CRITICAL THINKING IN SCIENCE

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A Bit of Info About Myself

- First job – Jan. 1965, U. of Waterloo Co-op Student at CRL
  - 6 co-op terms and two summer terms (MSc research)
- MSc and PhD at U. of Toronto, 1969 to 1974 in Nuclear Physics
- PDF 1974, 1975 in Accelerator Physics (AP) at CRL
- 1976 and 1977 PDF at Columbia University in AP
- 1978 –1984 Research Scientist at Schlumberger – Doll mainly in AP
- 1984 – 1989 Senior Accelerator Scientist at Continuous Electron Beam Accelerator Facility (CEBAF), a DOE Lab
- Returned to CRL in 1989 as a Senior Accelerator Physicist
  - Tandem Accelerator SuperConducting Cyclotron (TASCC)– 1989 –1997 Fluid Sealing Technology Branch 1997 until retirement in 2010

Why Is Critical Thinking So Important

- Many in audience are near the beginning of their career in science
- Throughout that career there will be numerous technical/scientific items reported in popular press claiming achievements (commenting on serious threats, etc.) that might have a major impact on Health, Safety and Environment or other aspects of life
- Classical example of this is the ongoing dialogues on climate change and energy
- Be prepared to challenge those claims with your own well-developed thoughts

How to Approach This?

- Some hints
  - If a claim seems far-fetched – it probably is
  - Ask yourself – does this make sense
- Remember that many of these big-picture questions have a basis in some fairly basic science
  - And all too often, these basic facts are ignored
- Try to develop a ***questioning*** attitude and be able to make reasonable estimates (often a ***back-of-an-envelope*** or quick mental estimate is sufficient)

From "Correct" Answers to "Estimates"or Guesses

- Most problems at high school or university have "correct" answers that are graded as such
- As one looks at a broader set of problems there may not be a simple "right" or "wrong" answer
- As we look at some truly broad issues such as climate change there may be only general answers – too complex to understand all of the implications
- Experience can help one to make better "guesses"
  - And you can use your understanding of the basics of science and technology to improve your guesses and question others
- One more point – many experienced people (experts?) often forget/ignore the basic science

What are some of the Basic Tools

- Your ability to think and use the basic tools of science and engineering, etc.

- What do I use routinely? Try to use basic principles
- One of my most used concept is Avogadro's Number
  - Avogadro's number is the number of particles in one **mole** of any substance. Its numerical value is 6.02225×10^{23} but 6×10^{23} works for most calculations
  - This is used in physics and chemistry on a routine basis
  - One should have a solid grasp of the importance of this number by high school science

- Equally important is the concept that one mole of an ideal gas also has a volume of 22.4 l at STP (Standard Temperature and Pressure)

Basic Tools (cont'd)

- Some other useful numbers
  - The elementary charge of an electron (e = 1.6×10^{-19} coulombs/electron) or 1.6×10^{-19} joules
  - *So 1 eV = 1.6×10^{-19} joules*
    - (one eV is the energy an electron gains as it travels through a potential of 1 volt)
  - $1/e = 6 \times 10^{18}$ electrons/coulomb
  - One ampere is equal to 6×10^{18} electrons/second

Basic Tools (cont'd)

- Some basic properties of water
  - Heat capacity of 1 cal/g/ ^{o}C (4.2J/g/ ^{o}C)
  - Heat of fusion of 80 cal/g
  - Heat of vaporization of 540 cal/g
- Water is used as a heat transfer agent for many methods of producing electricity
- These properties also influence weather and climate strongly – one needs good understanding of these basic properties

Steam Tables
temperature at which water boils as function of pressure

Pressure kPa	Pressure (atmospheres)	Temperature (^oC)
101	1	100
220	2.2	123
400	3.96	143
800	7.9	170
1250	12.4	190
2600	25.7	226
4000	39.6	260

We also need a high comfort level with scientific presentation of numbers

- **SI prefixes:**
- Z: 10^{21} zetta E: 10^{18} exa P: 10^{15} peta
- T: 10^{12} tera G: 10^{9} giga M: 10^{6} mega
- k: 10^{3} kilo h: 10^{2} hecto da: 10^{1} deka

- d: 10^{-1} deci c: 10^{-2} centi m: 10^{-3} milli
- mu: 10^{-6} micro n: 10^{-9} nano p: 10^{-12} pico
- f: 10^{-15} femto a: 10^{-18} atto

