THE UNIVERSITY of TENNESSEE
KNOXVILLE

A new Interdisciplinary PhD in Energy Science and Engineering

Reactor and Nuclear Systems Division Seminar

Lee Riedinger
Director
UTK/ORNL
Center for Interdisciplinary Research and Graduate Education (CIRE)
Professor of Physics

July 14, 2011

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

THE UNIVERSITY of TENNESSEE
KNOXVILLE

Center for Interdisciplinary Research and Graduate Education (CIRE)

- **January 2010: Tennessee General Assembly passed legislation authorizing UT to establish an academic unit at UTK for interdisciplinary research and graduate education in collaboration with ORNL - CIRE**
- **The goals of CIRE are to:**
  - **Increase the number of UTK STEM PhD students**
  - **Enhance research collaborations between UTK and ORNL**
  - **Solve problems of national significance in energy-related areas**
- **February 2010: Thom Mason and Jimmy Cheek chartered a UTK-ORNL Task Force to create and implement CIRE**
  - **Wayne Davis and Jim Roberto co-chairs**
- **May 2010: UTK and ORNL entered into an agreement to develop CIRE**
  - **This includes facilitating an increase in ORNL staff who hold faculty appointments at UTK and can supervise doctoral research**
- **June 2010: internal search for a director - Lee Riedinger hired September 1**

Energy Science and Engineering doctorate

- New *interdisciplinary* Energy Science and Engineering PhD
  - Provides breadth while ensuring a "deep dive" in a specific area
  - Specialty areas chosen to resonate with DOE priorities
  - Initial specialties: nuclear energy, bioenergy, energy conservation and storage, renewable energy, distributed energy and grid management, environmental and climate sciences related to energy
  - Entrepreneurial component
  - Approved by the Tennessee Higher Education Commission on January 12, 2011
- Traditional PhD with a concentration in ESE
  - Includes same knowledge breadth and entrepreneurship core as the ESE PhD
- This PhD program is administered and housed in the *Center for Interdisciplinary Research and Graduate Education - CIRE*

The ESE doctoral program leverages the assets of ORNL - DOE's largest science and energy laboratory

- $1.4B budget
- 4,550 employees
- 3,900 research guests annually
- $500 million invested in modernization

- World's most powerful open scientific computing facility
- Nation's largest concentration of open source materials research

- Nation's most diverse energy portfolio
- Operating the world's most intense pulsed neutron source
- Managing the billion-dollar U.S. ITER project

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ESE curriculum overview

- **Core Curriculum (6 credits)**
  ESE 511 and ESE 512 - Introduction to Energy Science and Technology - will be taught by Lee Riedinger with contributions from CIRE faculty - Mondays and Wednesdays from 12:20 to 2:15 pm - room 306 of Nielsen Physics Building
- **Knowledge Breadth Curriculum (6 credits): two courses from following areas**
  - **Political, social, legal, ethical and security issues related to energy**
  - **Entrepreneurship, leadership, and management**
  - **Environmental and climate sciences related to energy**
- **Knowledge Specialization Curriculum (15 credits)**
  Choose five courses from participating department as defined in CIRE Graduate Student Handbook
  - **Nuclear energy**
  - **Bioenergy and biofuels**
  - **Renewable energy**
  - **Energy conversion and storage**
  - **Distributed energy and grid management**
  - **Environmental and climate sciences related to energy**

Many existing courses (500 and 600 level) will be used for specialization in the six major energy tracks

- **ESE 599 Seminar (3 credits; 1+1+1): Topical seminars in the focus areas of CIRE - time and place to be determined - need talks by CIRE faculty**

72 hours of graduate credit required for PhD, including at least 36 hours of course work

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Knowledge breadth curriculum - 6 credit hours
Ideas so far

- Entrepreneurship
  - MGT 551 - New Venture Planning (Management, College of Business Administration)
  - MGT 552 - Entrepreneurial Strategy Implementation (Management, College of Business Administration)
  - AGNR 530 – Entrepreneurship and Discovery Commercialization - Fred Tompkins (Agriculture and Natural Resources)
  - Mechanical Engineering and Industrial Engineering 457 – Engineering Entrepreneurship - Lee Martin (College of Engineering)
  - Mechanical Engineering and Industrial Engineering 557 – Technology Product Development and Entrepreneurship - Lee Martin (College of Engineering)
- Policy
  - PS 410 - Special Topics – Energy Policy - Bruce Tonn (Political Science)
  - PHY 405 - Science, Technology, and Public Policy - Tom Handler (Physics)
- Climate
  - ENVE 595 - Special Topics - Climate Seminar - John Drake (College of Engineering)

Space for CIRE

- **At UT - Greve Hall**
  - Taken out of commission as a dorm in summer of 2009
  - CIRE has 4th floor, which has 40 dorm rooms
  - Renovation is proceeding slowly - will *not* have this space ready by August
  - Will use the first floor of Temple Court for much of new academic year
- **At ORNL - Joint Institute for Computational Sciences**
  - Use the open room in the northeast corner on first floor
  - Some renovation is needed to make a few offices in part of this space

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Two UT/ORNL opportunities for graduate students

- **Energy Science and Engineering (ESE) interdisciplinary PhD**
  - Goal is to recruit 20 to 40 new PhD students per year
  - Support by the CIRE program until a research group is chosen from possibilities presented by CIRE faculty
  - 18 students will start in August
- **UT-ORNL Distinguished Graduate Fellowship (DGF)**
  - Research in one or a combination of three areas:
    - Materials science and engineering, including neutron science
    - Computational science and engineering
    - Nuclear science and engineering
  - Goal is to recruit 10 to 12 new PhD students per year
  - 3 students started last fall
- **$28K annual stipend with a few $30K stipends for the top performers**

Web sites:
- CIRE: http://cire.utk.edu
- ESE: http://ese.utk.edu
- DGF: http://distinguished.utk.edu

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Graduate student recruitment

- ORNL recruited at 30 top universities in the fall
- Deadline for application was end of January
- Interviewed 43 at ORNL and UT on February 28 and March 1
- Made 29 CIRE fellowship offers - 15 students accepted
- Those declining the ESE offer going instead to Berkeley (2), Michigan (2), Texas A&M (2), MIT, Johns Hopkins, Purdue, UC Santa Barbara, Vanderbilt
- Recently added three more students who were finishing their Master’s degrees at UT

43 students interviewed on March 1

CIRE class of 2011

	Name	University	Degree unit	Possible mentor	Mentor institution	Comment	Last Degree
1	Allen, Melissa	Univ. of Tenn - Master's in Civil and Environ. Engineering	CIRE - climate	Erickson and Fu	ORNL/UT	Climate	Civil and Environ. Eng
2	Chin, Charles	Univ. of Tenn. - Master's in Biomedical Eng.	CIRE - materials	Doktycz	ORNL	Biomaterials; shared support	Biomedical Eng
3	Culliss, Jerel	Virginia Tech; now at Idaho National Lab	EECS	Liu	UT/ORNL	Arrives January 2012	Electrical Eng
4	Ginder, Ryan	Northwestern University	Materials Science and Eng	Pharr	UT/ORNL		Materials Science & Eng
5	Goetz, Callie	Middlebury College; now at ORNL	CIRE - nuclear	Grzywacz	UT/ORNL	Measurements important for nuclear fission	Physics
6	Hartnett, Chris	Univ. of Tenn. - current grad student - Physics	CIRE - materials	Rack	UTK/ORNL	Materials, shared support; CIRE TA	Physics
7	Hutchins, Ryan	Brandeis; Master's from Univ. of Rhode Island	CIRE - materials	Simpson	ORNL		Physics, Math
8	Jackson, Timothy	Rensselaer Polytechnic Institute	Nuclear Eng.	Hall	UT/ORNL		Nuclear Eng
9	Jones, Steven	Ohio State University	Nuclear Eng.	Hall	UT/ORNL		Materials Science & Eng
10	Kandala, Bhargav	GE Health Care	CIRE			Building technology	Mechanical Eng
11	Kodra, Evan	Univ. of Tenn. - Master's in statistics	CIRE - climate	Ganguly	ORNL	Climate; shared support	Statistics
12	Li, Meng	University of Tennessee - current grad student	Biology	Bruce	UTK - BCMB	Biosciences	Biochemistry & Cellular & Molecular Biology
13	Pezeshki, Alan	California Institute of Technology	CIRE				Chemical Eng
14	Ribbons, Relena	University of Massachusetts Amherst	EEB	Classen	UTK- EEB	Biosciences	Forest Resources
15	Sander, Kyle	Oregon State University	Chemical and Biomolecular Eng.			Biosciences	Biological and Ecological Eng
16	Talley, Kemper	Clemson University	CIRE - nuclear	Nazarewicz and Williams	UTK and ORNL	NSF fellowship winner	Physics
17	Thompson, Adam	Georgia Tech; Master's at Georgia State University	CIRE - Biology			Biosciences	Biochemistry
18	Zhang, Xiwen	Temple University - working in a BCMB lab at UT	CIRE - Biology			Biosciences	Biochemistry

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Overview of CIRE faculty

- First group of 38 faculty appointed by Provost on December 20 - many of the best researchers at UT and ORNL:
  - 18 ORNL
  - 2 UT Institute of Agriculture
  - 18 UTK
- Energy research areas of these 38 faculty:

  1 - Nuclear energy - 5

  2 - Bioenergy and biofuels - 6

  3 - Renewable energy - 3

  4 - Energy conversion and storage - 6

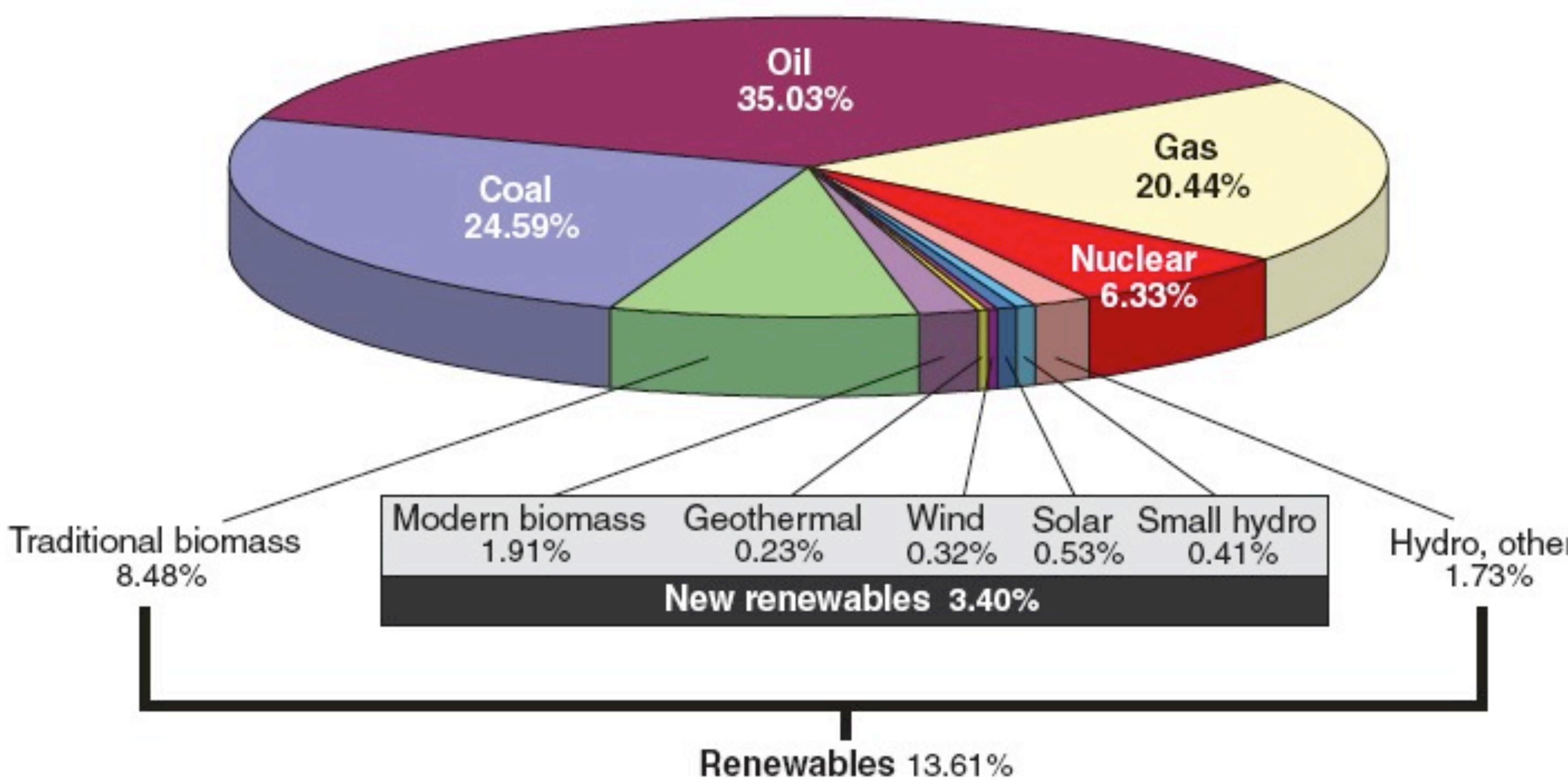
  5 - Distributed energy and grid management - 5

