tim Hogan, Elias Strangas, Fang Peng, Greg Swain, Jeff Sakamoto.

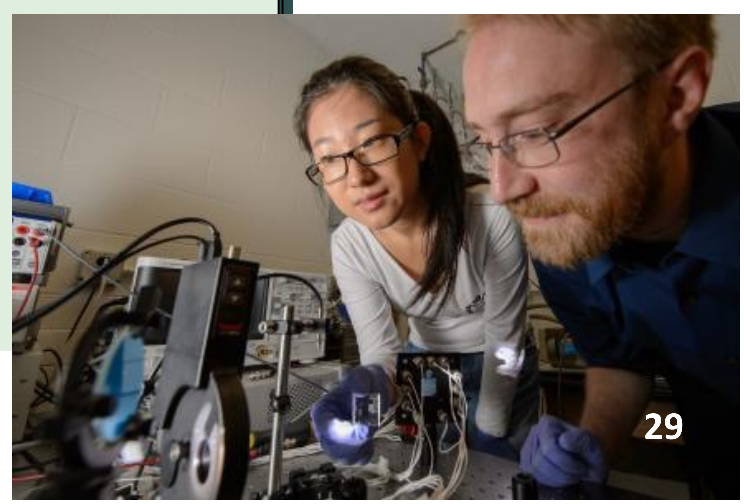
4. *Biomimetic Microsystem for High Throughput Evaluation of Engineered Nanomaterial.* **NIH-Grand Opportunity. MSU Faculty:** R. (Marc) Worden (PI), Andrew Mason, Greg Baker, Phil Duxbury, Jack Harkema, James Wagner, Norbert Kaminski, Barbara Kaplan.

5. *Interdisciplinary Bioelectronics Training Program.* **DE-GAANN. MSU Faculty:** R. (Marc) Worden (PI), Scott Barton (co-PI), Phil Duxbury, Michael Garavito, Gemma Reguera, Jon Sticklen, Stuart Tessmer, Claire Veielle.

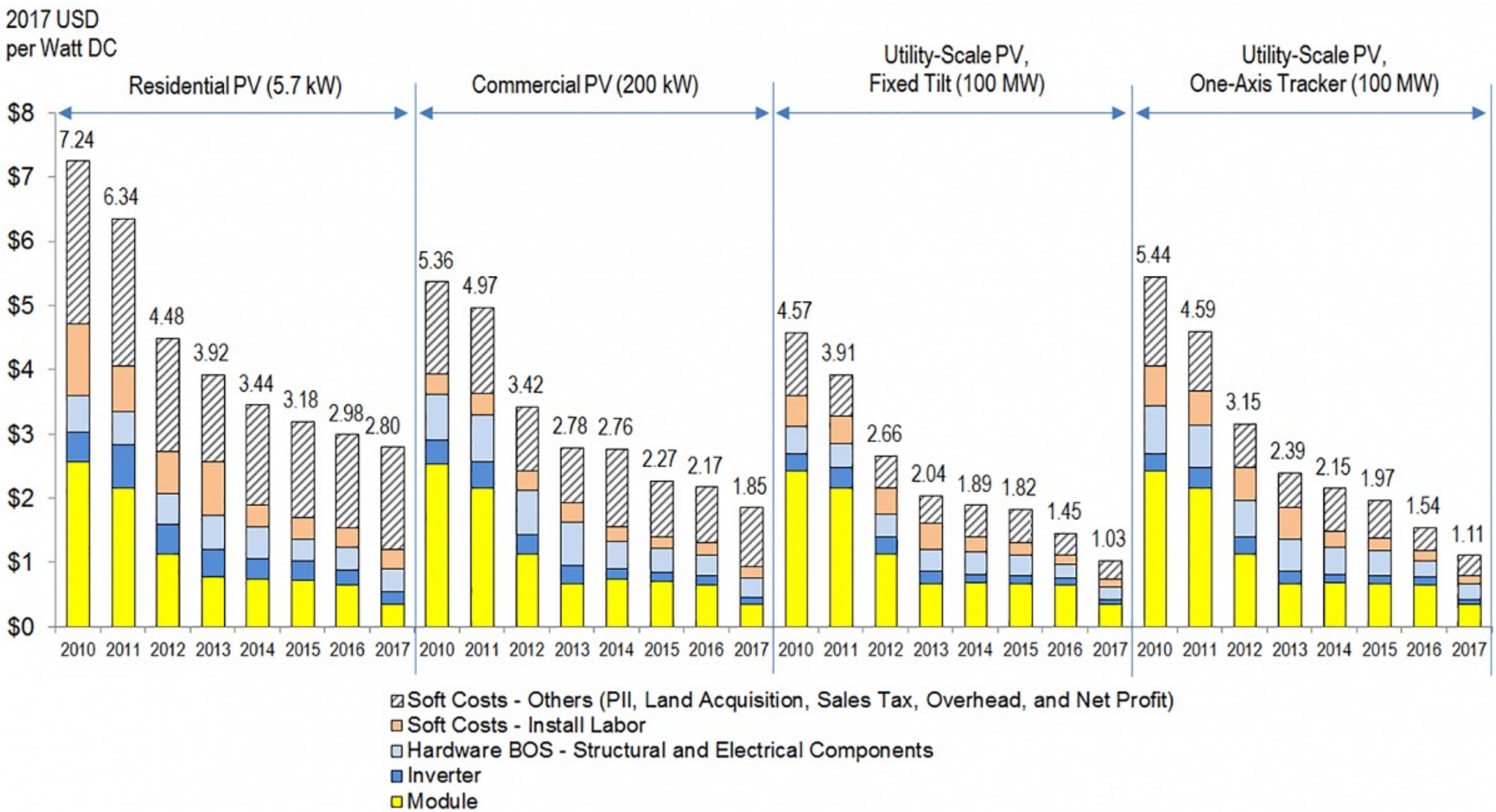
MSU centers in related areas

Composite Materials and Structures Center.
Great Lakes Bioenergy Institute (DOE).
Institute for Cyber-Enabled Discovery.