Now Let's Look at Energy and Energy Production as Examples

- What is energy? Quick check on Google
- **Definition:** Energy is the capacity of a physical system to perform work. Energy exists in several forms such as heat, kinetic or mechanical energy, light, potential energy, electrical, or other forms. According to the law of conservation of energy, the total energy of a system remains constant, though energy may transform into another form.
- The SI unit of energy is the joule (J) or newton-meter (N * m). The joule is also the SI unit of work

Now Look at Energy from a Practical Point-of-View

- Energy is a bit of a tricky concept – we hear it discussed routinely but what are the more interesting aspects from the point of view of "real-world" usage
- Chemical energy – two atoms of oxygen combine with one of carbon to produce CO_2
  - This is an exothermic reaction in which a few eV of energy is produced for each molecular bond formed
- Fission - ^{235}U atom split producing about 200 MeV (Million electron Volts) of energy and two lighter atoms
  - About 40 million times higher than chemical reactions
- Fusion – deuterium plus tritium fuse, producing 17.6 MeV of energy (reaction of stars) and a helium nucleus

Let’s Do a Simple and Very Approximate Example

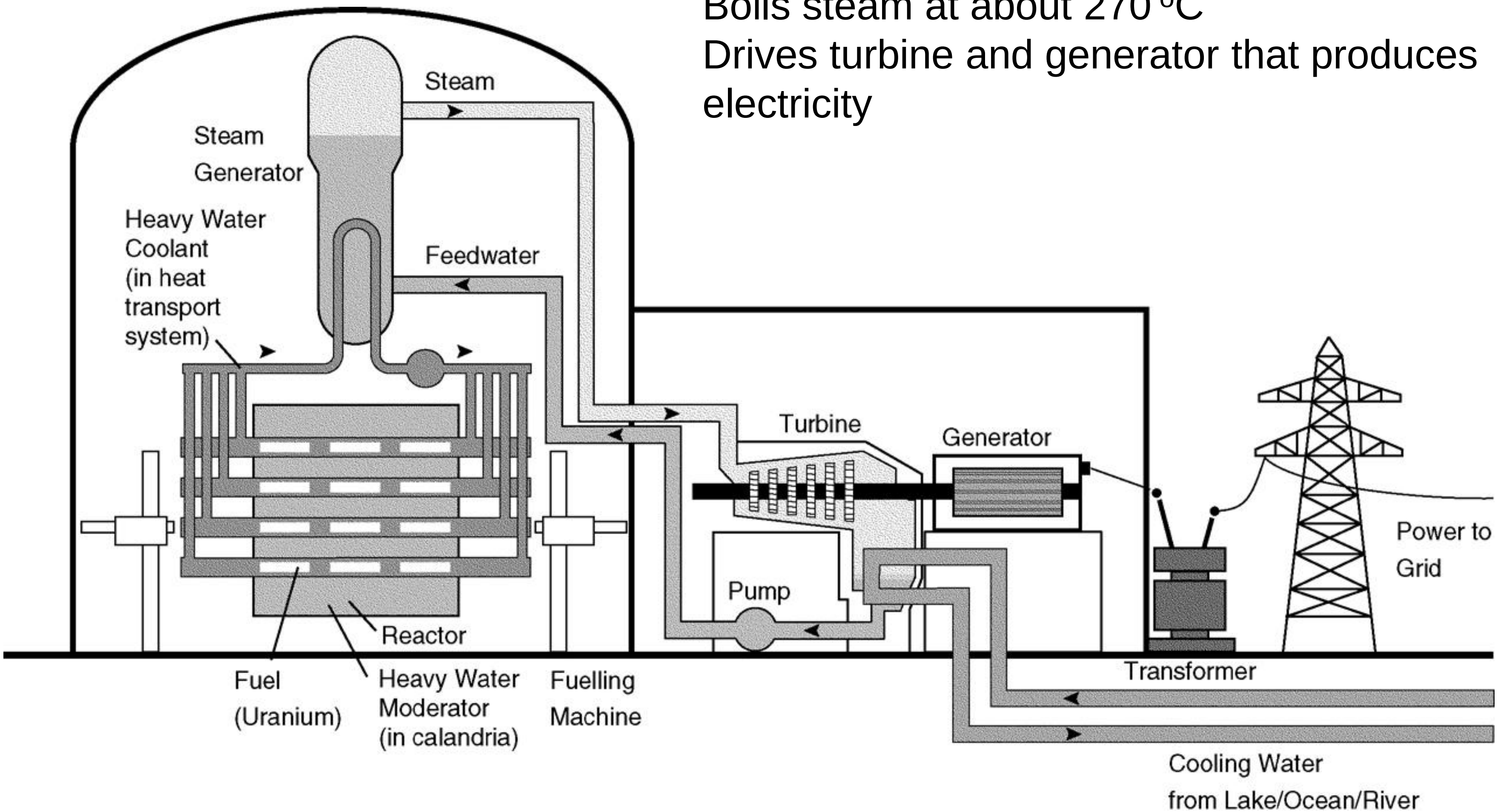
- React one mole of carbon (12 g of coal) with one mole of oxygen to produce CO-2
- Use “seat-of-pants” estimate of 5 eV per reaction
- 6×10^{23} atoms/mole x 5 eV = 3×10^{24} eV/mole
- Times 1.6×10^{-19} joules/eV = 480,000 joules/mole (actual # 394,000 J/mole but can use 400,000 as an easy approximation)
- And this produces 22.4 l (and 44 g) of CO-2 at STP