  6 - Environmental and climate sciences related to energy - 4

  7 - Cross cutting - 9 - many are materials people
- More faculty will be added by a *Credentials Committee* of the faculty
- These CIRE faculty are attacking some of the country's top energy problems

Energy is the defining challenge of our time

- **Energy use and supply is the major driver for**
  - Climate change
  - National security
  - Economic competitiveness
  - Quality of life
- **Incremental changes to existing energy technologies cannot meet the challenges we face**
  - Transformational advances in energy technologies are needed
  - Critically dependent on the best science and technology



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Problem #1 - Climate change is real according to world's body of scientists

- Each of the last 12 years has been one of the warmest on record: warmest were 2005, 1998, 2002, 2004, 2006
- Average temperature is 1º C higher now than 100 years ago
- Glaciers are retreating all around the globe
- This is happening faster than scientists anticipated

Change in a glacier in Argentina in 20 years

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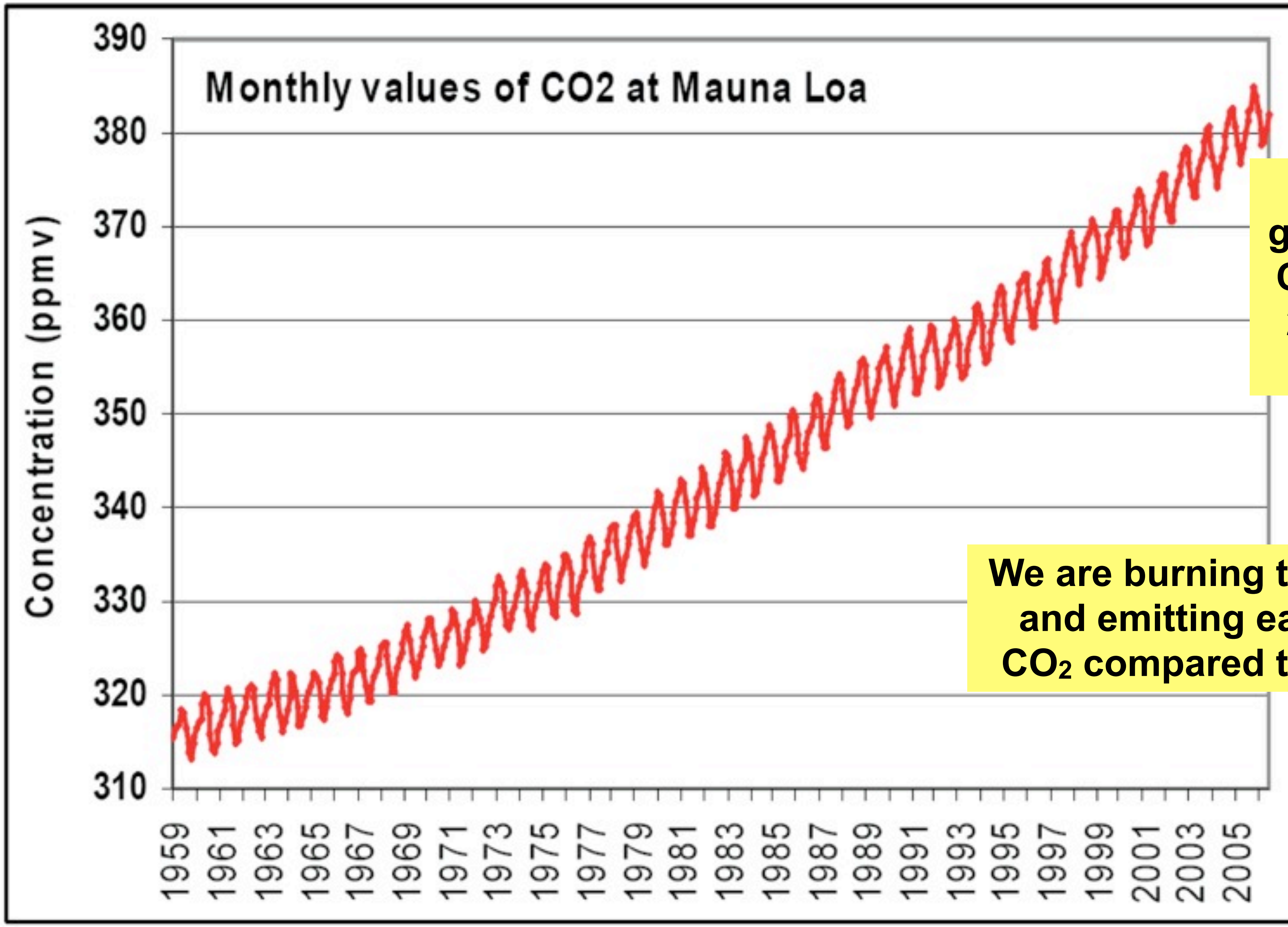
Concentration of CO_2 in the atmosphere in parts per million, 1957–2006



The Earth is better greenhouse now with CO_2 content up from 280 ppm (100 years ago) to 380 now

We are burning too much fossil fuel and emitting each year twice the CO_2 compared to the natural cycle

Source: CDIAC, Oak Ridge National Laboratories.

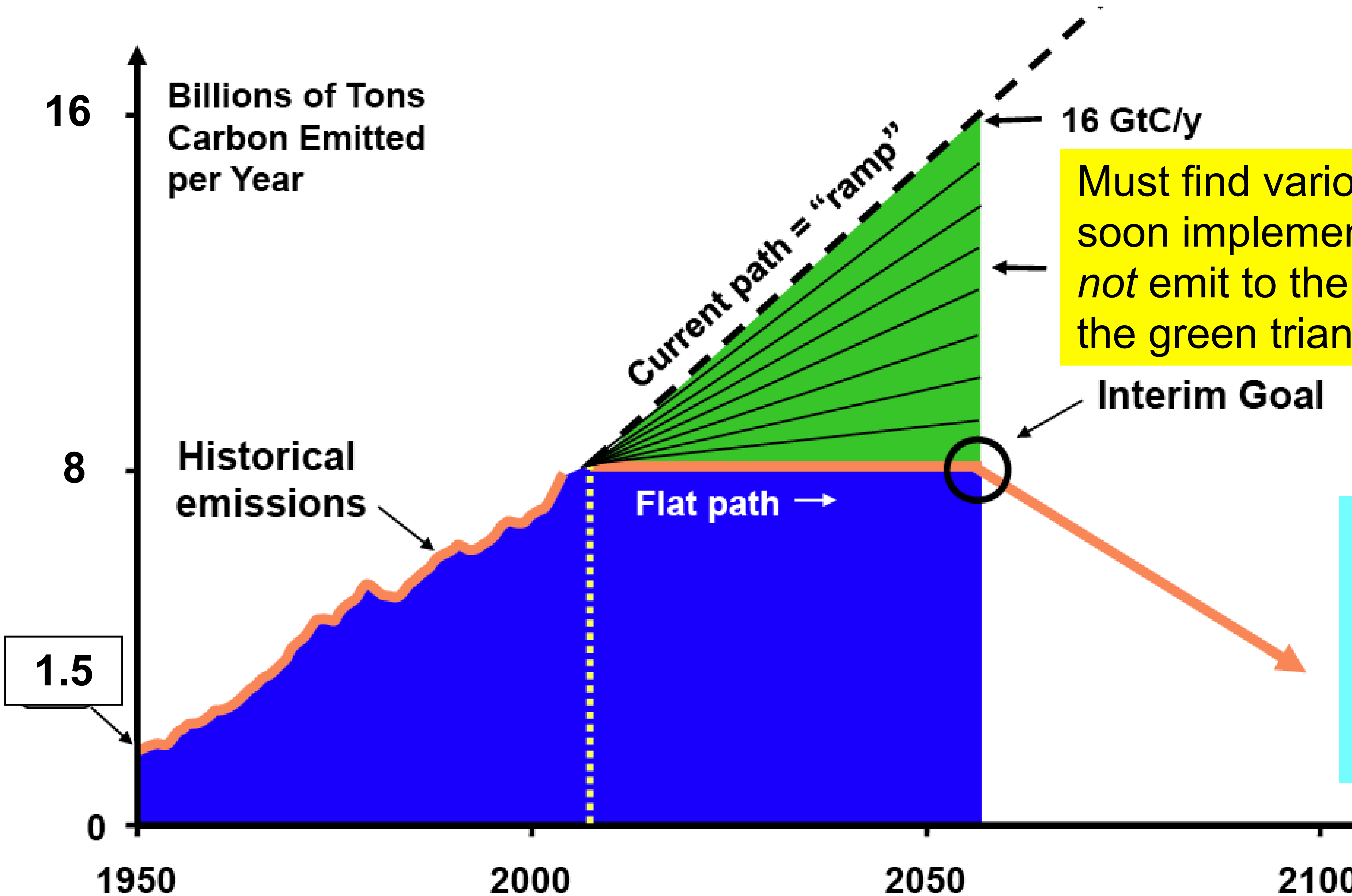
Problem #2 - world energy consumption is projected to increase by 50% by 2030

China and the U.S. each use now around 100 quads of energy per year

Source: International Energy Outlook 2008, DOE/EIA-0484(2008), Energy Information Administration, June 2008

Need plan to keep carbon emissions flat for next 50 years with current technology

- **Doing nothing will lead to doubling current level of CO_2 emissions by 2060**
- **Must lay out options to avoid this extra 8 Gigatons of carbon/yr**

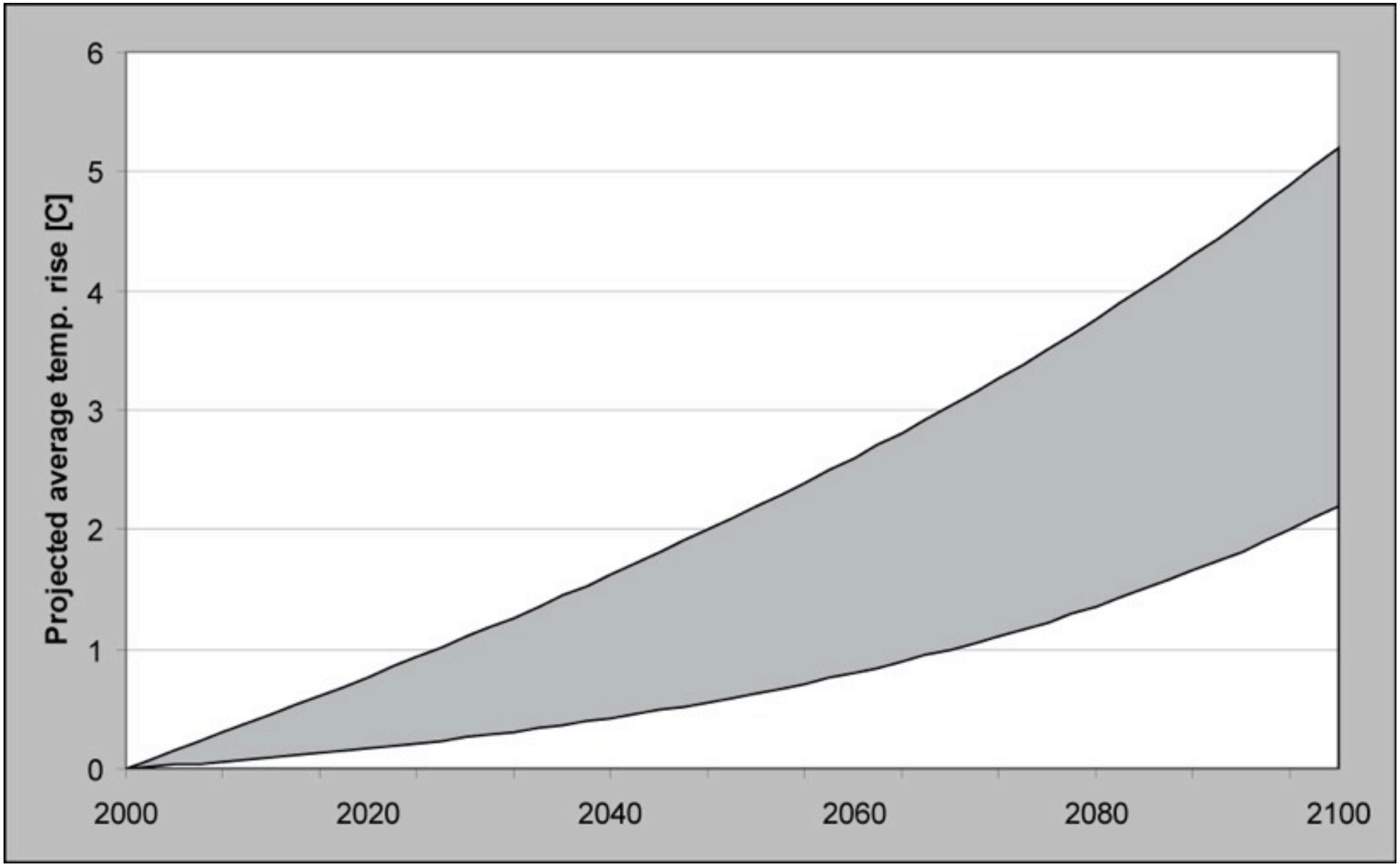


Must find various scenarios that can be soon implemented to allow the world to *not* emit to the atmosphere the carbon in the green triangle