MICHIGAN STATE UNIVERSITY

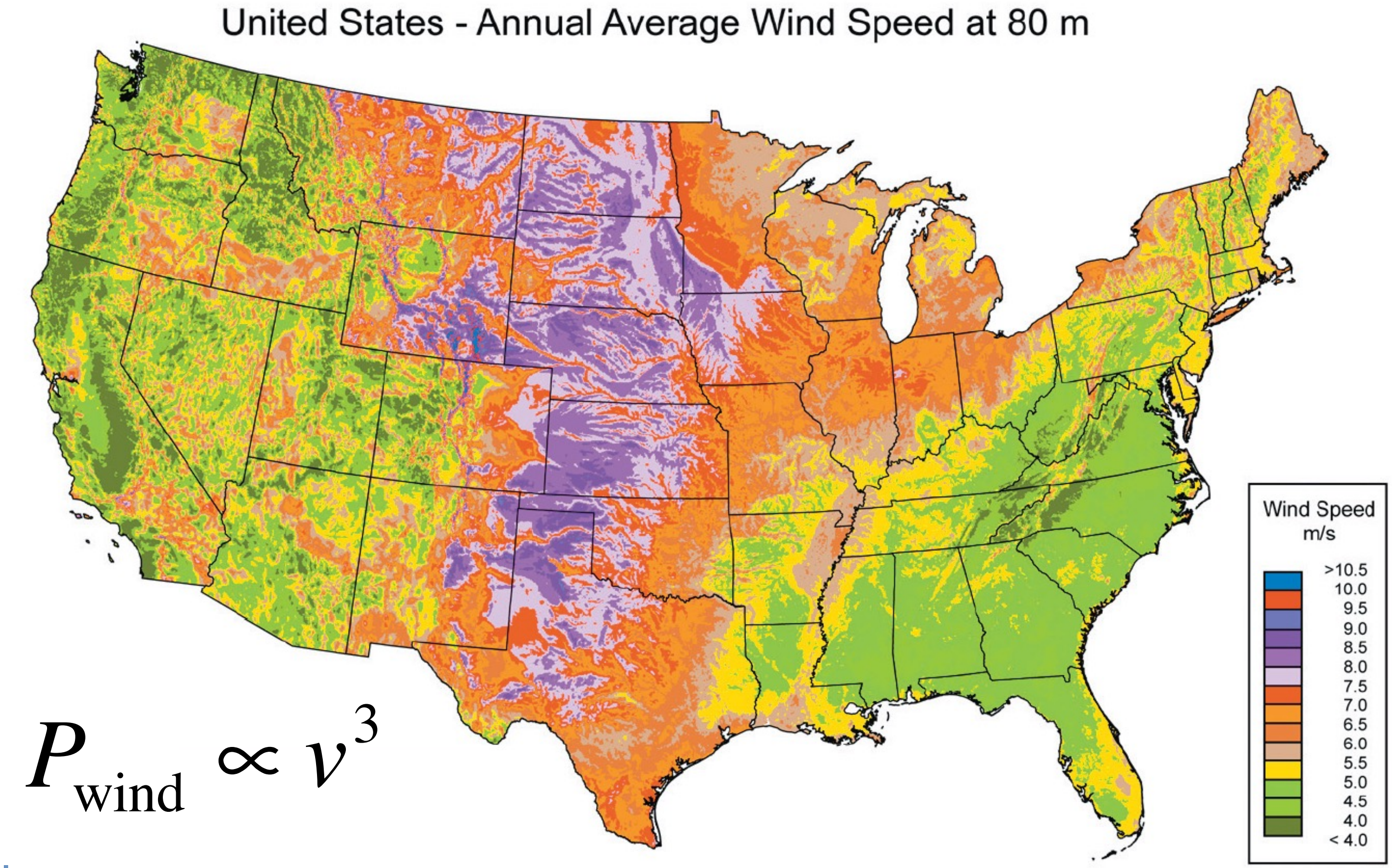


NREL PV system cost benchmark summary (inflation adjusted), 2010–2017



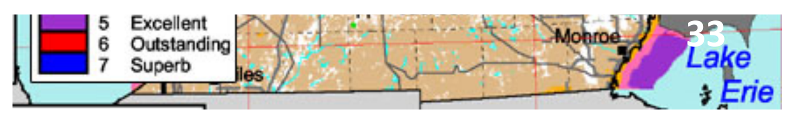
Let’s Teach Renewables: Wind

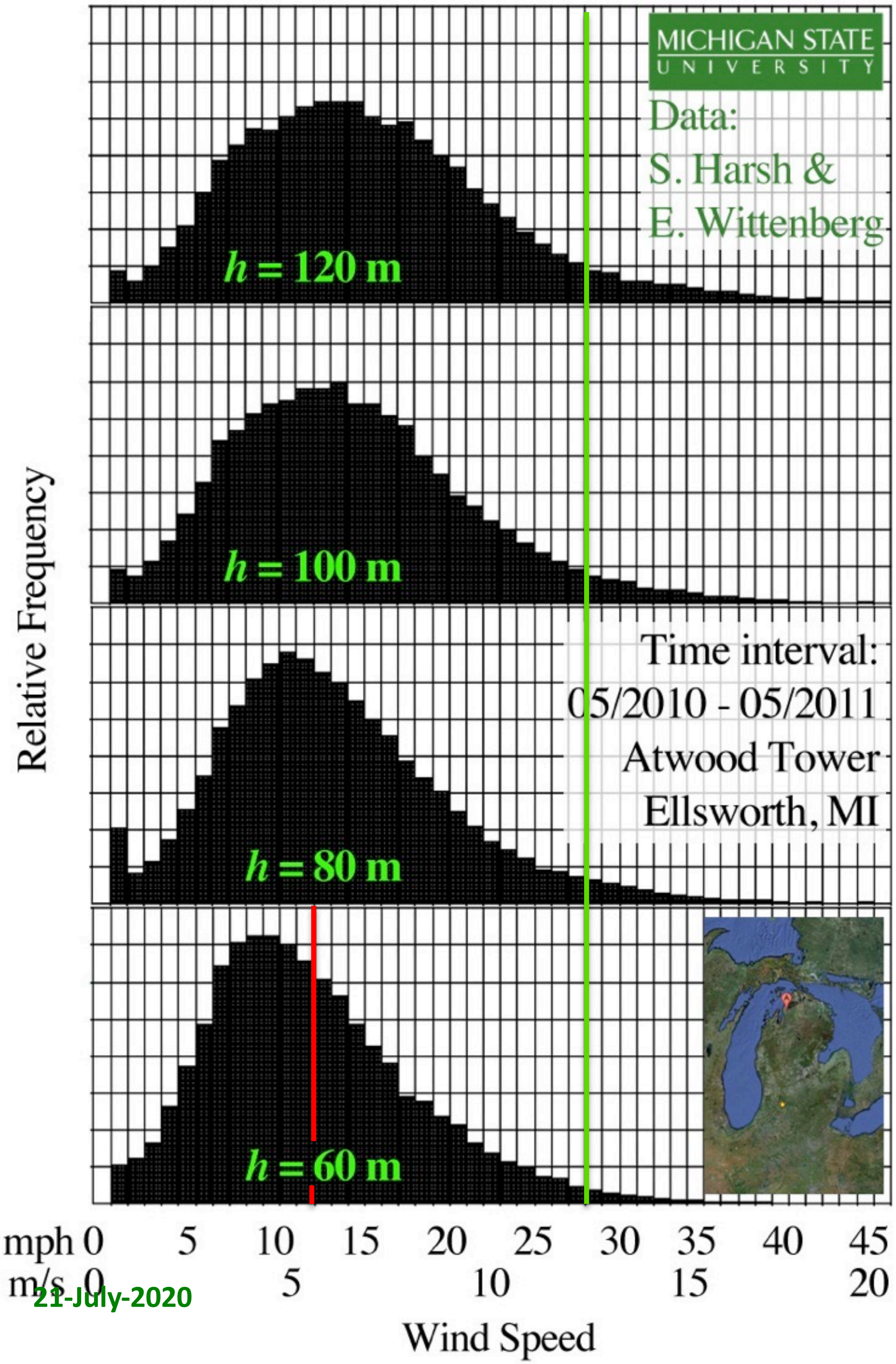
Wind



$$P_{\text{wind}} \propto v^3$$

Wind





Wind Speed

- Wind speed increases with *h*
  - More power from taller towers
- Broad distribution
  - Intermittency
- Capacity factor (@ 60 m)

$$c = \frac{\langle P \rangle_t}{P_{\max}} = \frac{\int f_t(v) P(v)\, dv}{P_{\max} \int f_t(v)\, dv} = 21\%$$

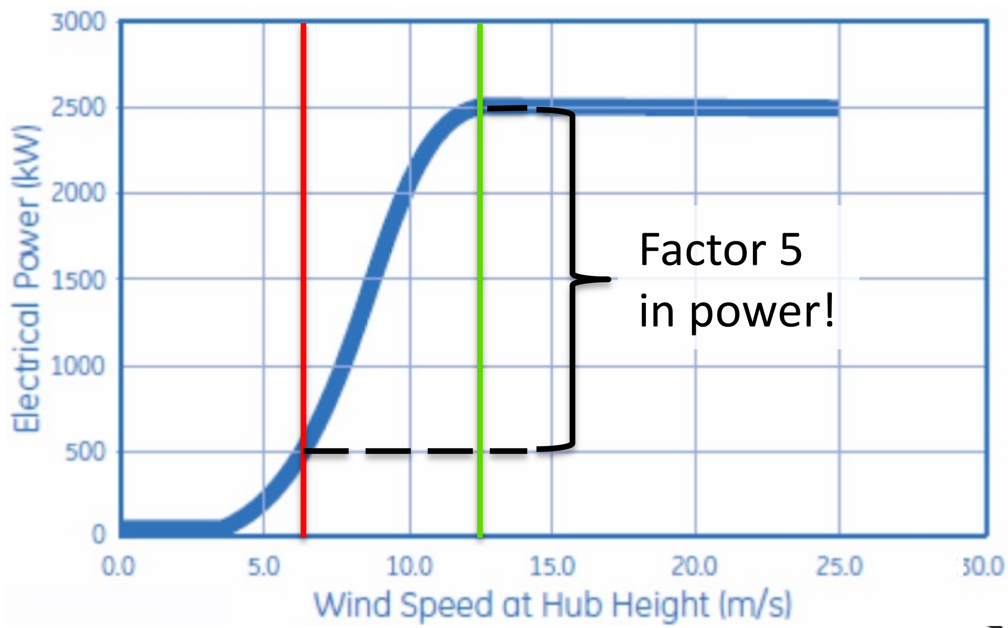


FIGURE 13.39 Wind speeds in front of, at, and behind a rotor.

EXAMPLE 13.7 Betz Limit

PROBLEM

In Chapter 5, we found that the power contained in wind moving with a speed v through an area A is $P = \frac{1}{2}Av^3\rho$, where ρ is the density of air. Now that we know about ideal fluids and energy conservation, we can derive a limit on the fraction of this power that a turbine can actually extract from the wind.

SOLUTION

Obviously, the wind speed has to change during the interaction with the rotor; otherwise, the kinetic energy of the wind would not change, and energy conservation would not allow the turbine to extract energy from the wind. If v_1 is the speed of the wind before it hits the rotor, v_2 is the speed after it passes through the rotor, and v is the speed at the rotor (see Figure 13.39), then v can be assumed to be the average of v_1 and v_2: $v = \frac{1}{2}(v_1 + v_2)$.

The average power is the kinetic energy that the wind loses from before hitting the rotor to after doing so:

$$P = \frac{\Delta K}{\Delta t} = \frac{1}{2}\frac{\Delta m}{\Delta t}(v_1^2 - v_2^2).$$

We already calculated the mass flow rate for an incompressible fluid:

$$R_m \equiv \frac{\Delta m}{\Delta t} = \rho A v.$$

Substituting for $\Delta m/\Delta t$ in our expression for the average power and then substituting the expression we obtained above for v yields

$$P = \frac{1}{2}\frac{\Delta m}{\Delta t}(v_1^2 - v_2^2) = \frac{1}{2}\rho A v(v_1^2 - v_2^2) = \frac{1}{2}\rho A \frac{1}{2}(v_1 + v_2)(v_1^2 - v_2^2).$$

Rearranging this and using a bit of algebra gives

$$P = \frac{1}{2}\rho A v_1^3 \frac{1}{2}\left(1 + (v_2/v_1) - (v_2/v_1)^2 - (v_2/v_1)^3\right).$$

This is the result that we found in Chapter 5 but with an extra factor, which is the sum of various powers of the ratio $\chi \equiv v_2/v_1$ of the wind speeds behind and in front of the rotor:

$$P = \frac{1}{2}\rho A v_1^3 f(\chi), \quad \text{with } f(\chi) = \frac{1}{2}\left(1 + \chi - \chi^2 - \chi^3\right).$$

To find the maximum extracted power, we have to differentiate the expression for the average power with respect to $\chi \equiv v_2/v_1$:

$$\frac{dP}{d\chi} = \frac{1}{2}\rho A v_1^3 \frac{df(\chi)}{d\chi}.$$

Taking the derivative, we obtain

$$\frac{df(\chi)}{d\chi} = \frac{1}{2}\left(1 - 2\chi - 3\chi^2\right) = 0 \Rightarrow \chi = \frac{1}{3} \text{ or } \chi = -1.$$

Since the ratio of the wind speeds has to be between 0 and 1, only $\chi_m = \frac{1}{3}$ is a solution. By taking the second derivative, you can convince yourself that this value is indeed the maximum. Inserting it into f, we find $f(\chi_m) = 16/27 \approx 0.593$.

What does this result mean? In order to extract the maximum fraction of the power contained in wind, the rotor of a turbine has to be designed so that the wind speed behind it is $\frac{1}{3}$ of the wind speed in front of it, and in this optimum case, approximately 59.3% of the total wind power can be extracted (see Figure 13.40). This limit is known as the *Betz limit*, after Albert Betz, who derived it first, in 1919.