What can we do with this basic information?

- Let's pose an interesting question as another example
- How much coal does it take to run a 1000 MW thermal electric plant per day?
  - 1000 MW of electricity requires about 3000 MW of heat energy
  - about 33 % efficiency
- 3000 MW = 3×10^9 joules/s x 3600 s/h x 24 h/d = 2.6×10^{14} J/d
- From previous slide, 12 g produces 4×10^5 J of energy or one gram produces 3.3×10^4 J/g
- Therefore electric plant uses
  - 2.6×10^{14} J/d / (3.3×10^4 J/g) = about 10^{10} g/d or 10 million kg/d
- Note, 10 million kg/d is about 100 rail cars of coal per day

Compared to a CANDU Reactor

Fuel – uranium at 200 MeV/fission
about 200 to 300 kg fuel/day
Water at about 300 ºC and 10,000 kPa
not particularly useful to produce electricity
Boils steam at about 270 ºC
Drives turbine and generator that produces electricity



Some Important Concepts

- Only about 33% of thermal energy converted to electricity
  - Depends upon delta T between input steam and heat sink
  - Fighting against steam table to get efficiency
- These same challenges are faced by any energy source using water to transfer energy
  - Includes some you might not think about such as solar thermal and geothermal

Let's Do an Assessment of an Electric Car

- Nissan Leaf – advertised as 100 mpg (2.4 l/100 km) (gas equivalent) or 35 kW-h/100 miles (=1.3 x 10^8 J/100 miles)
- Similar-sized Internal Combustion Engine – over 40 mpg
- Electric car produces zero-emission during use
- However, using coal-fired electricity (about 50% of US production), 35 kW-h requires about 4.3 x 10^8 J at the station and uses 13 kg of coal and produces 47 kg of CO-2
- 2.5 gallons (9.6 l) of gasoline contain about 6 kg of carbon and produces about 22 kg of CO-2
  - About ½ the CO-2 produced by coal-fired electricity required for electric car recharge

Look at Changing to Electric Cars and Using a Carbon-free Source Electricity

- Petroleum usage in USA is about 40 EJ/y
  - One EJ is equal to 1×10^{18} J/y
- Rough Estimate that 1/3 to ½ of petroleum use is transportation with cars, say 15 EJ
- Convert 1/3 of this to electric cars or 5 EJ
- 5×10^{18} J/y /(3×10^{7} s/y) = 2×10^{11} J/s
- Or 2×10^{11} J/s/(3×10^{9} J/s from a 1000 MW reactor) = 66 new nuclear reactors
- These changes are not easy!