Then there will be new technology by middle of century that will allow world to *decrease* its annual CO_2 emissions

Predicted temperature rise on Earth

- **Use various global climate models to predict temperature rise due to economic scenario of *business as usual***
- **Expect *at least* a 2º C rise in average global T by end of century; maybe 5º C rise**



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CIRE faculty in environmental and climate sciences related to energy are leaders in this area

- **We have a world-level scientific computing facility - *Jaguar***
- **Jaguar focuses on computationally intensive projects of large scale and high scientific impact**
- **UT and ORNL have also an NSF petascale computing center - *Kraken***
- **The country's top climate codes run on these computers**

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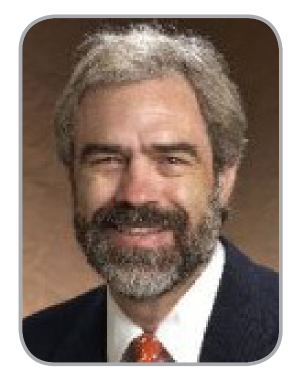

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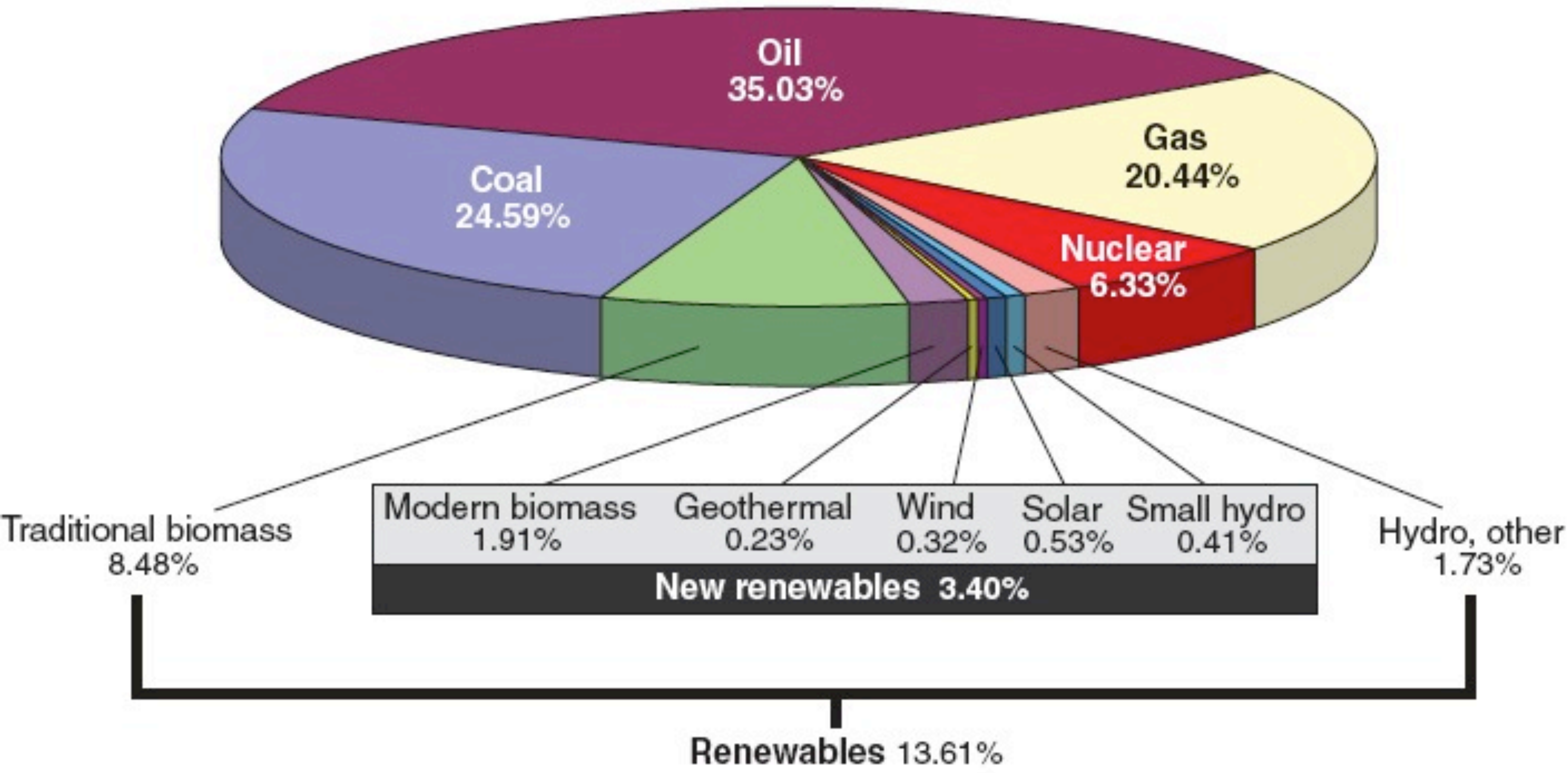
World energy supply - over 80% from burning fossil fuels - that's the big issue



2004 energy use numbers

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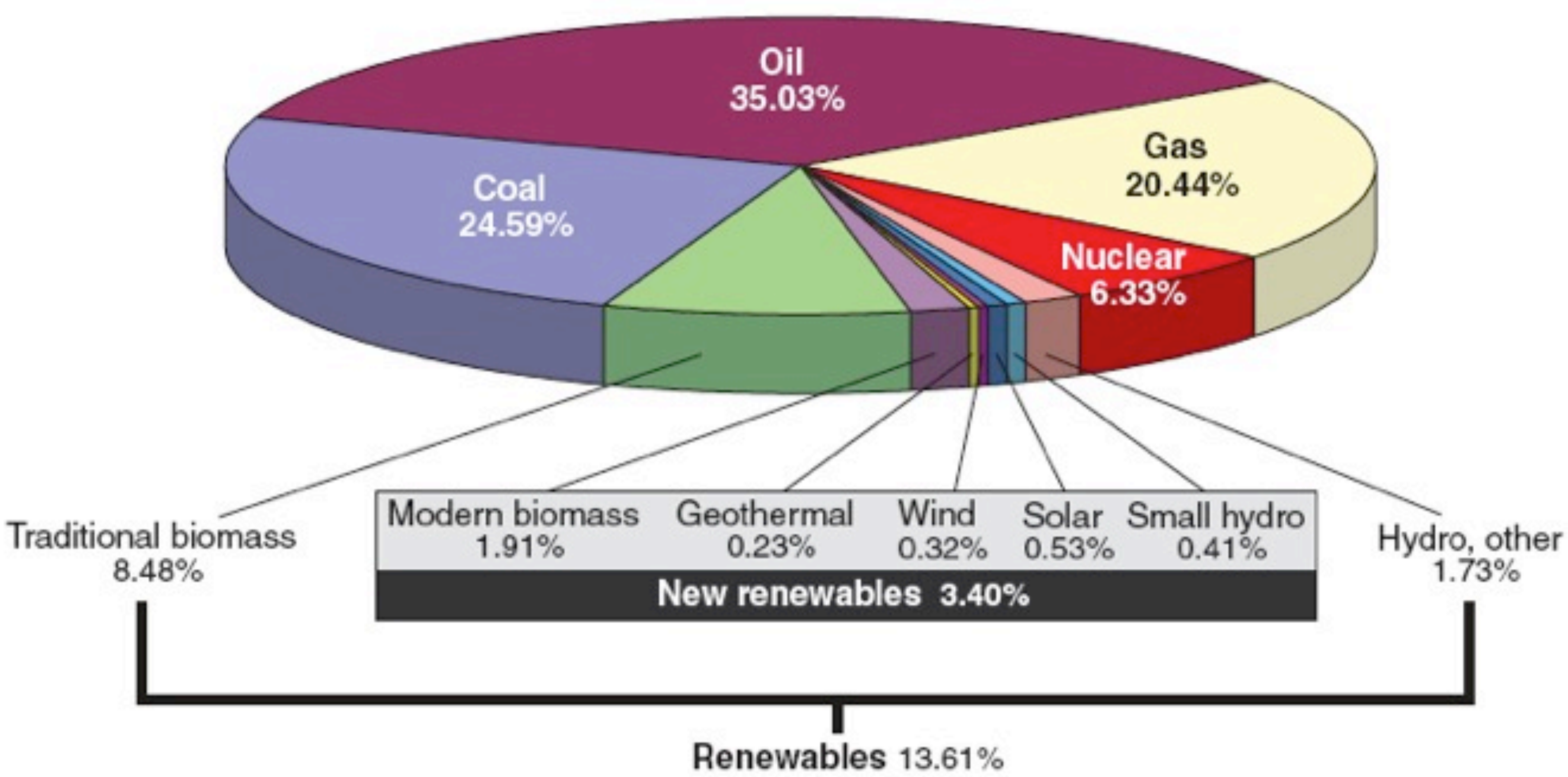
Problems with our current energy supply

- Fossil fuels represent ~80% of total world energy supply
- At constant production and consumption, known reserves of oil will last around 41 years, natural gas 64 years, and coal 155 years
- Production costs will increase as reserves approach exhaustion
- Fossil fuel use presents serious environmental problems, particularly global warming
- Increasing concerns for security of oil supply, originating mainly from politically unstable regions of the world



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What can we do about the huge dependence on burning fossil fuel? Must do many things to solve these problems

- Use mostly existing technologies to *cap* carbon emissions over next 40 years
  1. Stop burning coal in the conventional way
  2. Build more nuclear power plants
  3. Replace existing coal plants
  4. Phase out most gasoline-powered engines, use increased amounts of ethanol in the transition to electric vehicles
  5. Increase to 20% the use of renewable sources for supply of electricity - wind and solar mostly
  6. Increase energy efficiency in buildings and transportation
  7. Make greater use of geothermal heating applications
- Develop radically new technologies for second half of this century - *decrease* annual carbon emissions

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A clean energy future: the President's vision

- Reduce greenhouse gas emissions 80% by 2050
- Increase electricity from renewable sources
  - To 10% by 2012
  - To 25% by 2025
- Put 1 million plug-in hybrid cars on the road by 2015
- Within 10 years, reduce oil consumption by the amount that we currently import from the Middle East and Venezuela

This will require a large amount of political cooperation - seems unlikely at this time