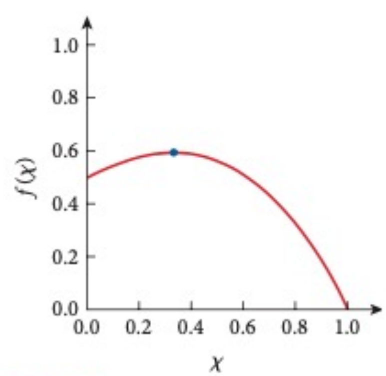
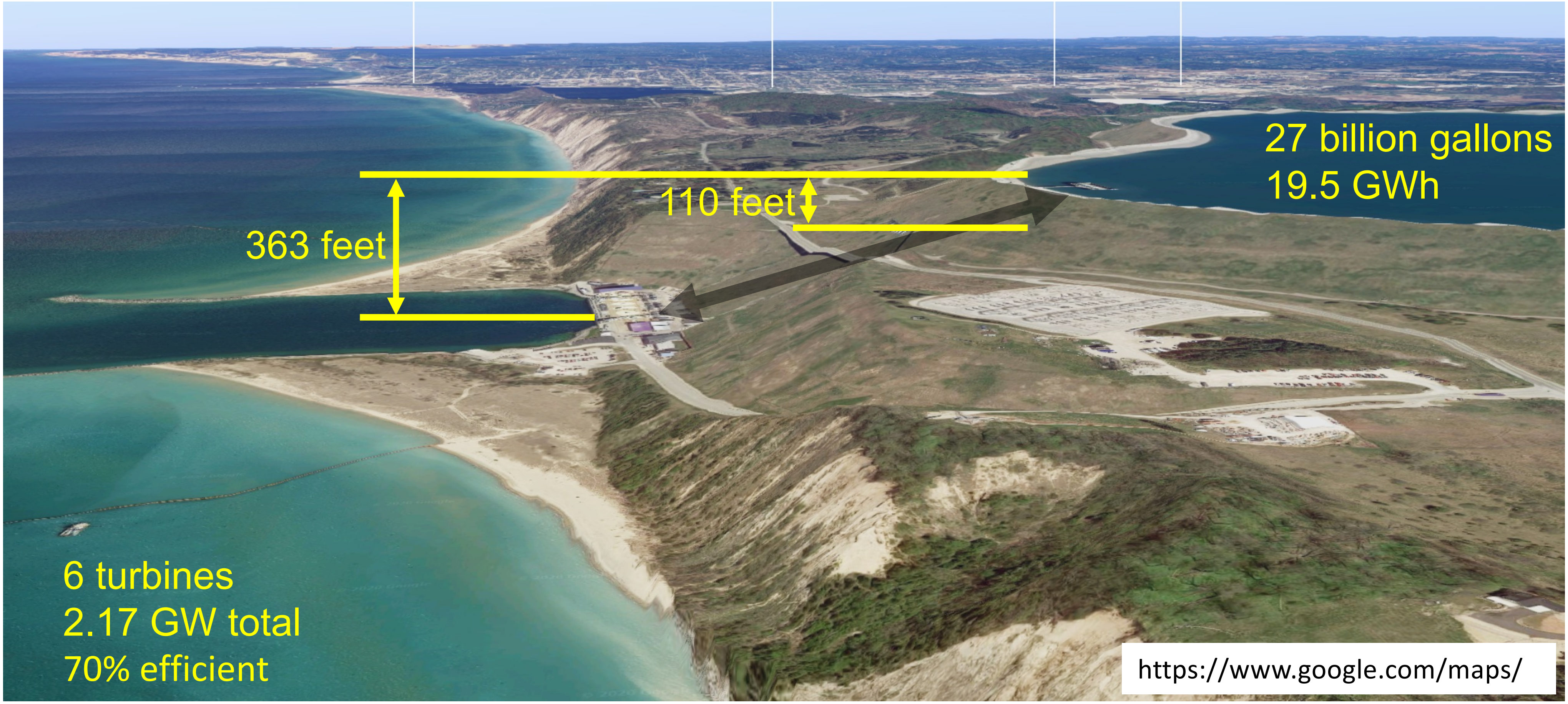


FIGURE 13.40 Dependence of the fraction of power that can be extracted from wind on the ratio of the wind speeds behind and in front of a rotor. The blue dot marks the maximum.

Let's Teach Renewables: Storage

Energy Storage: Example Ludington Pump Storage

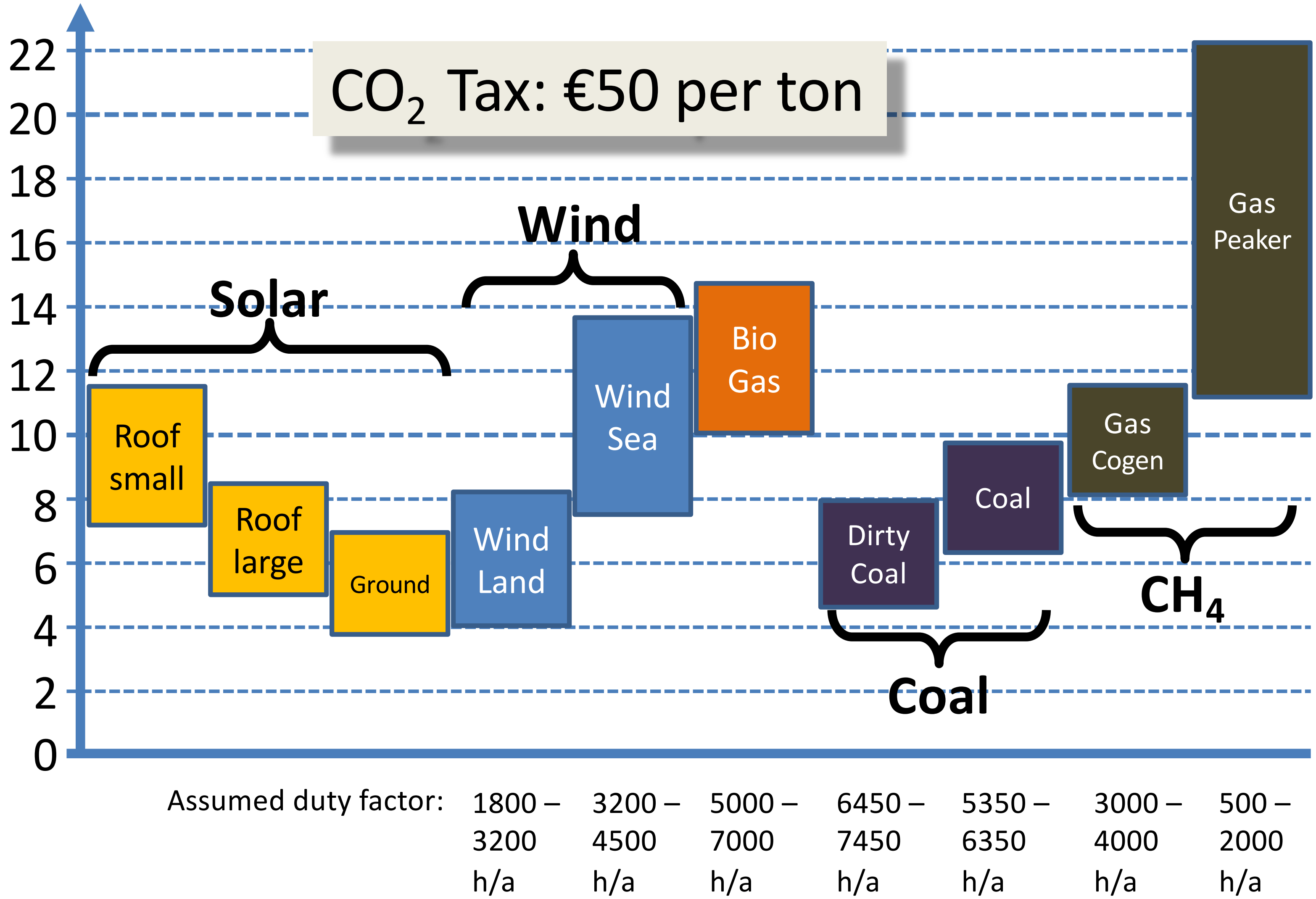


Potential Energy: $U = m\ g\ h = 7.0 \cdot 10^{13}$ J

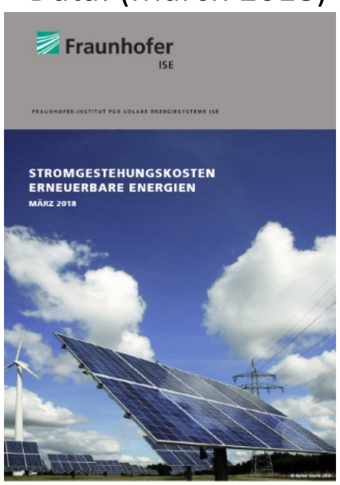
The same energy storage as 260,000 Tesla Model Y batteries