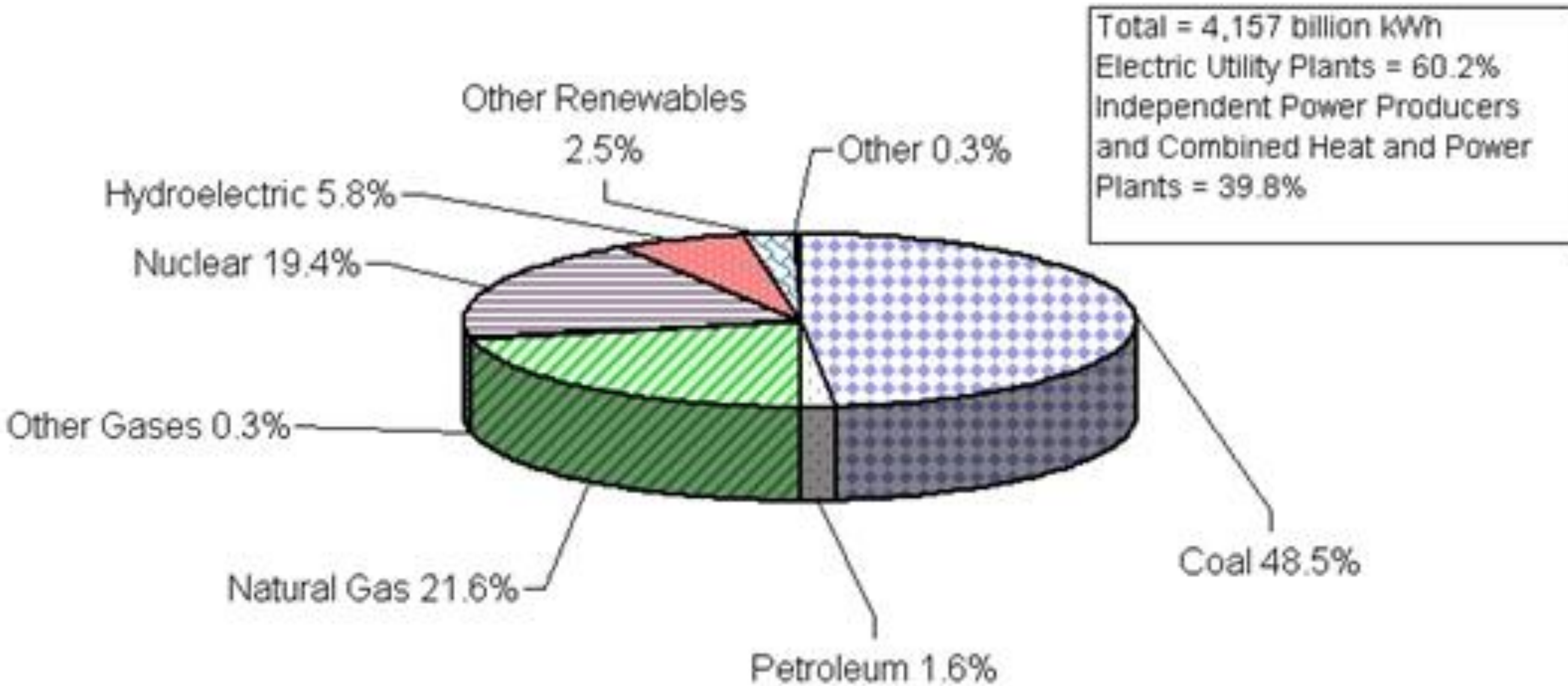
Recent Energy Consumption Data
- USA Data (about 30% of World Use in 2000)

- Coal, Oil and Natural Gas remain the major sources of energy throughout the world – Recent US Energy Data (1 EJ =10E18J)

	1985	1990	1995	1999
Consumption (EJ)	78	89	96	102
Fossil Fuels	70	76	81	86
Coal	19	20	21	23
Nat Gas	19	20	23	23
Petroleum	33	35	37	40
Nuclear	4.4	6.5	7.6	8.2
Renewable	3.6	6.5	7.1	7.8
Hydroelectric	3.6	3.3	3.7	3.6
Geothermal	.21	.37	.36	.35
Biofuels	.01	2.5	3	3.7
Solar + Wind	0.0	.09	0 .11	0 .12

Electricity Production by Sources in the USA

Coal is major source – not as bad in Canada but still important



An Exercise in Estimating

Let’s Apply Some Critical Thinking to a Broad Topic of Current Interest

- CO-2 is the main byproduct of combustion of coal (also a significant fraction of combustion of hydrocarbons) and a key greenhouse gas
  - CO-2 Sequestration – Does it make sense?
- There are routine comments on sequestering the CO-2 into deep underground reservoirs – thus permitting “Clean Coal”
- Let’s “estimate” if this claim makes sense