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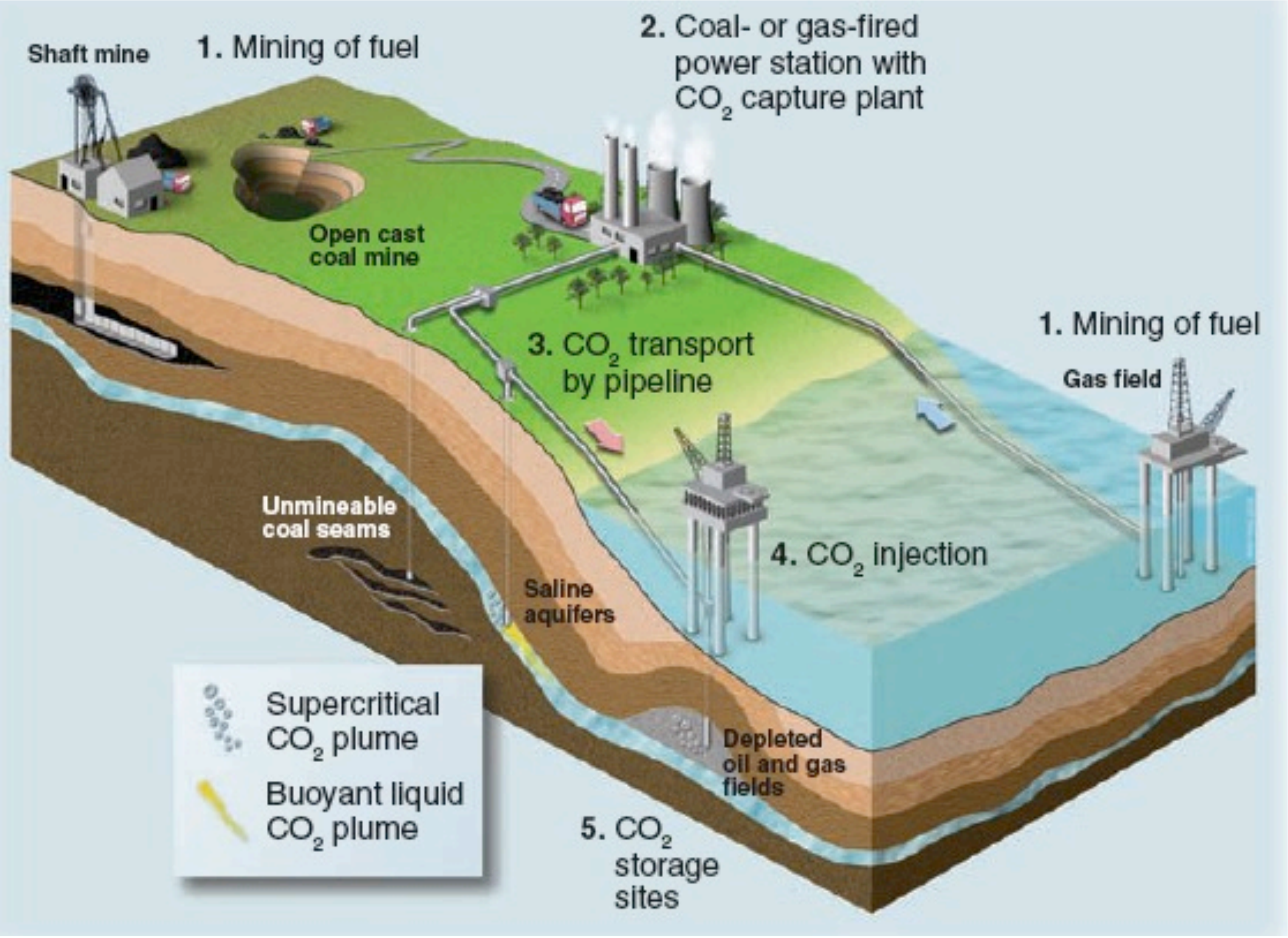
What can we do about burning coal?

- Replace coal burning with burning of natural gas to generate electricity
  - The U.S. gets almost as much electricity from natural gas as from coal
  - Coal emits twice as much CO_2 as natural gas when burned
- Burn coal by first *gasifying* it to make synthetic gas, which one can burn and then capture and sequester the emitted CO_2



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Part of the solution is nuclear energy - ORNL and UT are well positioned to support advanced fuel cycle research

- DOE Center for Advanced Simulation of LWR's (CASL)
- Coupled End-to-End (CETE) demonstration for advanced nuclear fuel cycle S&T
- Fuel examination and reprocessing
- Materials irradiation at HFIR
- Reactor design and engineering
- Nuclear research facility infrastructure (REDC, HFIR)

Nuclear Energy Faculty

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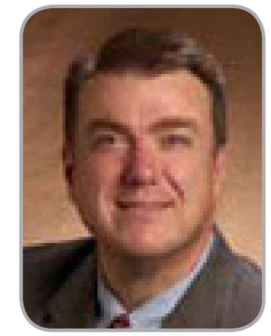

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Status of nuclear power in the world

- **U.S. has 104 operating nuclear power plants - 19% of our electricity**
- **France - 78% of their electricity from nuclear**
- **China in 2011 - 13 nuclear power reactors at 4 separate sites - 1.9% of electricity; plans to increase to 6% by 2020, 16% by 2030**
- **Japan - 30%**

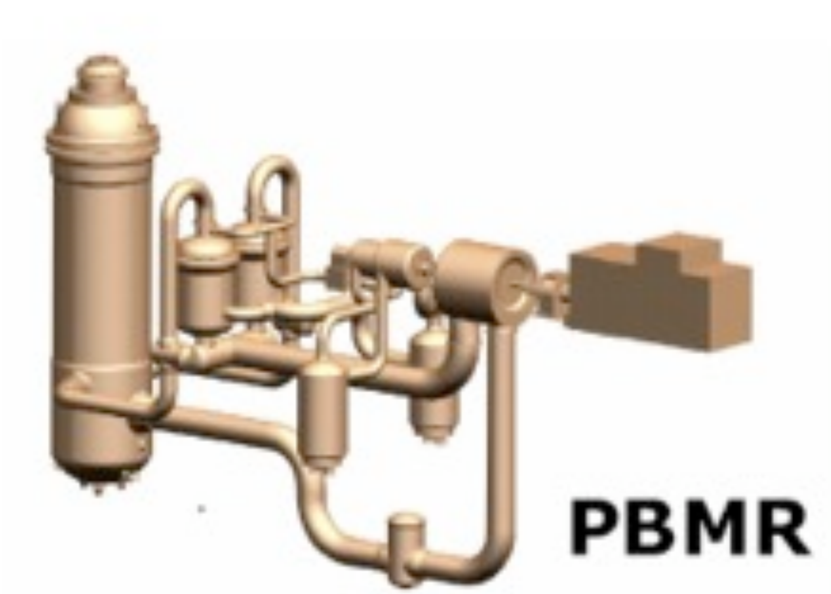
Country	Output [bill. kWh]	Share (%)
Armenia	2.4	42.0
Belgium	44.3	54.4
Bulgaria	18.1	43.6
Canada	92.4	15.8
Czech Republic	24.5	31.5
Finland	22.0	28.0
France	428.7	78.1
Germany	158.7	31.8
Hungary	12.5	37.7
Japan	291.5	30.0
Korea	141.2	38.6
Lithuania	8.0	72.3
Russia	144.3	15.9
Slovakia	16.6	57.2
Slovenia	5.3	40.3
Spain	57.4	19.8
Sweden	65.1	48.0
Switzerland	26.4	37.4
Ukraine	84.8	47.5
UK	69.2	19.9
US	787.2	19.4
World	2661.0	16.0

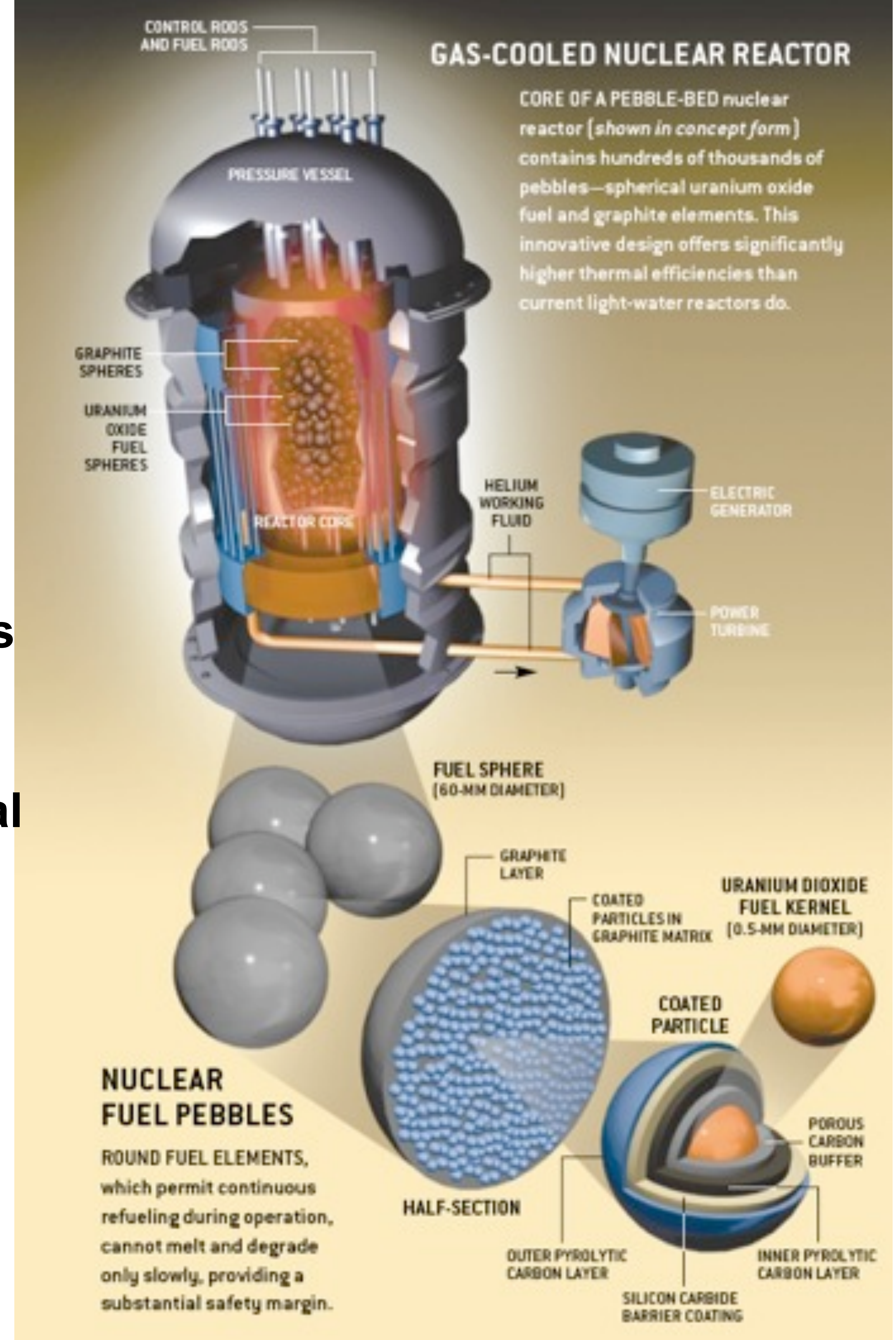
2006 numbers

Source: IAEA

The Pebble Bed Modular Reactor - possible reactor of the future

- Small modular reactor (400 MWt)
- Helium cooled, graphite moderated
- High outlet temperature (900ºC), good thermal efficiency (42%)
- High degree of inherent safety
- Use Brayton cycle - gas coolant drives turbine directly
- Demo plant was to be built in South Africa, but support canceled by federal government





What can we do about the huge dependence on burning fossil fuel?
Must do many things to solve these problems

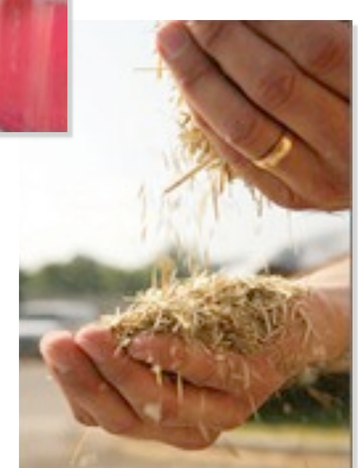
- **Use mostly existing technologies to *cap* carbon emissions over next 40 years**
  1. **Stop burning coal in the conventional way**
  2. **Build more nuclear power plants**
  3. **Replace existing coal plants**
  4. **Phase out most gasoline-powered engines, use increased amounts of ethanol in the transition to electric vehicles**
  5. **Increase to 20% the use of renewable sources for supply of electricity - wind and solar mostly**
  6. **Increase energy efficiency in buildings and transportation**
  7. **Make greater use of geothermal heating applications**
- **Develop radically new technologies for second half of this century - *decrease* annual carbon emissions**

Part of the solution is bio-ethanol

- **We are developing bio-based solutions for energy, the environment, and carbon sequestration**
- **ORNL - $135M DOE BioEnergy Science Center to advance cellulosic ethanol research**
- **UT - $73M Tennessee Biofuels Initiative**
  - **Brings UT, ORNL, and industry together**
  - **Includes bioenergy research, a 250,000 gal/year pilot plant, and agricultural incentives for switchgrass**

BESC
BioEnergy Science Center

UTBI
Biofuels Initiative



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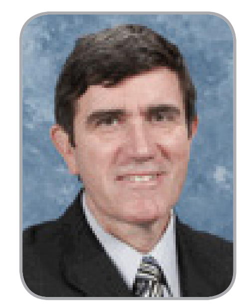

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World oil market

- World uses over 84 million barrels of petroleum oil/day
  - 1 barrel of crude oil = 42 gallons; gives 19.9 gallons of motor gasoline + 7 gallons of diesel gas
- 56% of petroleum used in U.S. comes from abroad