Let's Teach Renewables: Economics

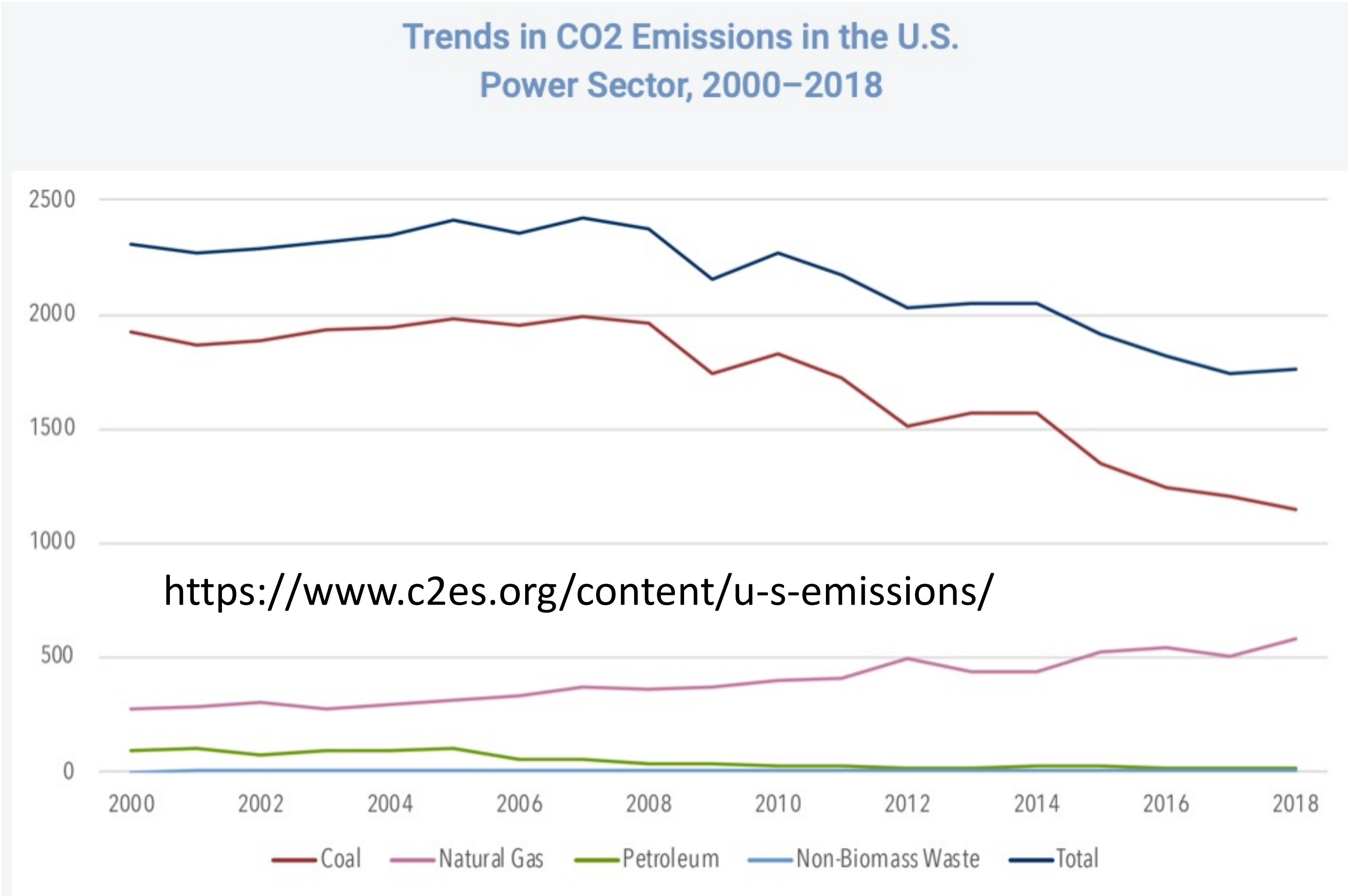
- First, remember: *E* = $
- Environmental Sustainability must also mean Financial Sustainability
- Energy Conservation measures are often the lowest hanging fruit



Data: (March 2018)



$50/ton ~ $100B/year total for USA ~ $300/person/year



What We Can Do:
Michigan State University

Sustainability / Renewables @ MSU

- Recycling center /surplus store
- Organic waste composting facility
- Geo-thermal array
  - Nursing building
- Anaerobic digester
  - Processing of food waste, reduction of artificial fertilizer use, electricity production
- Solar arrays
- Demand reduction
  - M$10/year energy conservation measures
  - Better building challenge
  - Data center challenge
  - Spartan treasure hunts

GE-Spartan-(Toyota) Treasure Hunts

- The greenest energy is the energy we do not consume
- 25 buildings
- 4.6 M sqft
- Participation from Facilities Staff, Students, and Faculty

Energy Conservation Measures

- Recurring investment
  - $5 - $10 million per year
  - ROI time of 5 years or less
- Sample projects:
  - LED lighting for dorms/offices/streets
  - Steam traps
  - Variable speed fans
  - Occupancy sensors
  - Double-paned windows

Data Center (2017)

- Power Utilization Efficiency (PUE) improvement
  - PUE = Total power to data center / power to computers
  - 70+ data centers on campus with average PUE ~ 2
  - New data center has PUE < 1.3
  - 2 MW compute load => ~ 12,000 MWh energy savings / year
- Cyber security, ...

History of Power Generation @ MSU

2016-2018: Re-balancing the T.B. Simon Plant

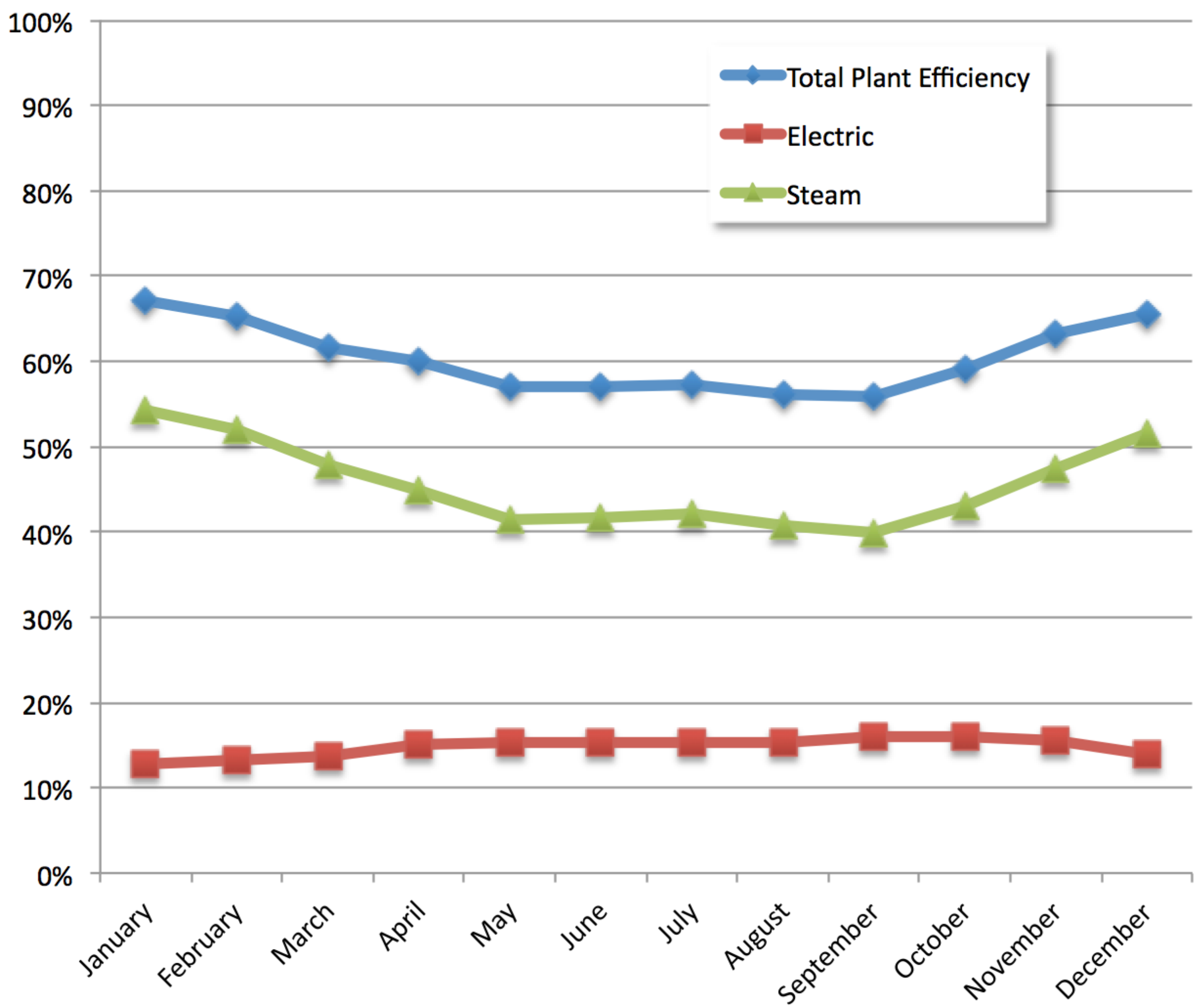
- Renewables
- Duct bank
- RICE

2000	Gas	2016-2018: Re-balancing the T.B. Simon Plant
1964: Michigan State University	Coal	1965: T.B. Simon Plant
1955: Michigan State University of Agriculture and Applied Sciences	Coal	1948: Shaw Lane Power Plant
1950	Coal	
1925: Michigan State College of Agriculture and Applied Sciences	Coal	1921: 3rd Power Plant
1909: Michigan Agricultural College	Coal	1904: 2nd Power Plant
1900	Wood	1894: First Power Plant (partial electrification)
1855: Agricultural College of the State of Michigan	Wood	1882: Central Boiler House
1850		

21-July-2020

Image Source: http://onthebanks.msu.edu/Exhibit/1-6-A/history-of-campus-energy-use/