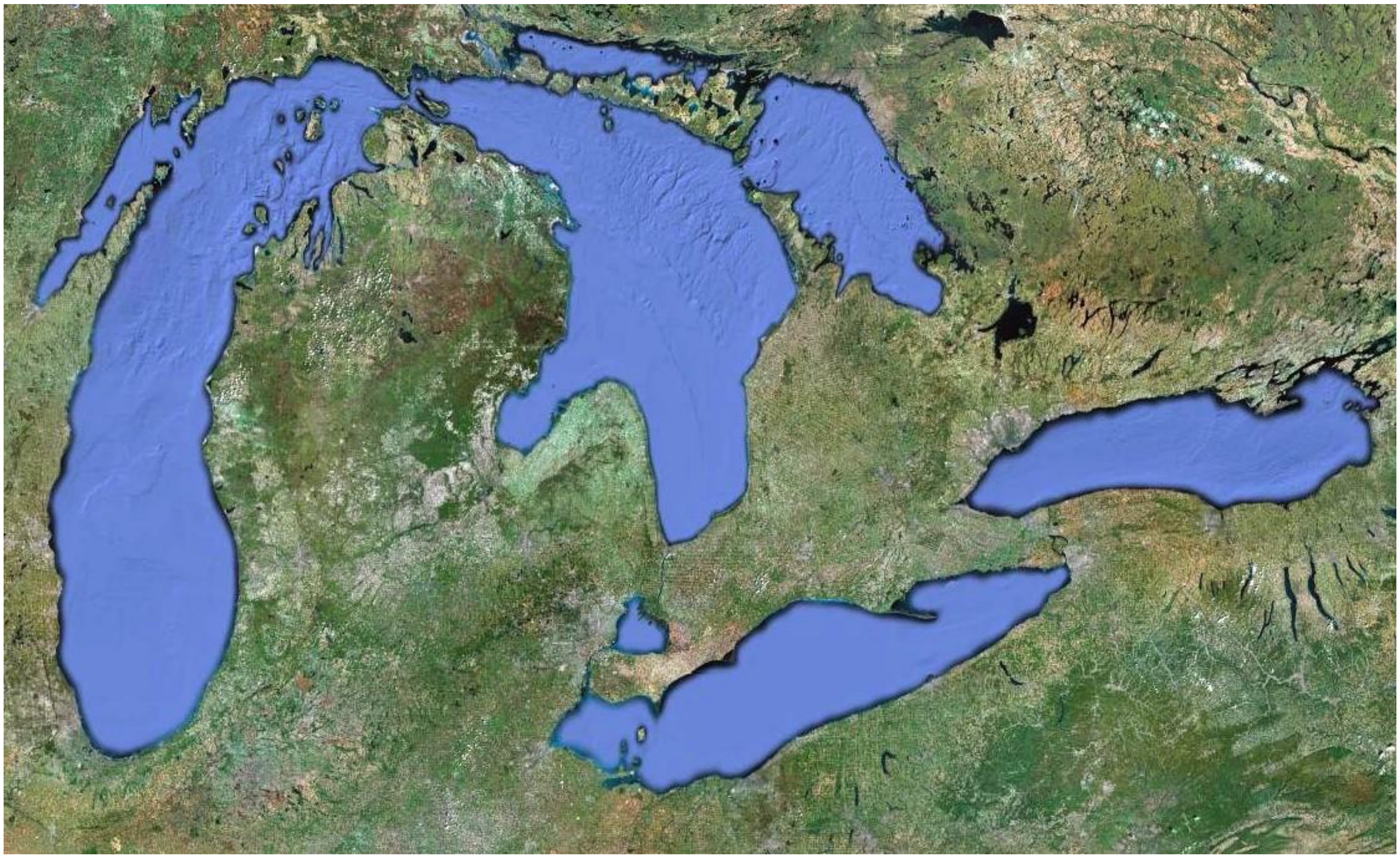
Let's Make Estimate of Effort to Sequester 10% of the CO-2 Produced From Coal in the USA

- About 25 EJ of coal use in USA per year
  - 1 EJ = 1.0×10^{18} J (EJ = Exa Joule)
- Try to sequester just 10% of the CO-2, equivalent to 2.5×10^{18} J of energy
- There are about 30,000 J/g of coal combusted
  - Can be found in an energy equivalent websites but we have already estimated this in simple calculation (note we used 3 instead of 3.3×10^4 J/g
- $2.5 \times 10^{18}/30{,}000 \sim 10^{14}$ g of coal/y
  - 12 g of carbon becomes 44 g of CO-2 (Remember Av. #)
  - 12 g carbon also produces 22.4 L of CO-2 at NPT
- Leads to $\sim 4 \times 10^8$ tonnes or $\sim 2 \times 10^{14}$ L (at STP) of CO-2 produced from just 10% of USA usage of coal