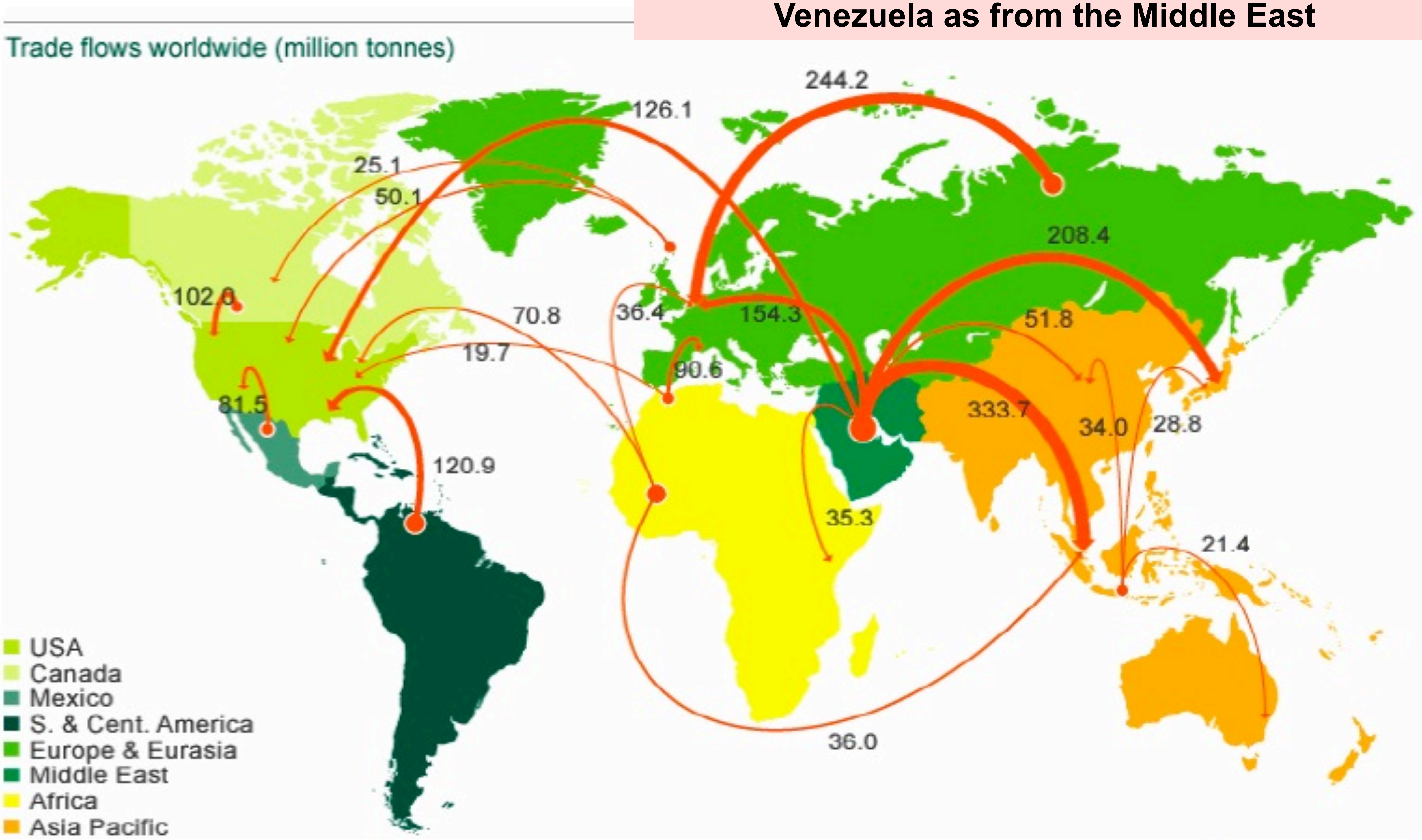
- 2004 producers of oil:
  - Saudi Arabia: 10.37 million barrels/day
  - Russia: 9.27
  - U.S.: 8.69
  - Iran: 4.09
  - Mexico: 3.83
  - China: 3.62
  - Canada: 3.14
  - Venezuela: 2.86
  - UAE: 2.76

- 2004 consumers of oil:
  - U.S.: 20.7 M barrels/day
  - China: 6.5
  - Japan: 5.4
  - Germany 2.6
  - Russia: 2.6
  - India: 2.3
  - Canada: 2.3
  - Brazil: 2.2
  - S. Korea: 2.1
  - France: 2.0
  - Mexico: 2.0

The *peak* of the world's oil production is likely to occur in next 20 years - cost will go up greatly at that point

World oil trade pattern in 2004

2004: we imported as much crude oil from Venezuela as from the Middle East



1 million tonnes of oil = 7.35 million barrels

2004: U.S. imported around 10 million barrels per day, 3650 million barrels per year or 496 million tonnes per year

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Develop electric vehicles - goal in U.S. is one million on road by 2015

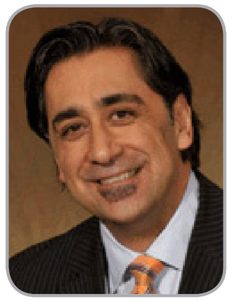
- **Fully electric vehicle**
  - Nissan Leaf - 50,000 in 2011, deliveries have started in five states
  - 23 kWhr lithium-manganese battery giving 160 km range
  - Recharge with 220-volt unit at home in 8 hours
  - Cost competitive with Toyota Prius with federal EV tax credit

Nissan Leaf

- **Plug-in hybrid electric vehicle**
  - Chevrolet Volt - General Motors, now being sold in 7 states
  - After battery charge drops to 35%, 4-cylinder internal combustion engine powers a 55 kW generator supplying electrical power to extend Volt's range
  - Range of 40 - 80 km on 16 kW·h lithium-ion battery; total range is 600 km

Chevrolet Volt

Renewable Energy Faculty



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CIRE faculty in renewable energy areas

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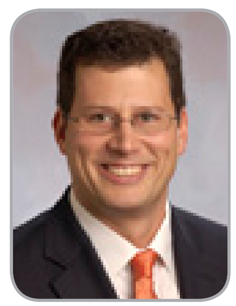

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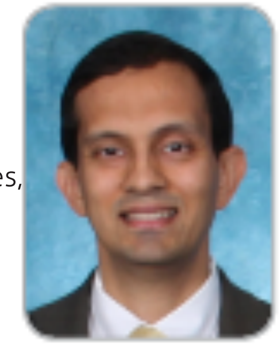

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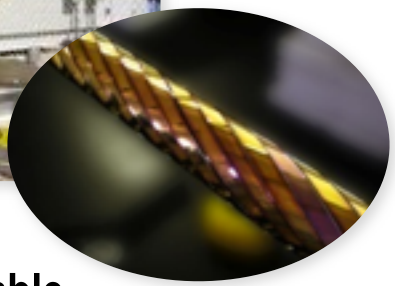
ORNL has a large and growing energy efficiency and renewable energy program

- **Largest national lab effort in transportation, industrial technologies, and superconductivity**
- **Significant growth in solar energy, electrical energy storage, biomass, and grid visualization/modeling**
  - **Includes Tennessee Solar Institute at UT/ORNL**
- **Major facilities include High Temperature Materials Laboratory, National Transportation Research Center, and Buildings Technologies Center**

Lightweight carbon fiber materials from lignin

“Zero-energy” homes



Triaxial superconducting cable installed at AEP Bixby

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What can we do about the huge dependence on burning fossil fuel?
Must do many things to solve these problems

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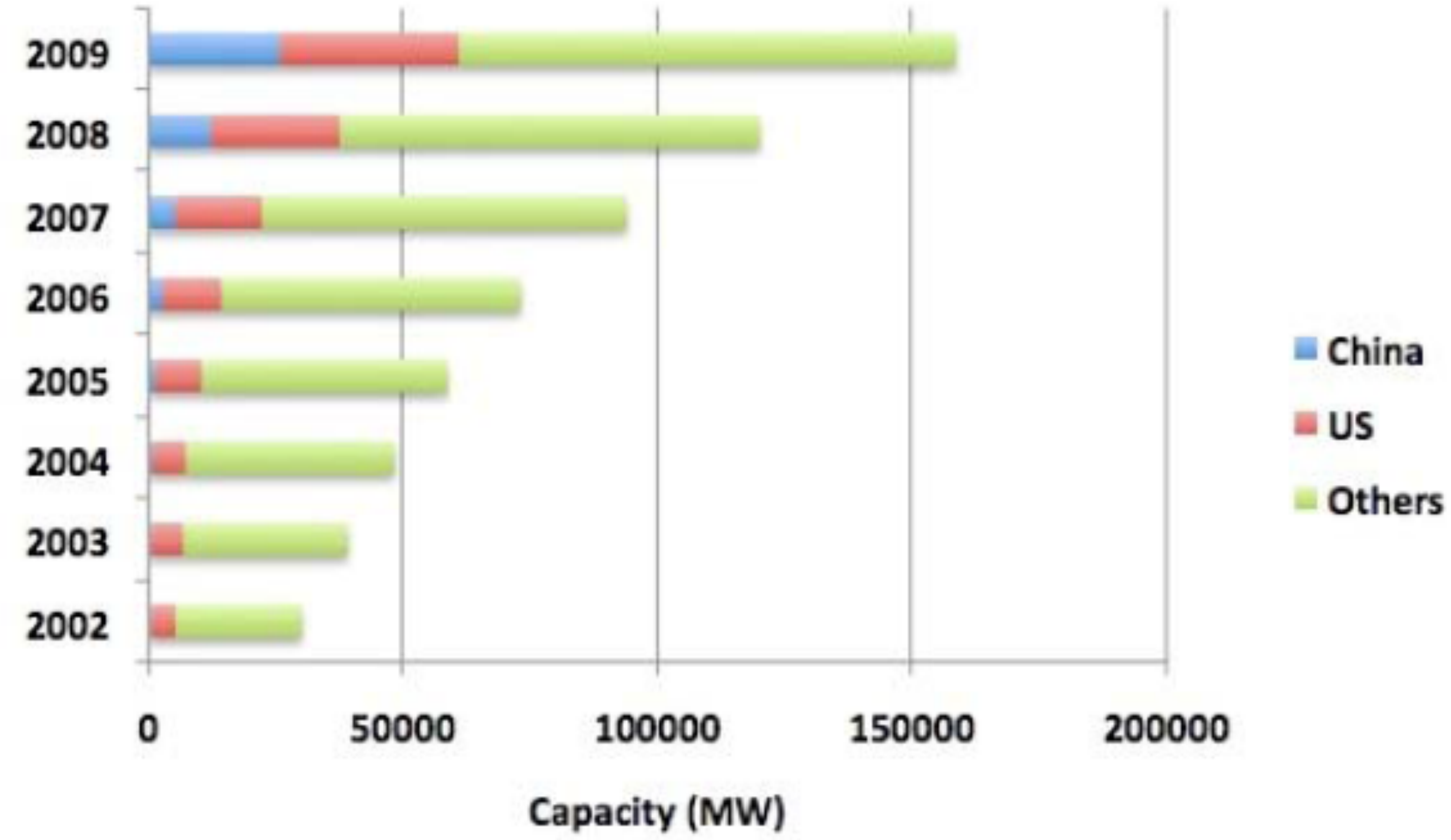
- Develop radically new technologies for second half of this century - *decrease* annual carbon emissions