Simon Plant: Electricity & Steam Co-Generation



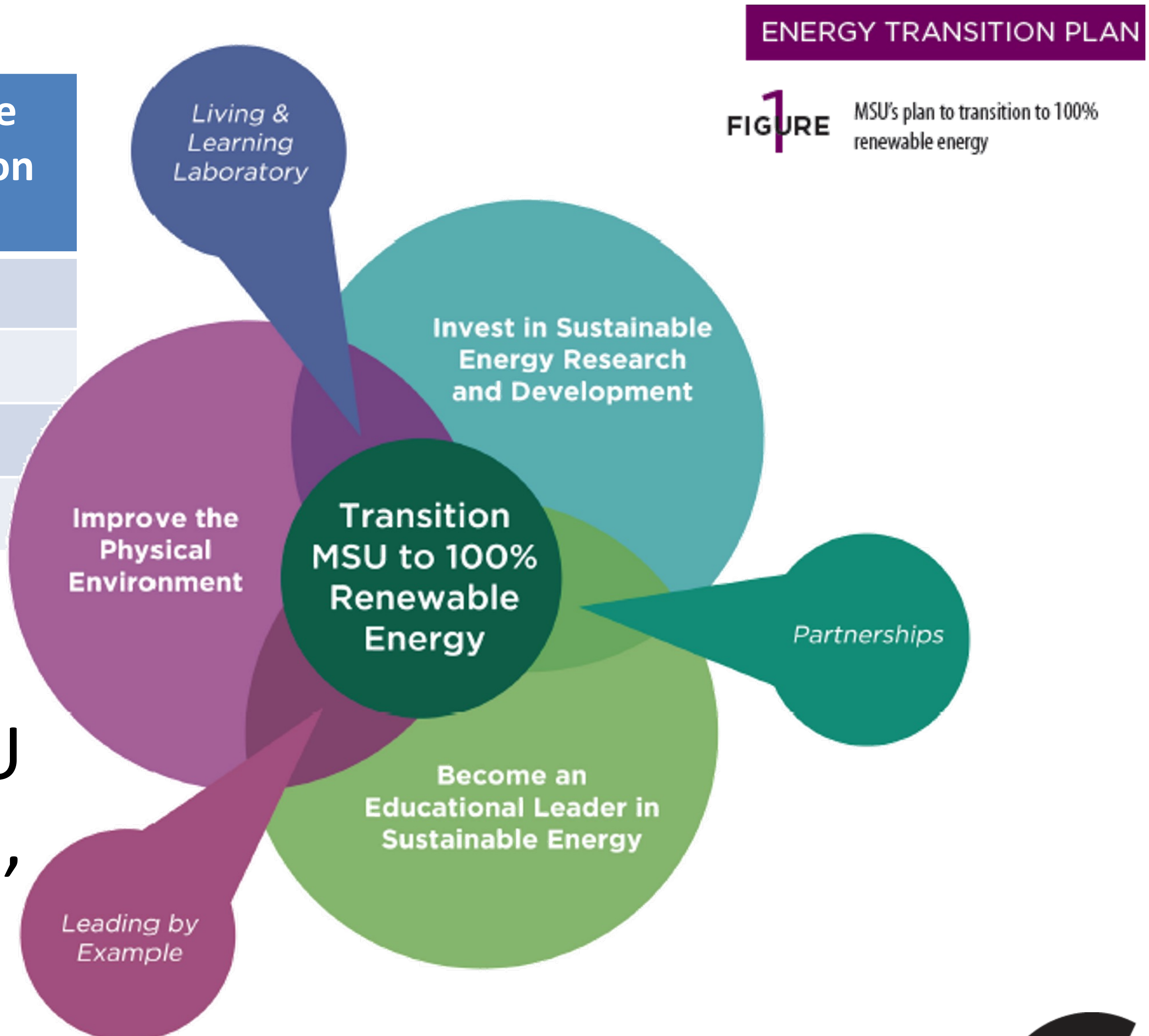
- Totally self-contained micro-grid
- Co-generates all heat and electricity for campus
- ~ 6 TBTU primary fuel consumption

MSU Energy Transition Plan

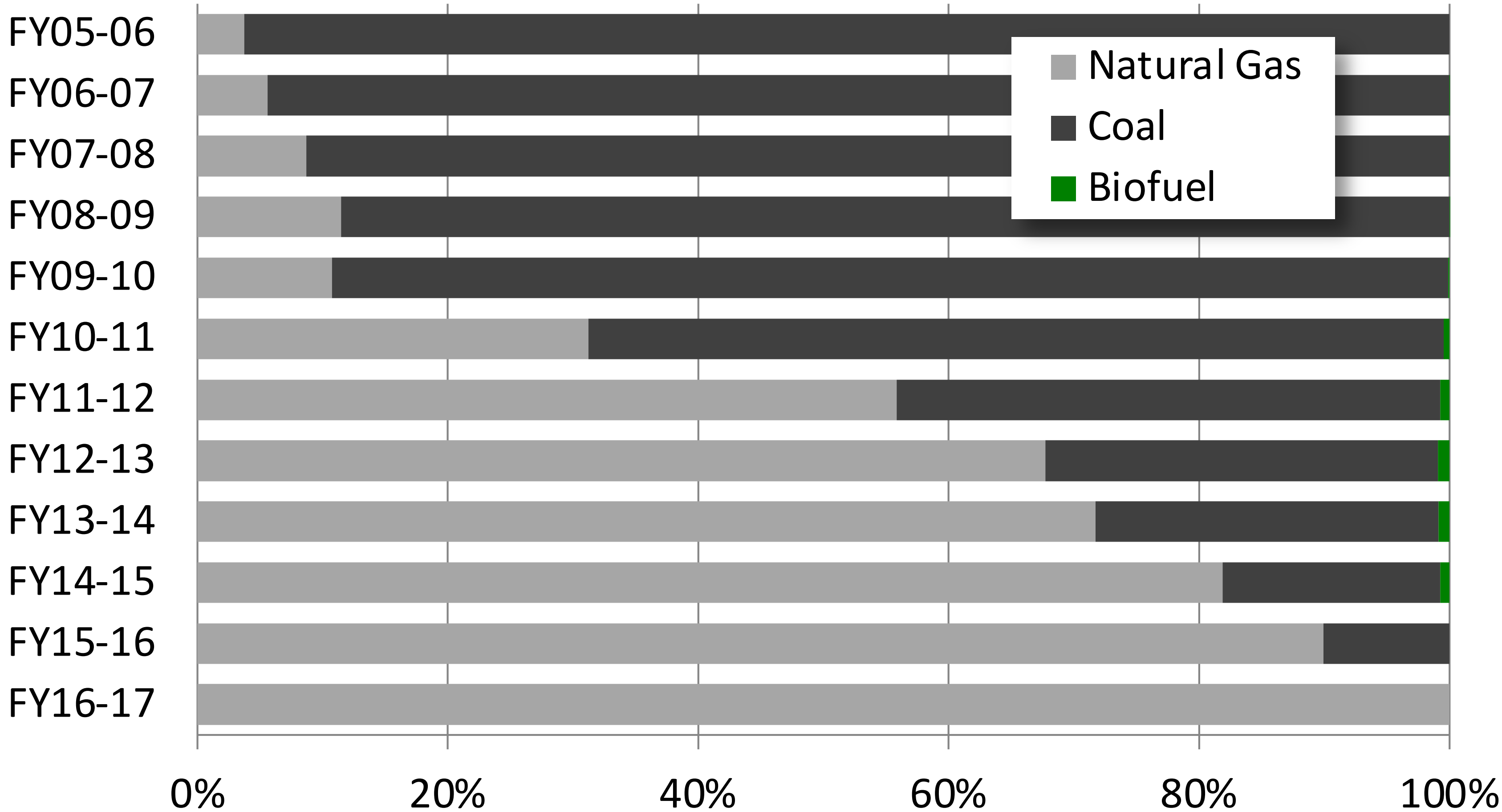
- Timetable

Year	Campus Renewable Energy	Greenhouse Gas Emission Reduction
2015	15%	30%
2020	20%	45%
2025	25%	55%
2030	40%	65%

- Approved by MSU Board of Trustees, April 2012



MSU Fuel Mix



Bituminous coal: 206 pounds of CO_2 per million BTU of fuel

Natural gas: 117 pounds of CO_2 per million BTU of fuel

Fuel switch from coal to gas results in CO_2 emission reductions of ~250,000 metric tons per year!


March 24, 2016:
Last Coal at MSU

Renewable Energy Sweet Spot: Solar Carports PPA!

- **Pros:**
  - No farmland used
  - Keeps sun, rain & snow off parked cars
  - Extends life of asphalt
  - Advertises 'green' efforts
- **Cons:**
  - $20-$30 / MWh cost premium due to car port structure
  - Need for phased construction

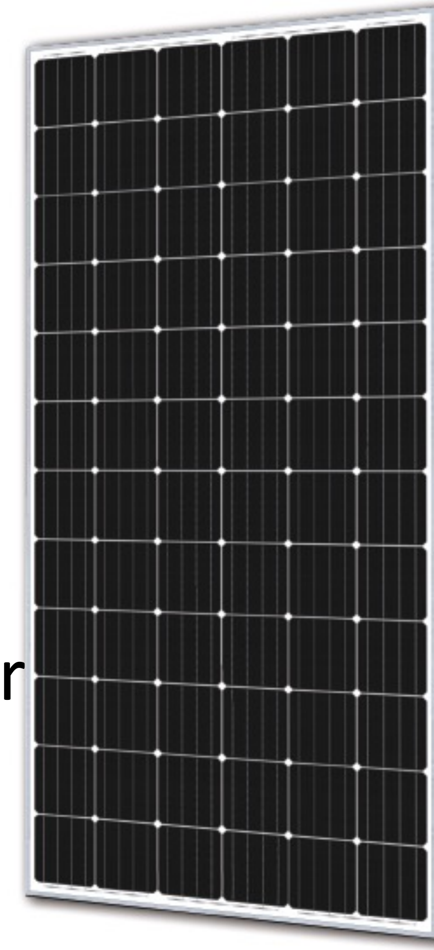
- **Power Purchase Agreement (PPA)**
  - Developer leases land from MSU
  - Developer invest capital and owns the array
  - MSU purchases all produced electricity for a fixed price per kWh during the next 25 years

WB et al., in Handbook of Theory and Practice of Sustainable Development in Higher Education (Volume 4), Springer (2017).

Solar Panel

TP672M
72 CELL SERIES

- 72 cells on each panel
  - Size: 6”x6”
  - Monocrystalline silicon
- Panel Size: 3’x6’
- Maximum power output: 335 W
- Power degradation < 0.7%/year
  - Year 25: no less than 80% of initial power



Senior Engineering Capstone Class Fall 2015

ECE 480 Engineering Building, Room 2250 | Second Floor **10:20 a.m.**

Michigan State University
Early Warning Sensing for Solar Panels

Michigan State University, in an effort to use renewable energy, is in the process of acquiring a solar panel array. The solar panels will be located in the southern section of Michigan State's campus and will cover five large parking lots via carport structures. Solar energy electricity output depends on the amount of light shining at any particular time. Since the electricity output depends upon the current weather a sudden change in cloud cover will create a reduction in the solar panel power output and create costs to import backup power go up greatly.