Some Visualization

- 2×10^{14} L of CO-2 produced from just 10% of USA usage
  - 2×10^{14} L is equivalent to 2×10^{11} m^3
  - This is equivalent to a volume of 100 km by 100 km by 20 m deep
  - Think of roughly area of Georgian Bay and say 15 m deep of CO-2 at STP
  - And this is just 10% of YEARLY US production from coal

Some Visualization (con't)



Where Do We Store The CO-2

Are Volumes Such as This Available?

- Most coal is used in eastern half of North America that is largely old shield formations
  - Very unlikely that such large sub-surface volumes exist
  - Piping to western oilfields is very costly
- Can potentially store as liquid CO-2
  - However, liquifaction is expensive and requires piping at about 10 atmospheres rating
  - Safety issues of leaking CO-2
- Broad conclusion must be that large scale sequestration of CO-2 is pretty impractical

It’s Worth Noting the Process

- Its only multiplying and dividing
  - No detailed math or science required
- Start from basic concept of few eV per molecular bond
  - X N_{Av} (6×10^{23}) to produce energy (J) produced per mole
  - Compare to number such as 2.5 EJ/y (10% of present coal use)
  - To produce nearly 10^{13} moles of coal used per year
  - Producing about 2×10^{14} g of CO-2 per year
- This basic process provides scale of effort required to have a significant impact
- One percent to 10% are about the lowest number I would use as a basis for some process producing meaningful reductions in CO-2

To Assist One in the Critical Thinking Process
Let's Look at What 1 EJ Means?

- 1 EJ (thermal) is equivalent to:
  - 10E18 J/(3 x10^9 J/s per power plant x 3 x10^7 s/y)

  = 10 power plants of 1000 MWe
- Therefore ten large 1000 MWe plants only replaces 1% of US energy usage (less than 1/3% of world usage)

- Replacement of even 1% of the US total energy requirements with new nuclear is an imposing challenge (10 new 1000 MWe builds)

1 EJ From Wind or Solar

- Large windmills of about 2 MW or 2 MJ/s
  - times 3×10^7 s/y times (capacity factor of 33%) will produce about 2×10^{13} J/y
  - *Note use of convenient estimate of 3×10^7 s/y instead of 3.15×10^7 s/y to make math easy*
  - implying 50,000 units for 1 EJ
- How do you store an EJ for periods of non-operation?
  - Because of problems of duty factor - massive storage system required if wind or solar are used as baseload power
  - Cannot easily store large amounts of electricity in any practical manner
  - Usually use natural gas turbines as backup

Solar Power

- Solar Collection at about 1 kW/m^2 or 1000 $J/s/\ m^2$
  - (peak daylight in southerly location) x 1/3 (hours of useful sunlight) x 3×10^7 s/y = 1×10^{10} J/y/sqm
  - Times about 10% collection efficiency = 1×10^9 J(e)/y/sqm
  - Requires 10^9 sq m or 1000 sq km of collector for 1EJ(e)

    Say 30 km by 30 km

    This is a large area of solar panels but manageable
  - Again, because of duty factor - massive storage system required

What Would Storage of Such Large Amounts of Energy Look Like?

- The single greatest source of hydroelectric power in the world, the Niagara River is home to several power plants. The 2 most famous plants on the Canadian side are the Sir Adam Beck I and II, named after the first head of the Hydro-Electric Power Commission. Combined, the Beck power stations produce over 2 million kW of electric power or 2 x 10^{9} J/s (note – equal to 2 modern reactors)

- One EJ/year is equivalent to an instantaneous use rate of
  - 10^{18} J/y /(3 10^{7} s/y) = 3 10^{10} J/s or 10 times the rate at which Niagara Falls is producing electricity

This is equivalent to a pumped storage system for 1/10% of Total US Energy (1/3% of Electricity)

Summary of the Main Thrust of This Presentation

- Energy and climate change are major issues at present and likely to be for foreseeable future
- Examine the many claims and reports with a serious view about value and strength of supporting evidence
- Use your skills in science (and often, a single sheet of paper) to check the validity of the claims
- Often a “big picture overview” such as suggested in this presentation is of more value than a lot of supporting details

- In conclusion – use critical thinking