Development of wind turbines around the world



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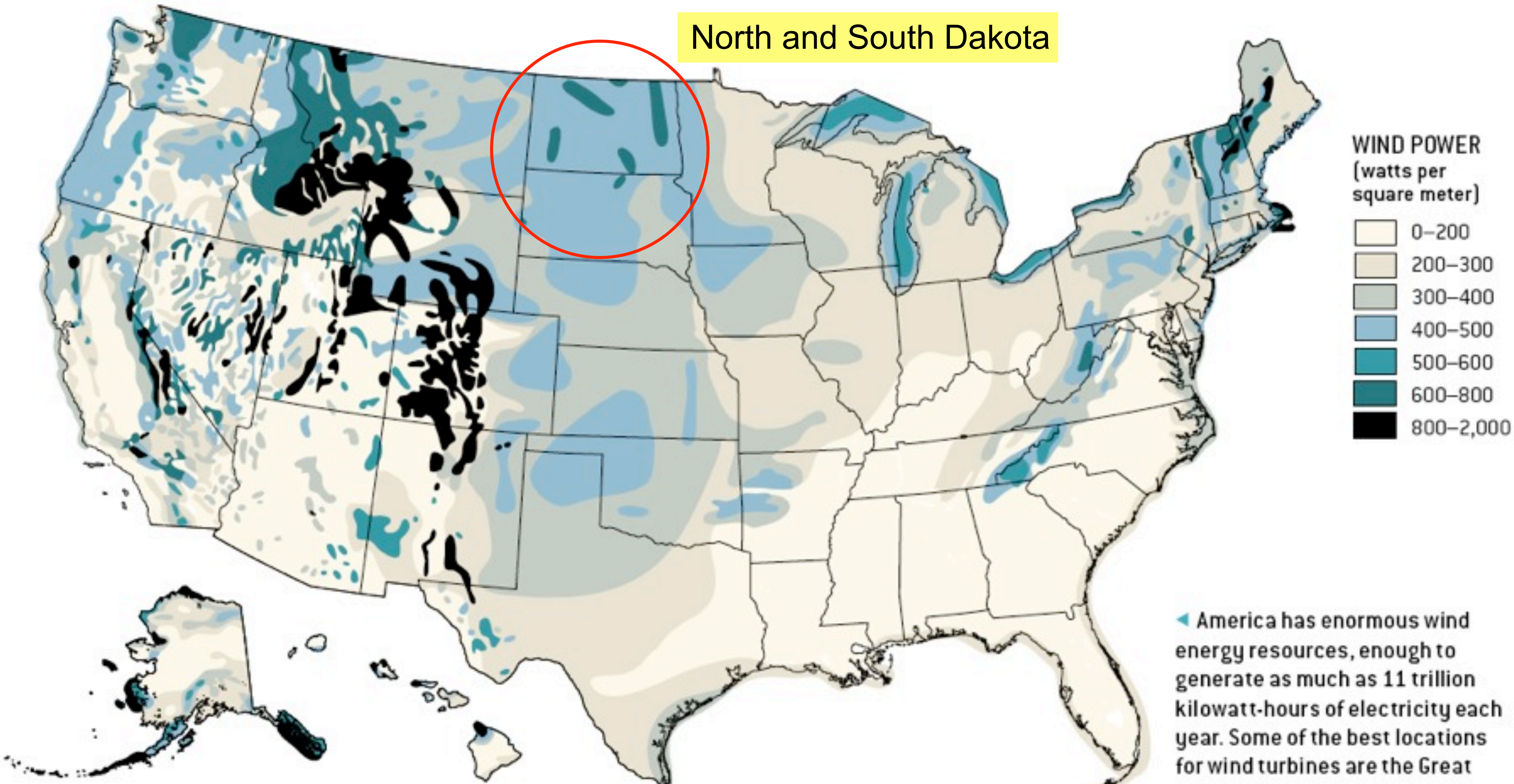
Much progress in the world on wind

- Denmark already gets 19% of its electricity from wind
- Germany is at 11% and is trying to get to the 20% level
- U.S. leads in total installed capacity for generating electricity from wind
- Still, we are at only 1.3% of total electrical needs
- U.S. Production Tax Credit for Renewable Energy is important:
  - Companies that generate wind, solar, geothermal are eligible for a 2.1¢/kWh tax credit for the first 10 years of a renewable energy facility's operation

Installed windpower capacity (MW)[1]

#	Nation	2005	2006	2007	2008
1	United States	9,149	11,603	16,819	25,170
2	Germany	18,428	20,622	22,247	23,903
3	Spain	10,028	11,630	15,145	16,740
4	China	1,266	2,599	5912	12,210
5	India	4,430	6,270	7850	9,587
6	Italy	1,718	2,123	2,726	3,736
7	France	779	1,589	2,477	3,426
8	United Kingdom	1,353	1,963	2,389	3,288
9	Denmark	3,132	3,140	3,129	3,164
10	Portugal	1,022	1,716	2,130	2,862
11	Canada	683	1,460	1,846	2,369
12	Netherlands	1,236	1,571	1,759	2,237
13	Japan	1,040	1,309	1,528	1,880
14	Australia	579	817	817	1,494
15	Ireland	495	746	805	1,245
16	Sweden	509	571	831	1,067
17	Austria	819	965	982	995
18	Greece	573	758	873	990

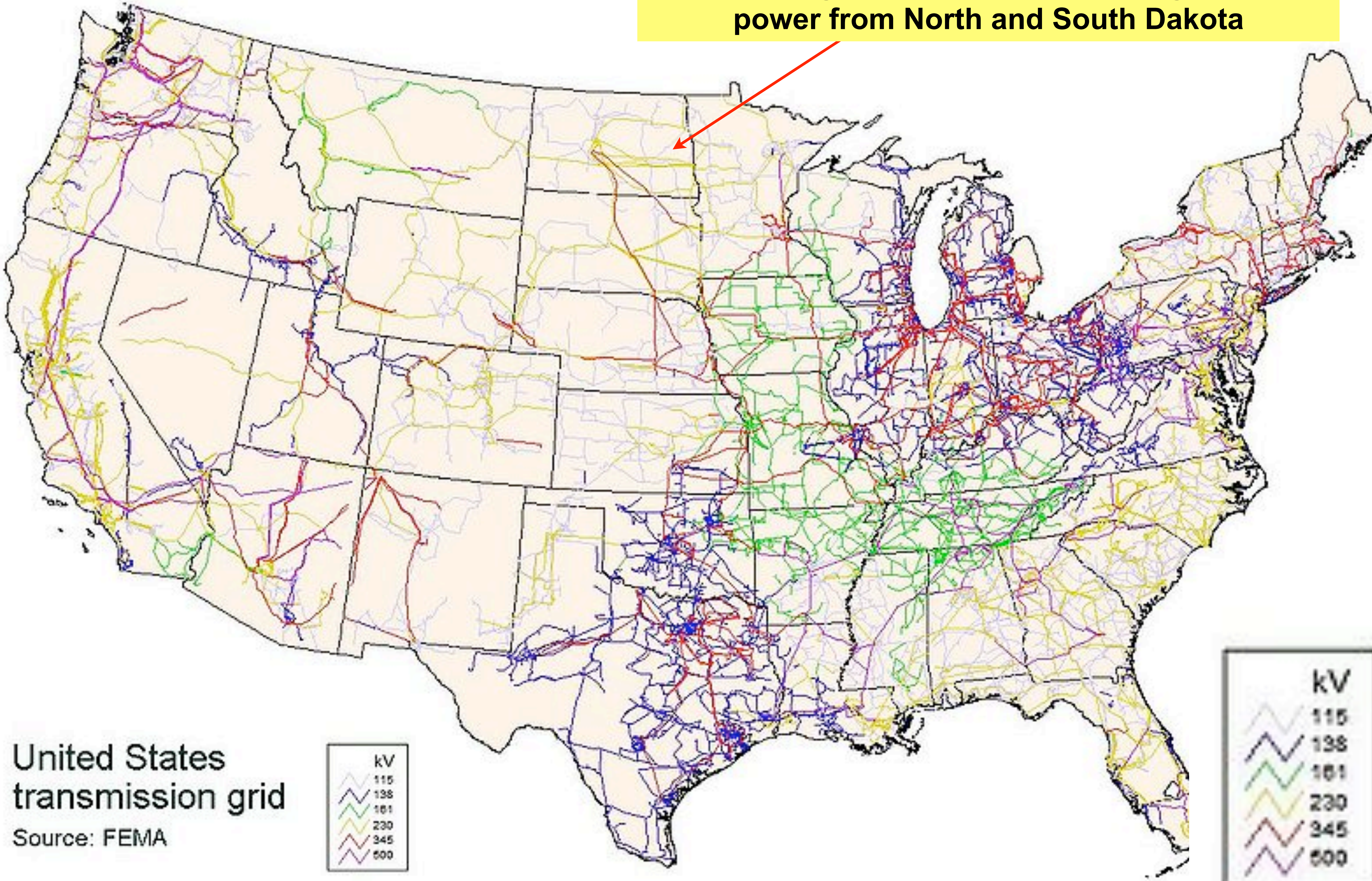
Best U.S. sites for wind power - Great Plains, Great Lakes, mountain ridges of Rockies and Appalachians



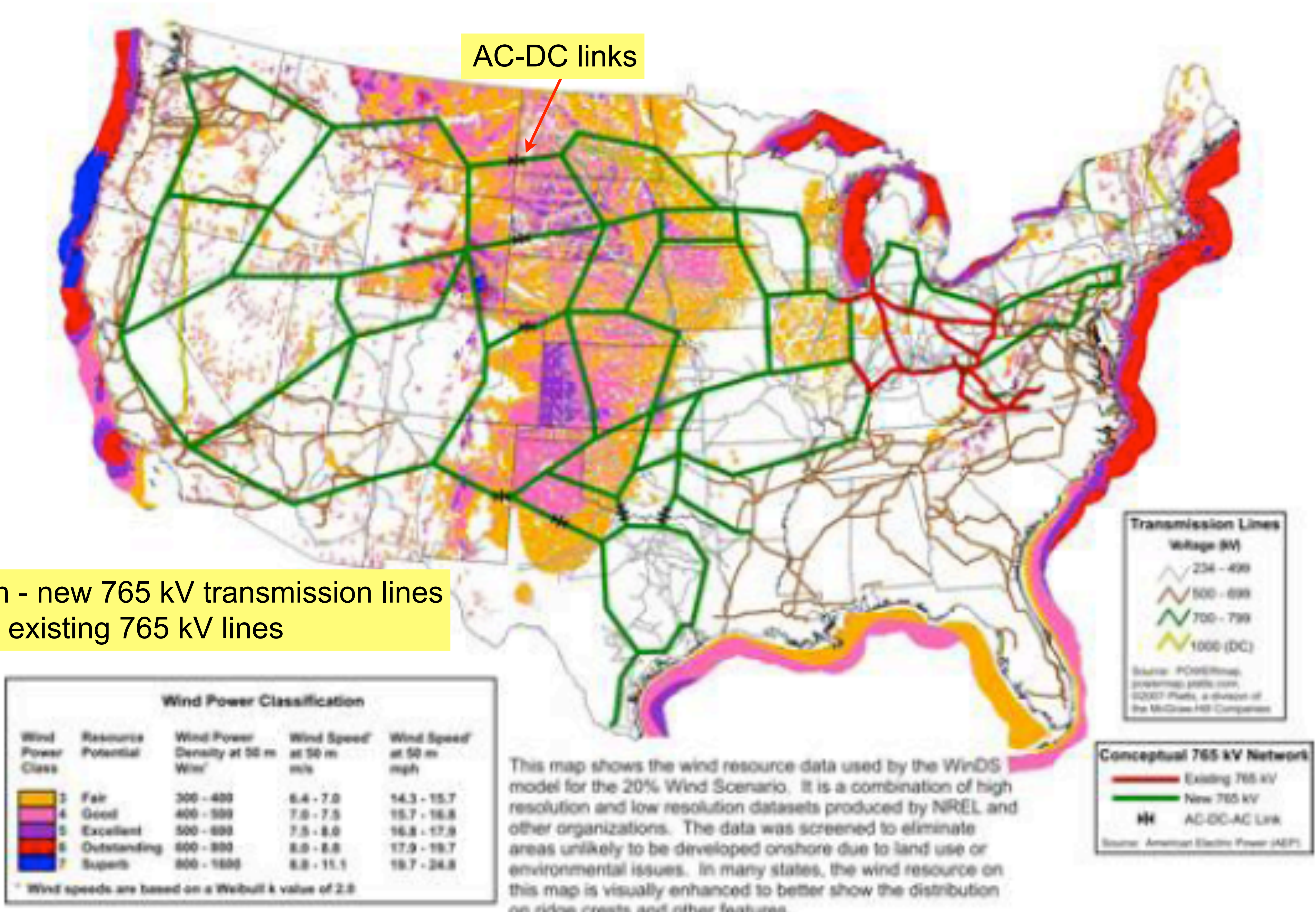
America has enormous wind energy resources, enough to generate as much as 11 trillion kilowatt-hours of electricity each year. Some of the best locations for wind turbines are the Great Plains states, the Great Lakes and the mountain ridges of the Rockies and the Appalachians.