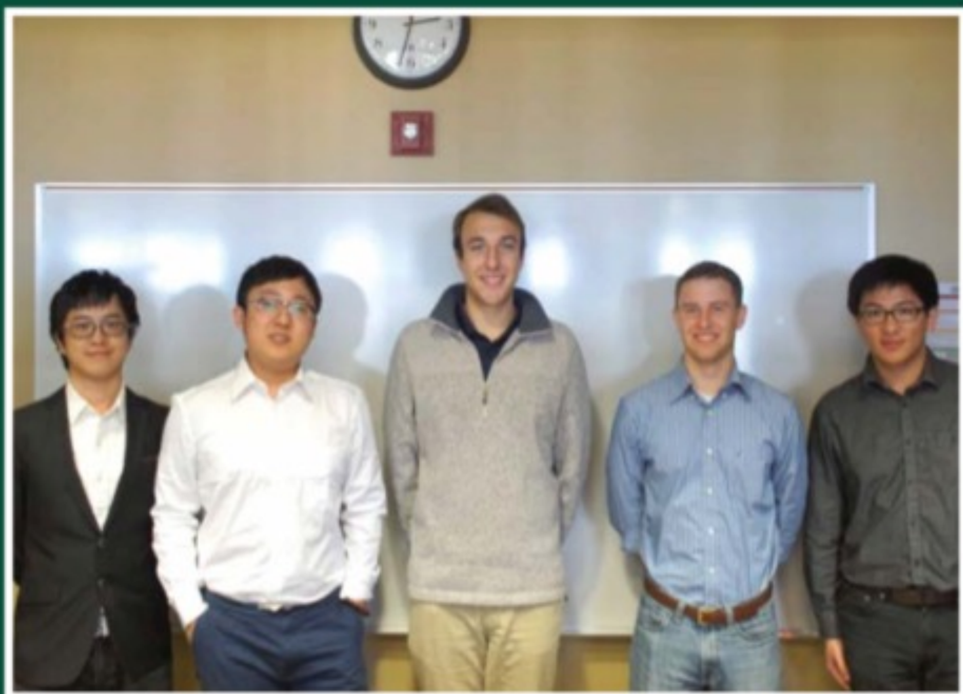
Our team is developing an early warning system based on remote sensors, which will enable users to anticipate changes in the output of the solar array and take appropriate action in the local profile.

By placing sensors a designated distance outside the solar panel array, a time series of the amount of light can be taken and relayed wirelessly to the control station. A software program takes the data and creates a real-time simulation of the weather around the solar panel array. Using real-time simulation, an early warning can alert users to changing weather conditions.

A sensor and microcontroller will be placed on residential homes around the area. At these locations the sensor data can be uploaded to the residential owners' Wi-Fi and to a server accessible for the software platform.

MICHIGAN STATE UNIVERSITY

Senior Engineering Capstone Class Fall 2015



Michigan State University
Team Members (left to right)

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Jiaxing, Zhejiang, China

Spencer Krug
Grand Haven, Michigan

Nate Vargo
Rochester, Michigan

Tianhang Sun
Wuxi, Jiangsu, China

Michigan State University
Project Sponsors

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East Lansing, Michigan

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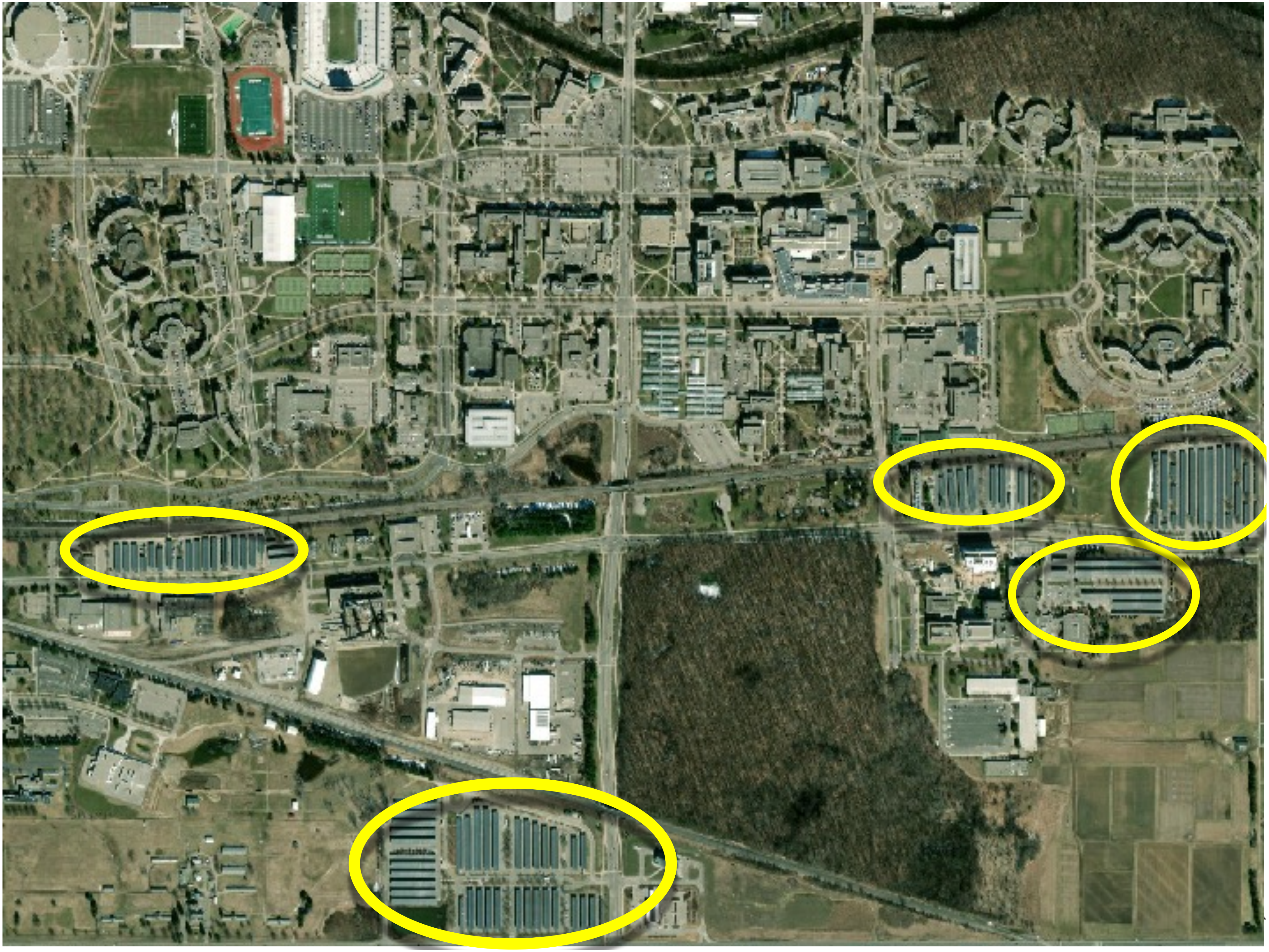
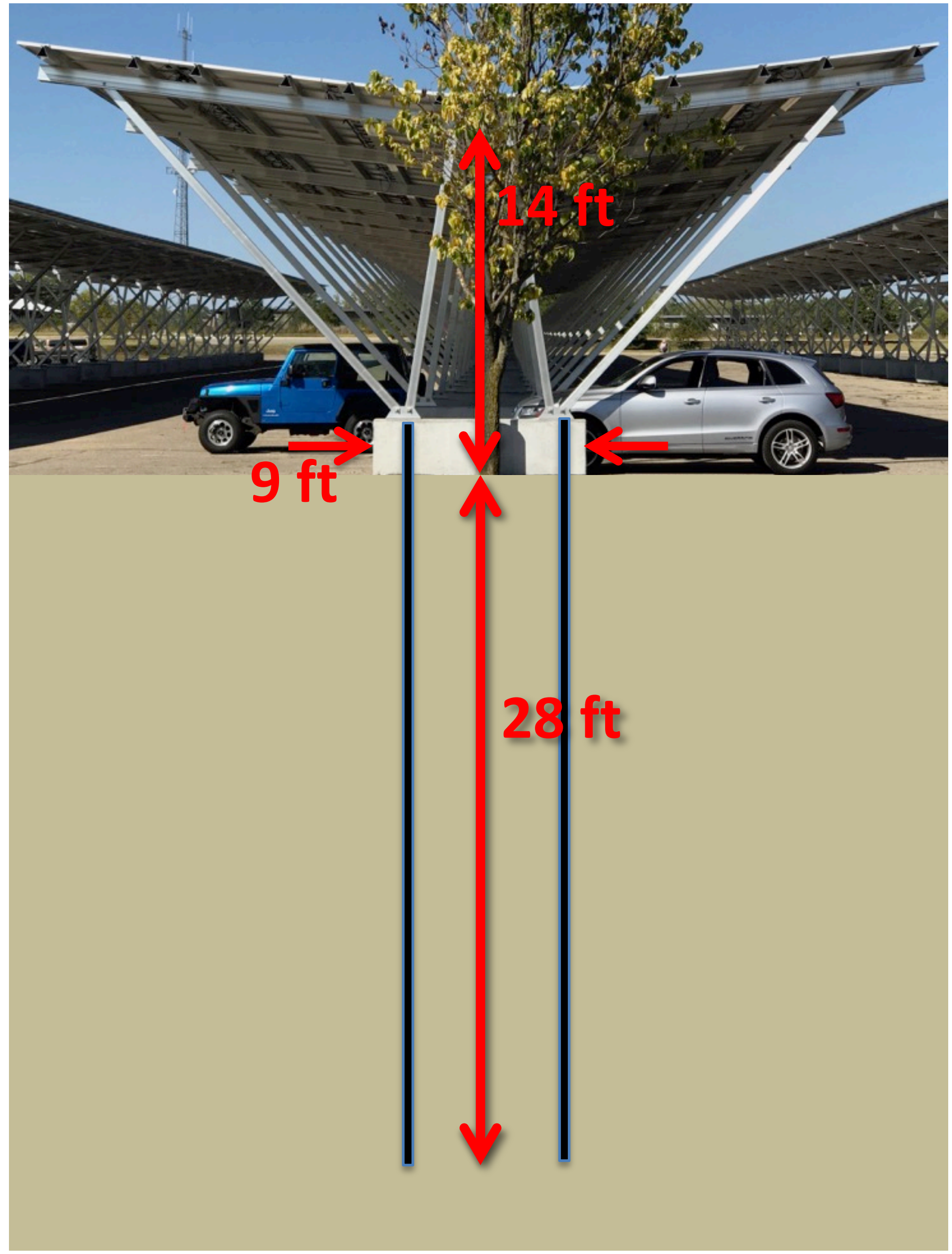
East Lansing, Michigan



Dimensions

- 5,000 parking spots
- 45 acres
- 40,000 solar panels
- 13.4 MW dc peak power
- 10.5 MW ac peak power
- 15,000 MWh/year of solar energy