U.S. electrical transmission grid

Not enough transmission lines to get wind power from North and South Dakota



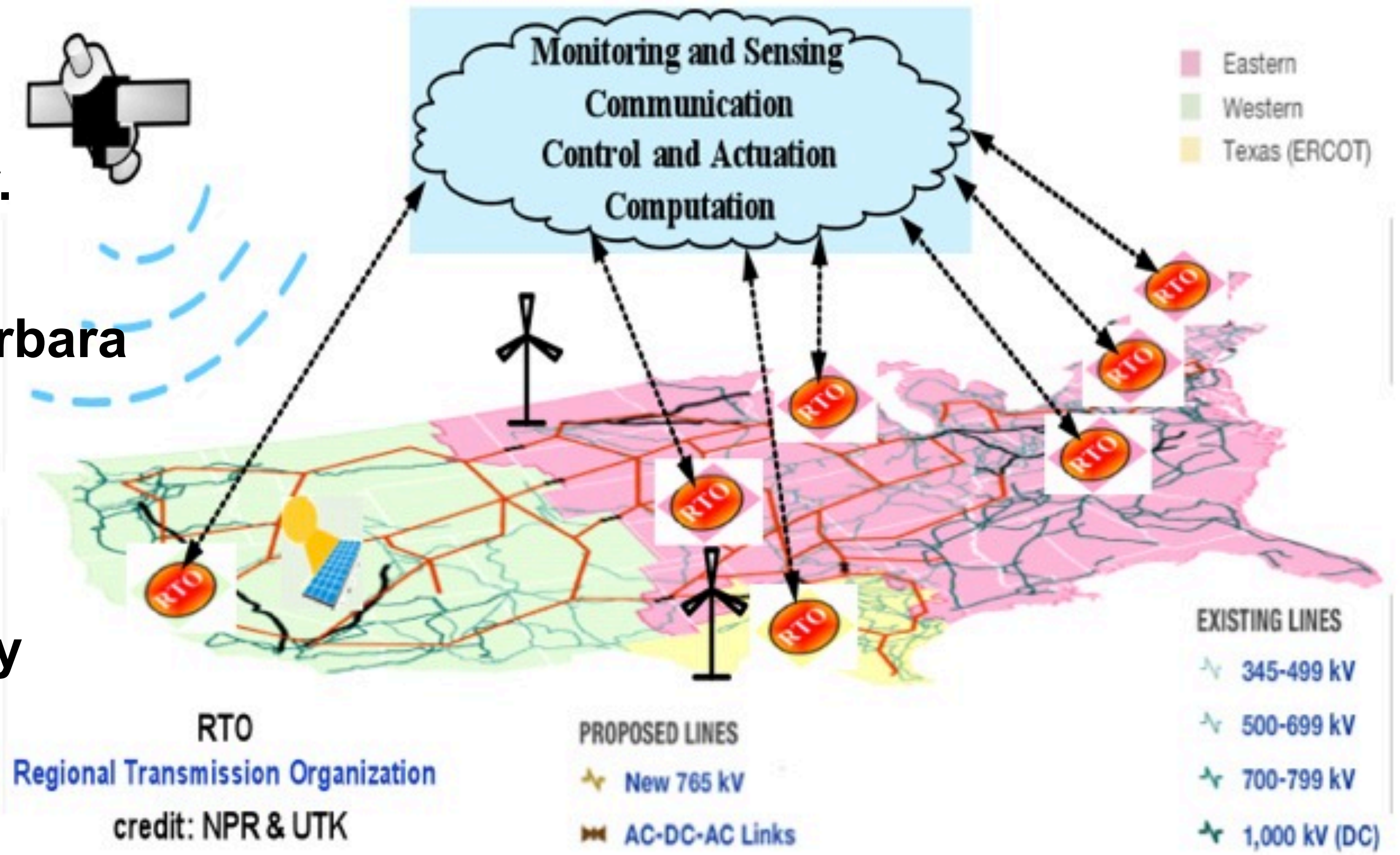
New 19K miles of transmission lines needed for 300 GW of wind power in best areas



Need a ‘smart grid’ to handle renewable energy input

New UT Center for Ultrawide Area Resilient Electric Energy Transmission Networks (CURENT)

- **NSF award for $4M/year - recently announced**
- **CIRE faculty Kevin Tomsovic is Director and Yilu Liu the Deputy Director**
- **Partner institutions:**
  - **Northeastern University**
  - **Tuskegee University**
  - **Montana Technological Univ.**
  - **Tufts University**
  - **Univ. of California, Santa Barbara**
  - **Tennessee State University**
  - **Tsinghua University**
  - **University of Waterloo**
  - **National Technical University of Athens**
  - **Supelec, Paris**
  - **Federal University of Rio de Janeiro**



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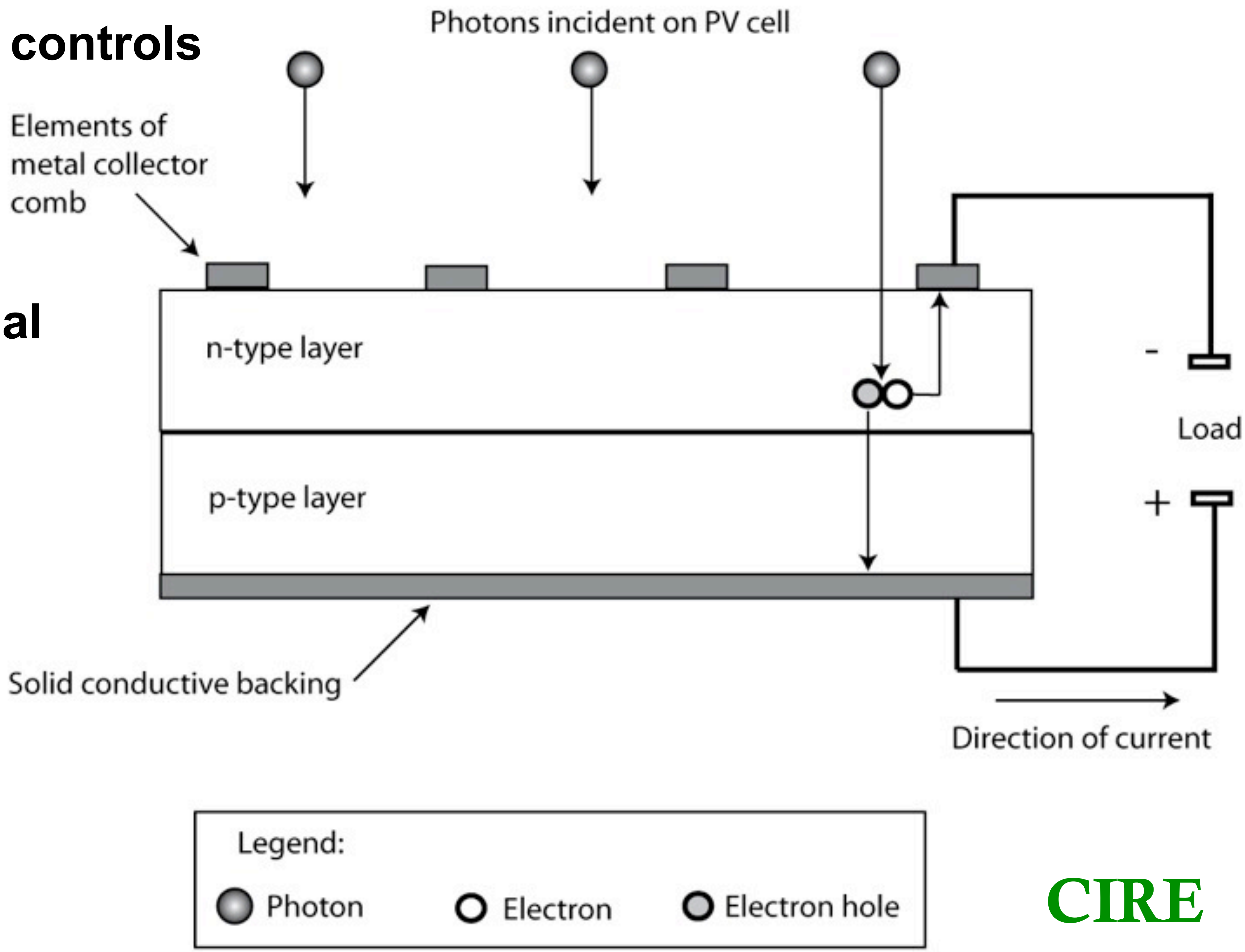
Photovoltaic cell - Sun's light produces electricity directly

- Incoming photon breaks bond
- Electron is free to roam lattice
- Vacancy left by electron is also able to move in lattice
- Structure of PV cell controls movement of electrons and vacancies so as to create useful current in an external circuit



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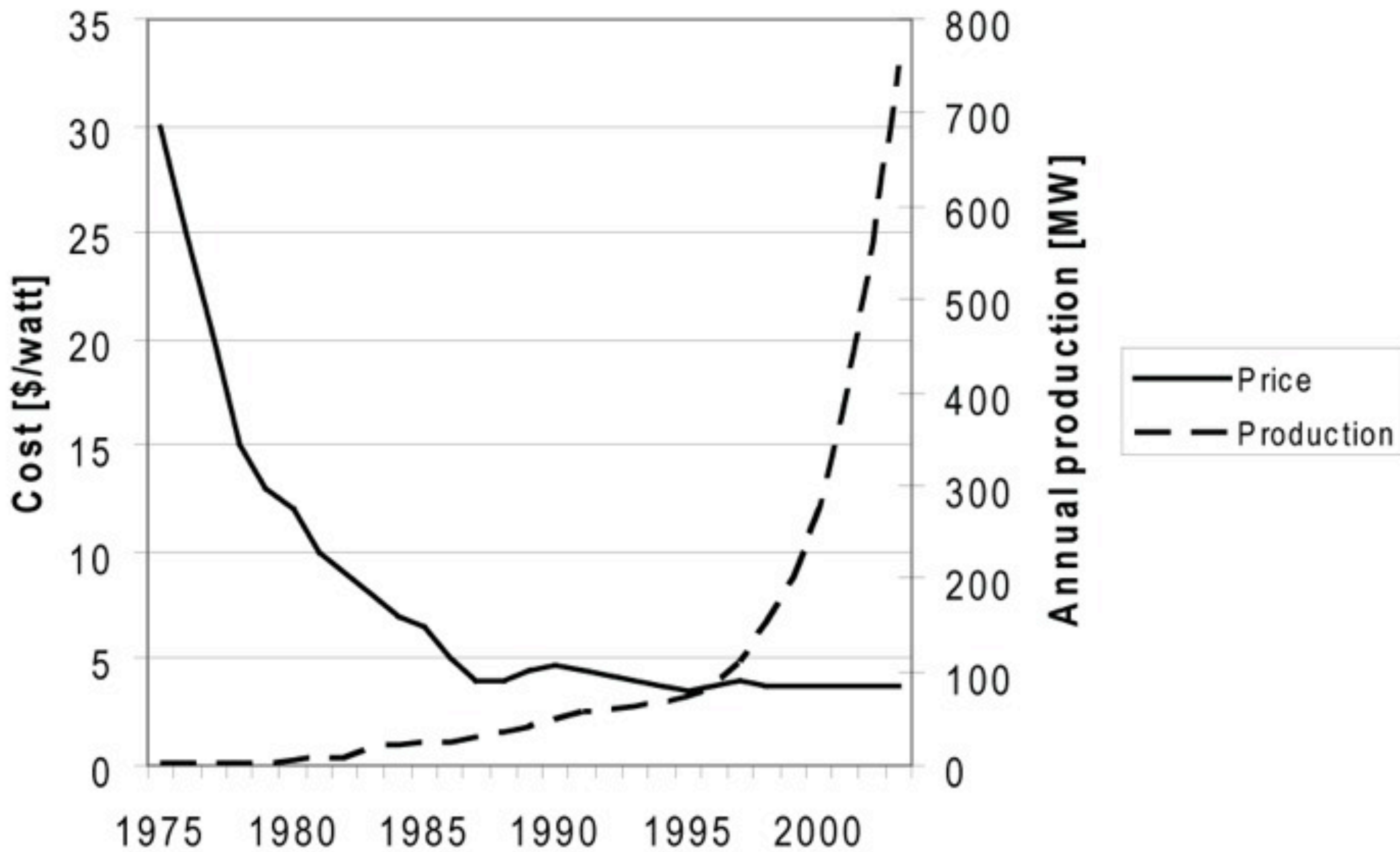
The challenge is bringing down the cost of electricity from PV cells

- PV technology developed for U.S. and Soviet space programs starting in 60s
- First PV cells made of crystalline silicon at a cost of $250/watt
- Now down to less than $5/W



- Price has come down from 1970s onward as PV devices developed for watches, calculators, road signs, etc.
- When price drops to $1.50/W, then can perhaps produce electricity at 12¢/kWh, close to being competitive

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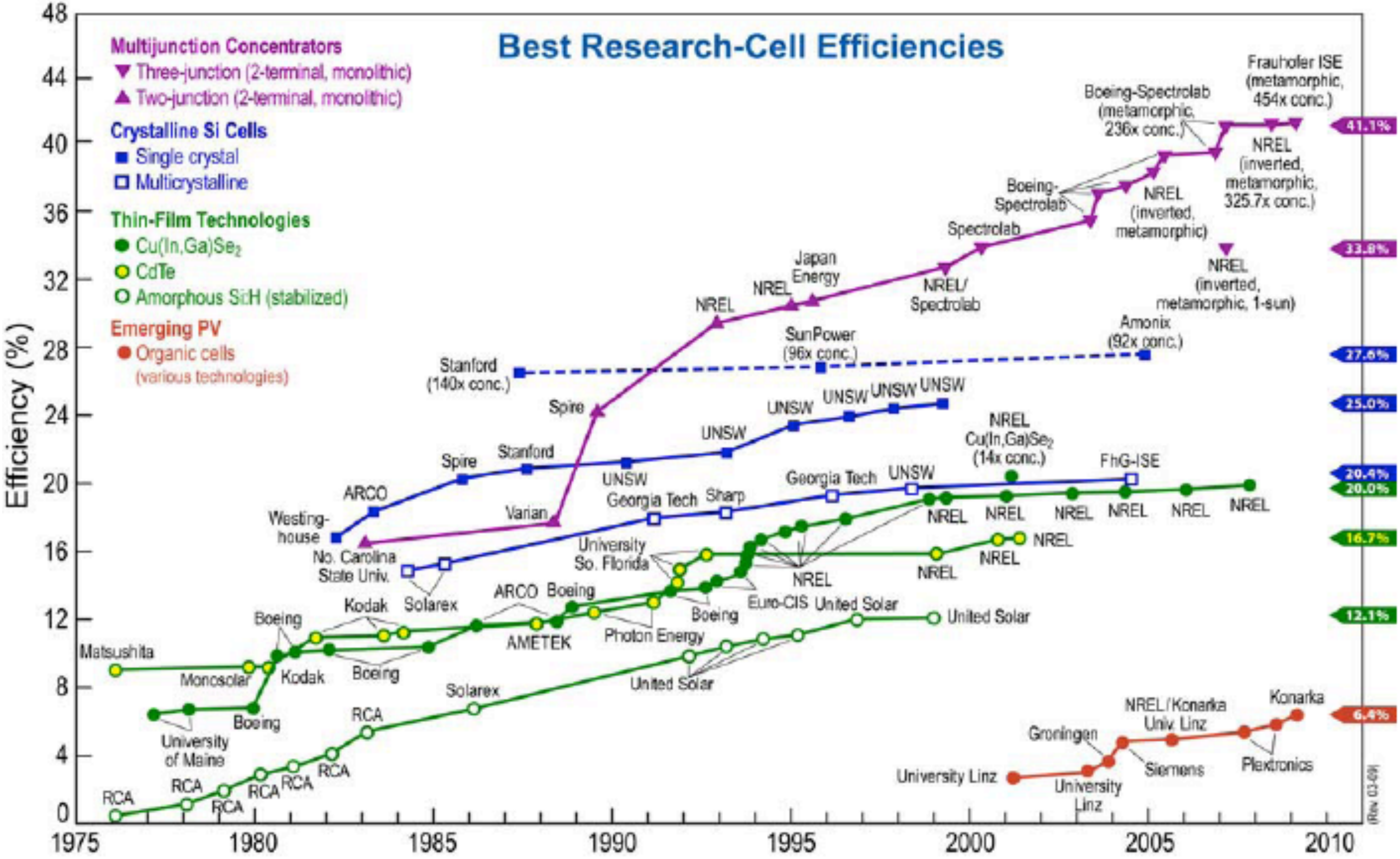
Much success in raising PV efficiencies - still much work to be done



Goal for renewables - move to 20% of electricity from wind and solar by 2030

- **Wind turbines - move to 15% of U.S.'s electricity needs**
  - U.S. has around 25 GW (peak) - equivalent to 8 GW of baseload capacity
  - Now 1.3% of our capacity
  - Go to 15% of our needs - build 200 GW_p of new capacity (70 GW base)
  - Save 70 x 1.6 million Gton/yr = 0.11 Gton/yr
- **Solar arrays - strive for 5% of our electricity needs from large arrays of photovoltaics or dishes for concentrating solar power**
- **Require passive solar units on roofs of homes in the SW of U.S.**
- **Push geothermal heat pumps**

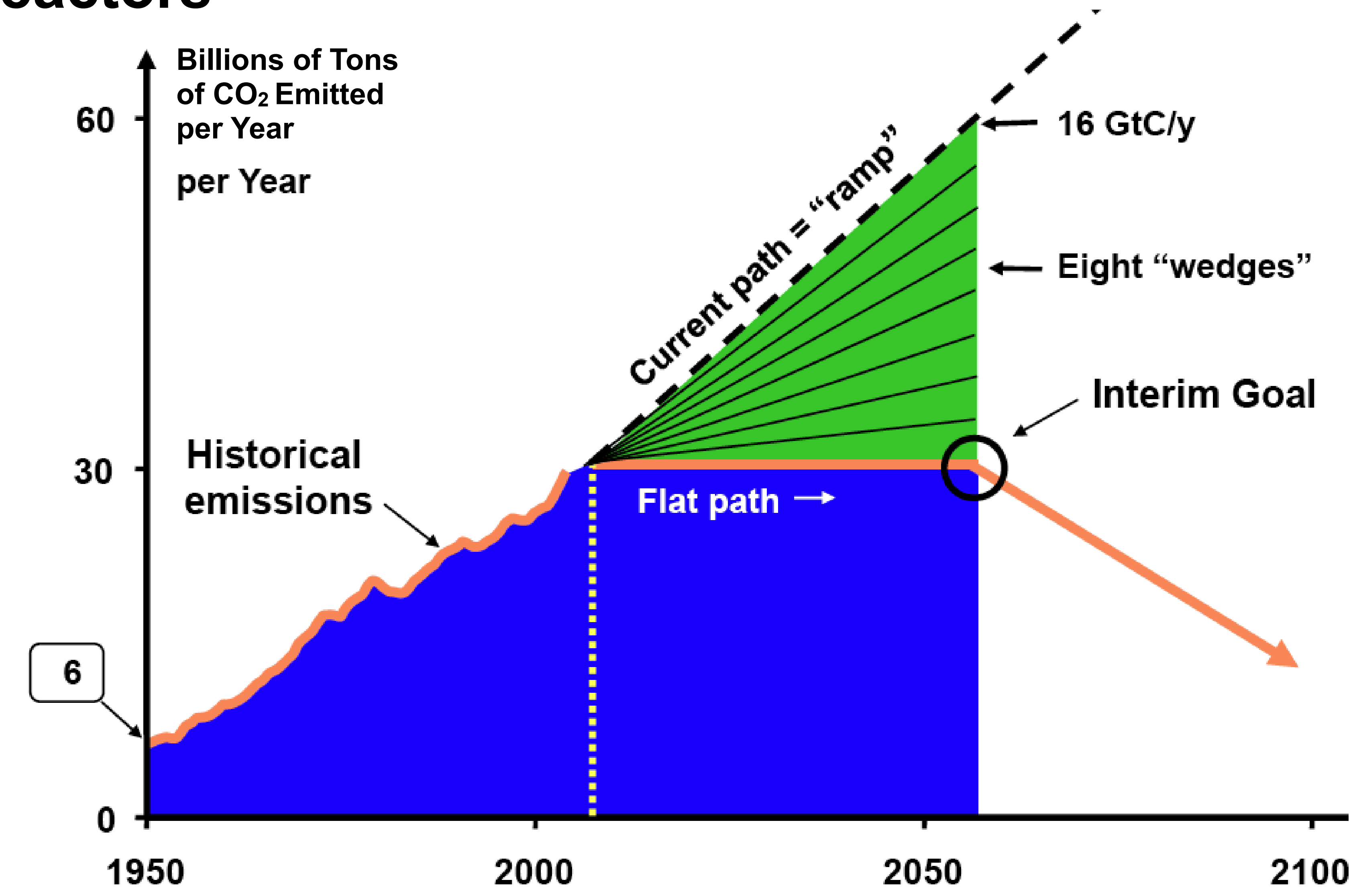
Shiloh Wind Power Plant in Solano County, CA

What can we do about the huge dependence on burning fossil fuel?
Must do many things to solve these problems

- Use mostly existing technologies to *cap* carbon emissions over next 40 years
  1. Stop burning coal in the conventional way
  2. Build more nuclear power plants
  3. Replace existing coal plants
  4. Phase out most gasoline-powered engines, use increased amounts of ethanol in the transition to electric vehicles
  5. Increase to 20% the use of renewable sources for supply of electricity - wind and solar mostly
  6. Increase energy efficiency in buildings and transportation
  7. Make greater use of geothermal heating applications
- Develop radically new technologies for second half of this century - *decrease* annual carbon emissions

Use new technologies to reduce CO_2 emissions in second half of century

- Scrubbing of CO_2 directly from air
- Storage of carbon in minerals
- Nuclear fusion
- Hydrogen from nuclear reactors
- Fuel cell vehicles
- Artificial photosynthesis
- Others?



Socolow, Scientific American, August 2004, September 2006

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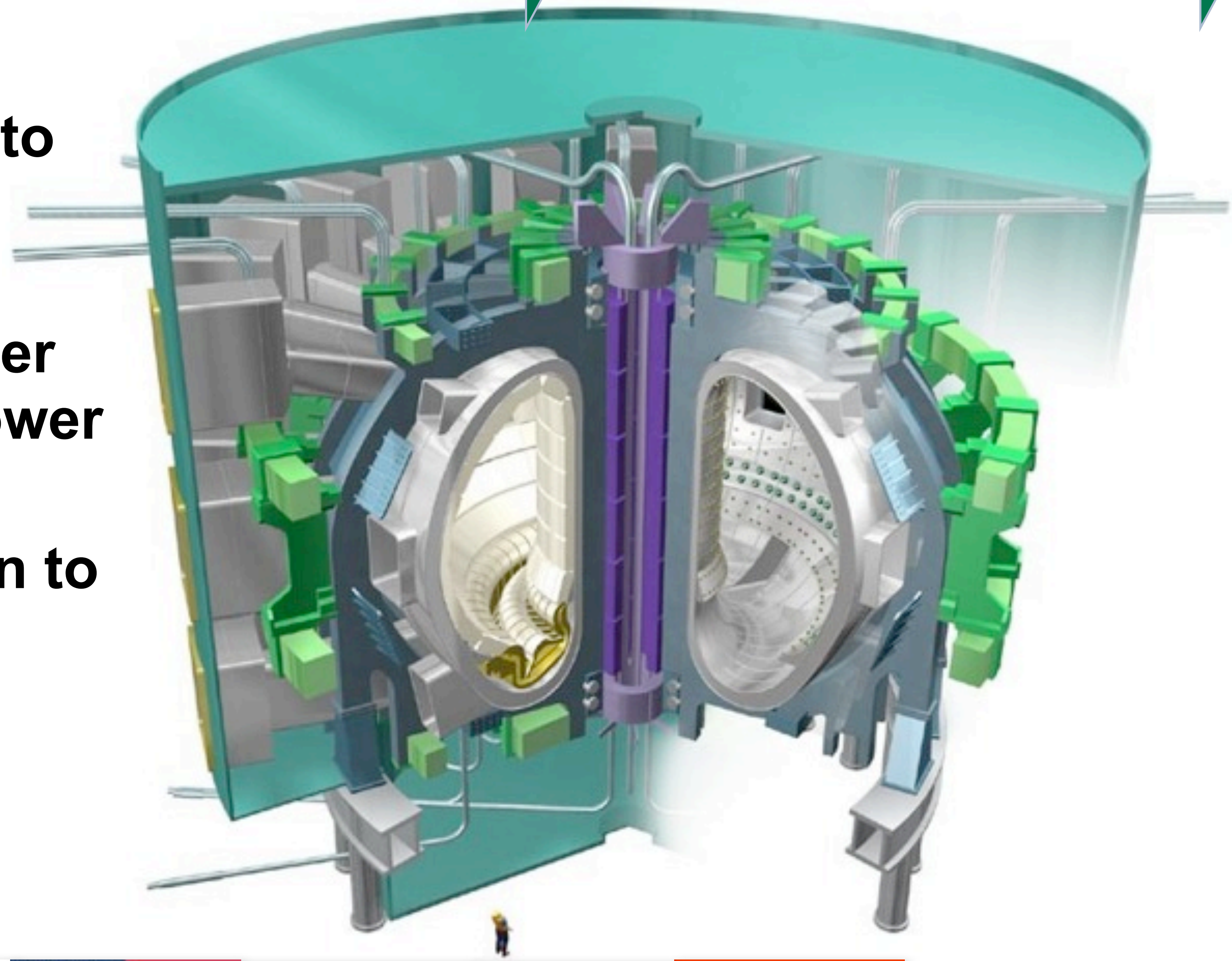
Fusion energy: on track to play a role in the second 50-year strategy

- **Many countries are teaming to build ITER in France - next generation Tokomak**
- **Several steps are needed after this to take us to a fusion power reactor**
- **ORNL leads U.S. contribution to ITER**



EU | Russia | Japan | USA | China | South Korea | India

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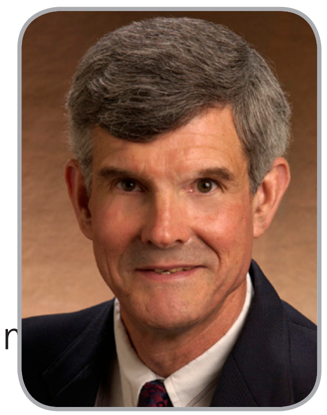

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Most of the energy solutions of the future depend on advanced materials, which is an area of strength of our CIRE faculty

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