Finished Product

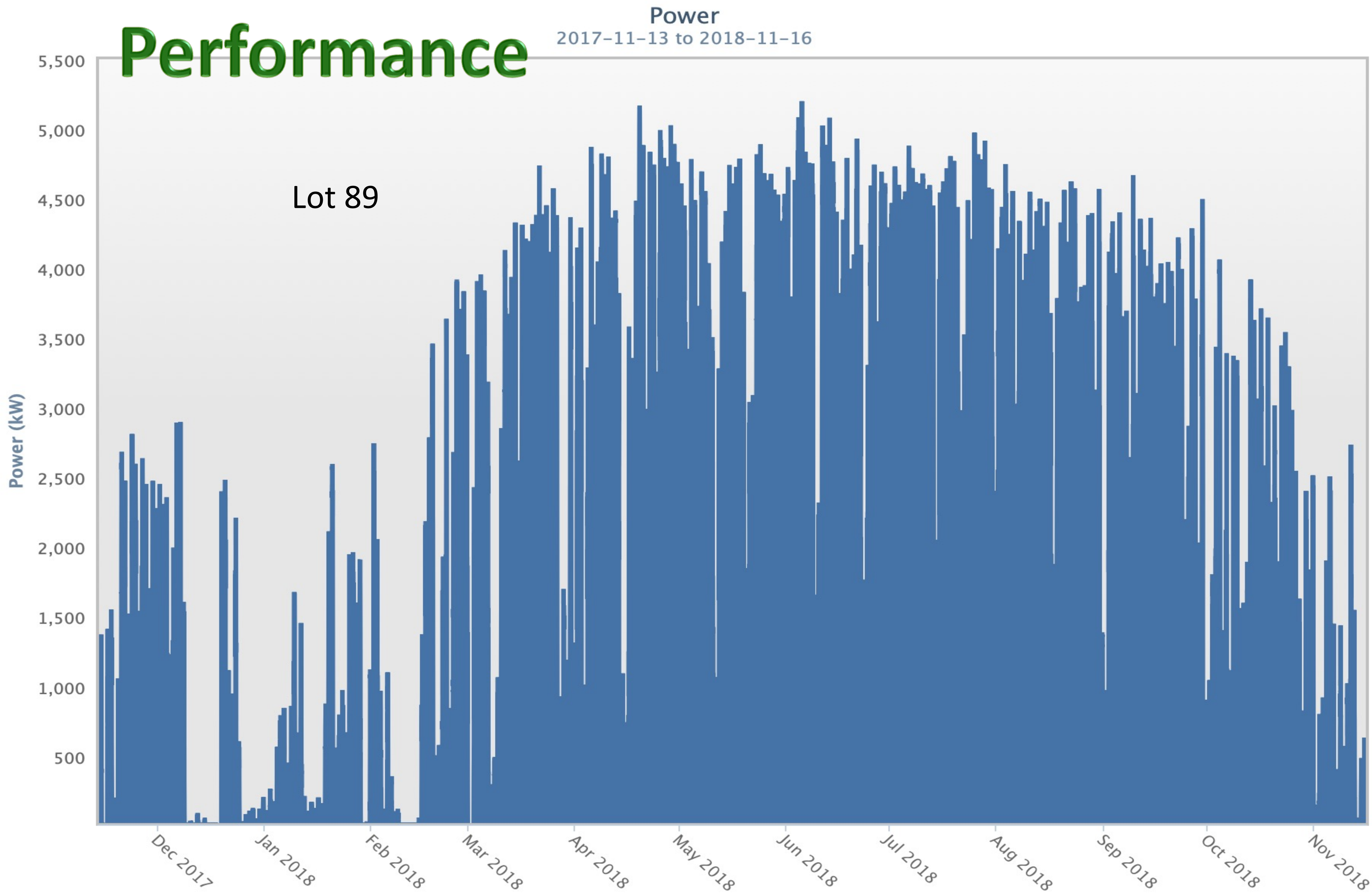
18% of MSU peak power demand, 6% of MSU total annual energy

Finished Product

Largest solar carport array in the USA

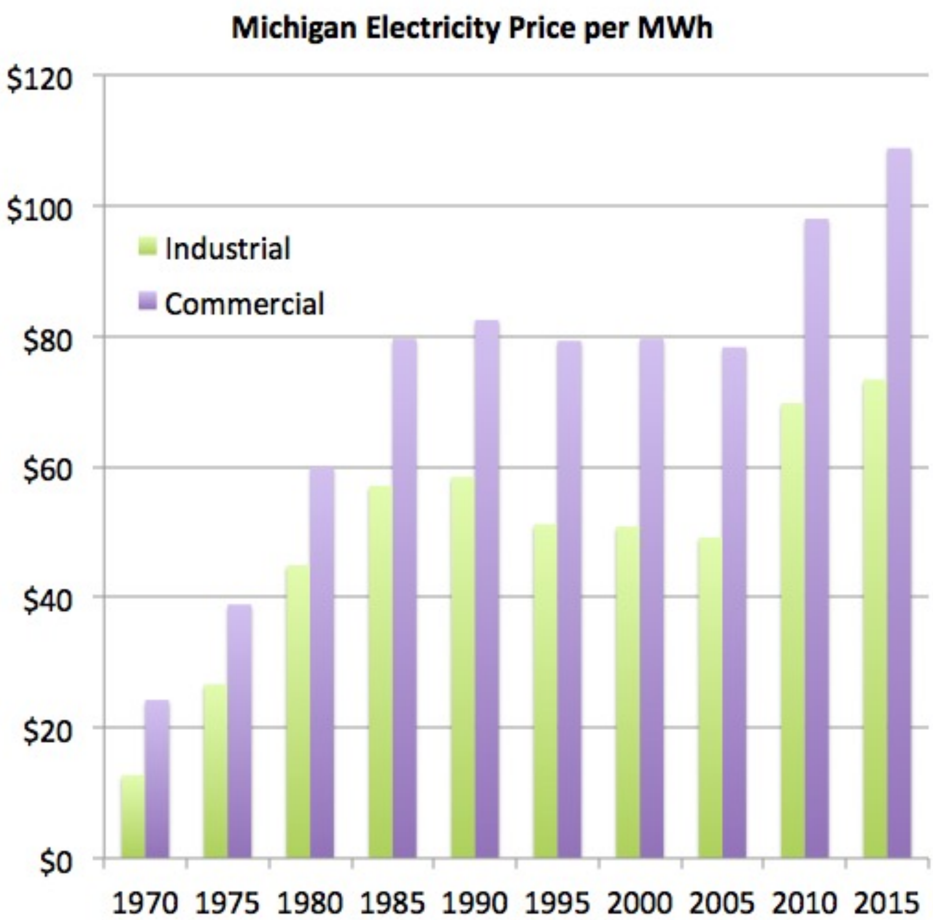
LED Night Lighting

Performance



Financial Benefits

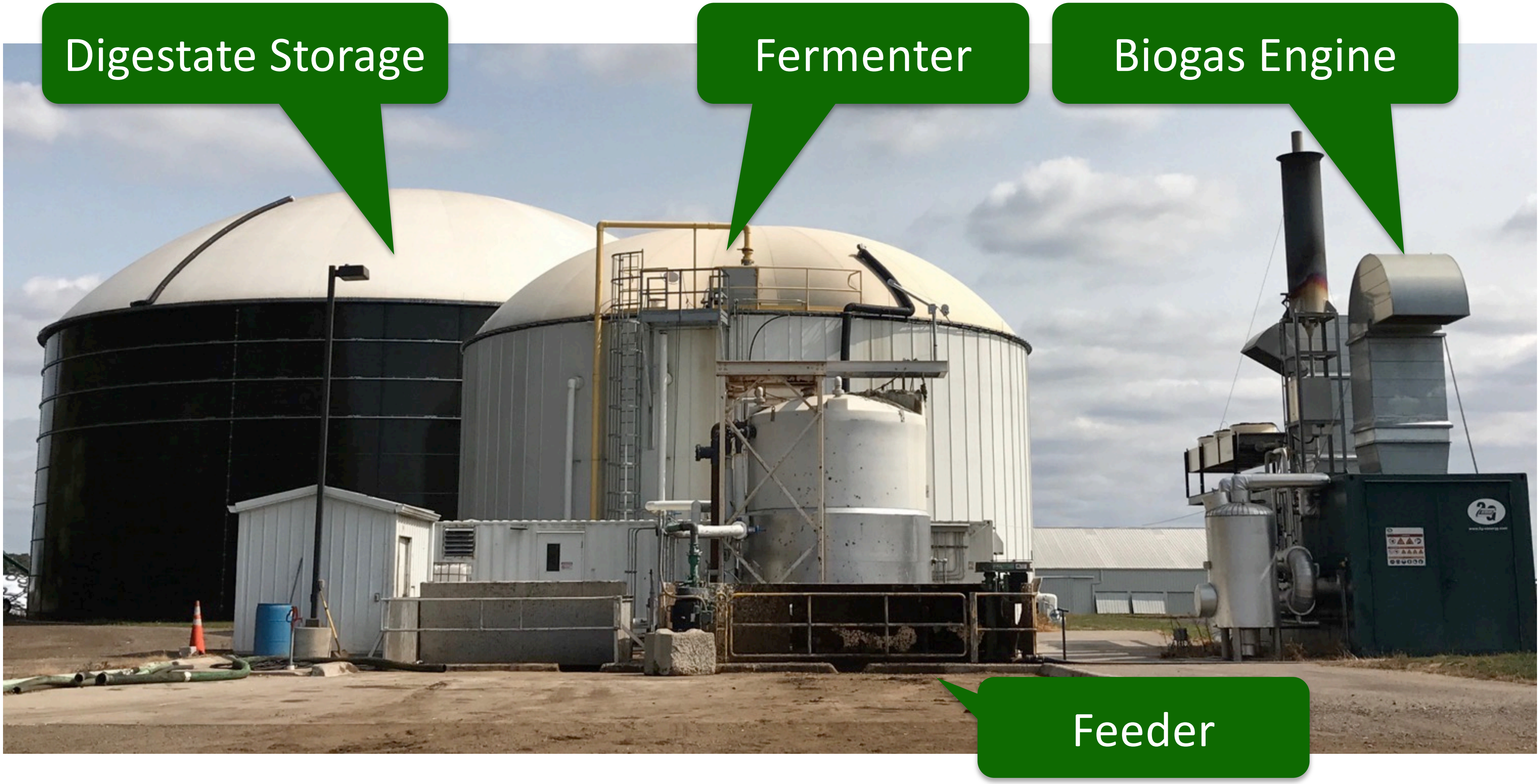
- PPA allows MSU to purchase power at a fixed price over the next 25 years
- 2015 public service commission utility rate **$91/MWh,** but will increase. (DOE-EIA projection: 2.3%/year; last decade: 3.35%/year)



Projected total net savings **~$10M** for MSU over the 25 year PPA period

Green power is now cheaper than **brown** power!

MSU Anaerobic Digester



W. B., Journal of Energy and Power Engineering 7, 1656 (2013)

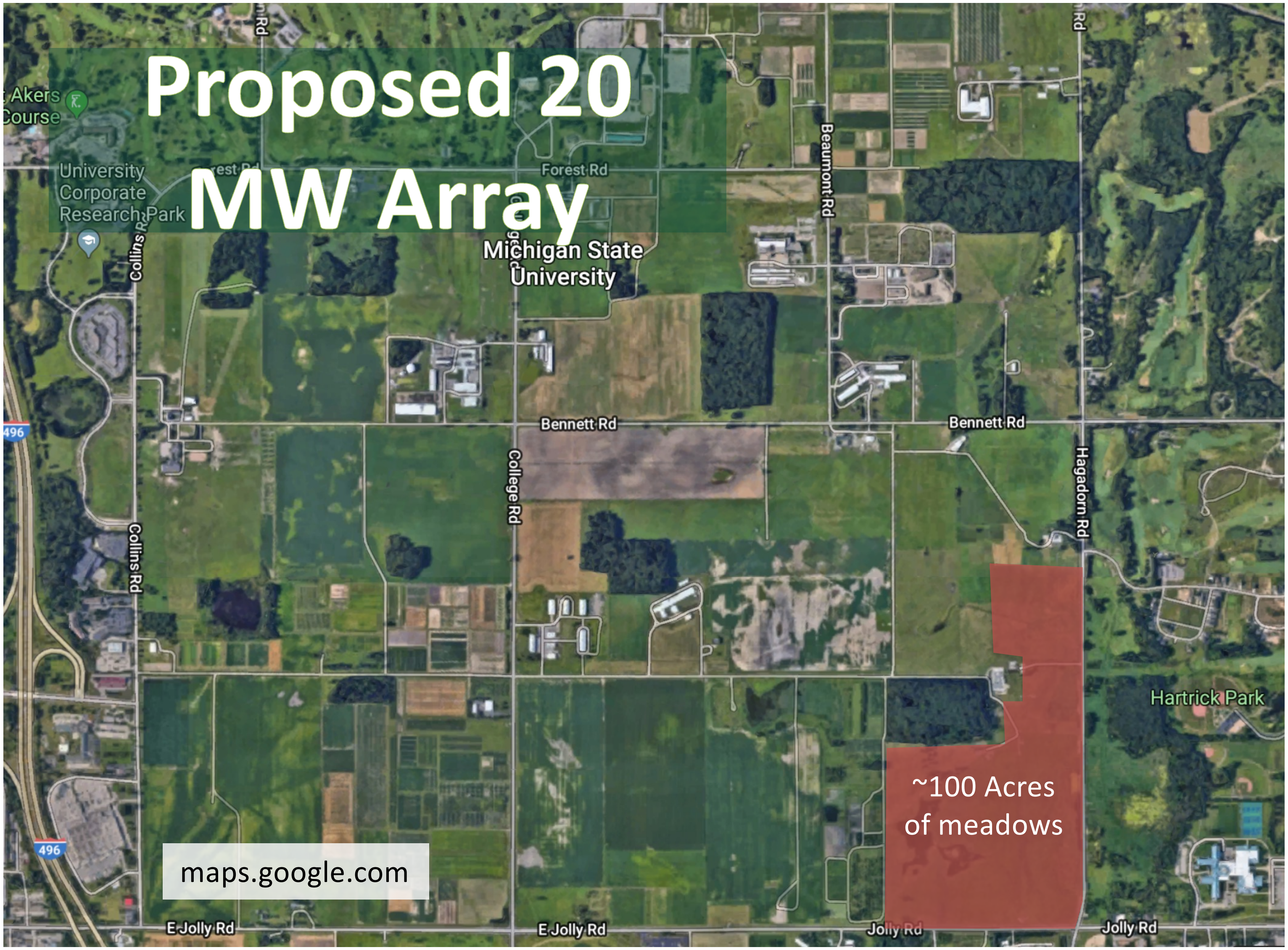
Digester Feedstock

Table 2: MSU South Campus Anaerobic Digester Feedstock

Feedstock	**TS** (%)	**Planned** (tons)	(%)	**2014** (tons)	(%)	**2015** (tons)	(%)	**2016** (tons)	(%)
Dairy manure	12	7,000	43	16,000	67	9,525	43	10,554	52
Fruit & vegetable	11	3,900	24	2,900	12	2,900	13	0	0
Fats, oil & grease	20	5,000	30	4,400	19	3,730	17	4,747	23
Cafeteria food waste	10	750	3	430	2	440	2	513	3
Milk process waste	12					5,475	25	4,444	22
Packing material	90					60	-	34	-
Glycerin	15							88	-
Total		**16,650**		**23,730**		**22,070**		**20,380**	

- ~2,000 garbage trucks / year of organic waste that do not get landfilled (and would release methane there …)
- Turned into
  - ~5,000 MWh of electricity
  - ~10,000 m^3 of valuable organic fertilizer

WB, J. Fundam. Renewable Energy Appl. 7:7 (Suppl), 67 (2017).


Proposed 20 MW Array
Akers Course
University Corporate Research Park
Forest Rd
Michigan State University
Beaumont Rd
Collins Rd
Bennett Rd
College Rd
Hagadorn Rd
Hartrick Park
~100 Acres of meadows
maps.google.com
496
E Jolly Rd
Jolly Rd

Dual Use

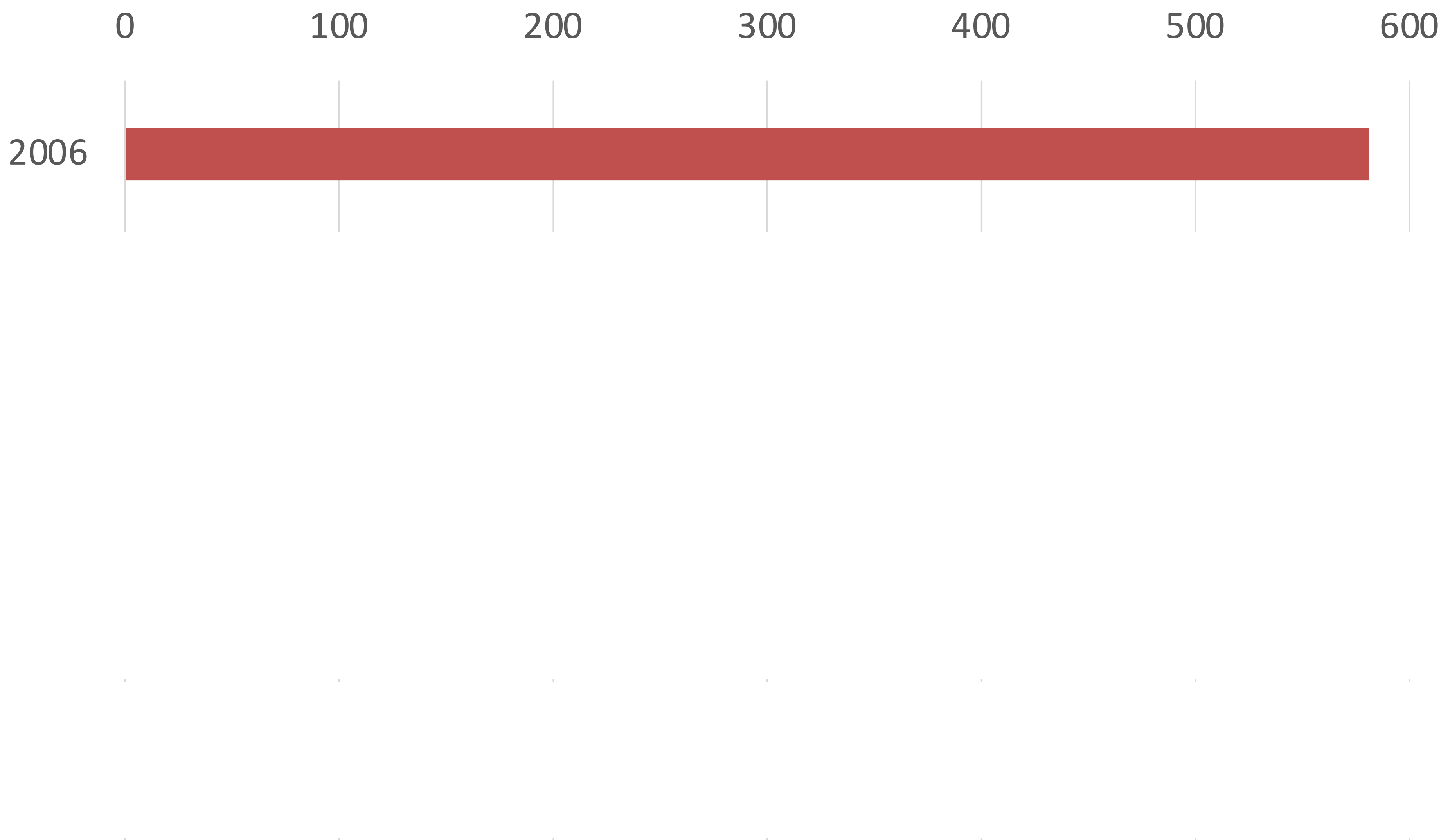
https://www.princeton.edu/news/2018/06/28/sheep-shear-maintenance-princetons-solar-field

Sheep Grazing Meadow

https://denison.edu/news-events/featured/131013

Wildflower/Pollinator Habitat

MSU Emissions: kiloTons of Carbon Dioxide / year



How many trees?

- 700 trees/acre
- 1000 pounds of CO_2 sequestered during life of a tree
- Total CO_2 emission reduction equivalent to planting 14 Baker Woodlots of trees (> 800,000 trees) *each year*.

Baker Woodlot, MSU:
78 acres (~ 320,000 m^2)
~55,000 trees

- *Contact Info*

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