Basic Tools for Energy and Climate Analysis

Week 3: Energy and Climate Policy
PB AF 595

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I didn't have any accurate numbers so I just made up this one.

Studies have shown that accurate numbers aren't any more useful than the ones you make up.

How many studies showed that?

Eighty-seven.
A starter set...

- IPAT and identifying key drivers
- Understanding units, energy (stock) vs. capacity (flow)
- Calculating emissions
  - tC vs. tCO2
  - multiple gases, GWP and tCO2e
- Estimating emission reductions
  - Always incremental to a counterfactual assumption or baseline scenario (need to be explicit)
  - Understand what you’re avoiding, don’t avoid it twice
- Interpreting marginal abatement cost (MAC) curves
  - Economic, technical, and achievable potentials (tCO2e)
  - Bottom-up abatement costs ($t/CO2)
Units

See and use the unit conversion handout. There’s also a handy conversion tool developed by IEA: [http://www.iea.org/Textbase/stats/unit.asp](http://www.iea.org/Textbase/stats/unit.asp)

Common physical units:
- Crude oil: barrels (bbl) or tons (t)
- Natural gas: cubic feet (cf) or cubic meters (cm)
- **Coal**: tons

Common energy and power units:
- **Electricity**
  - power - generation capacity in Watts (W, kW, MW..)
  - energy - generation & consumption in Watthours (Wh, kWh;...)
- **Anything energy**
  - BTUs or Quadrillion BTUs (Quads or or $10^{15}$BTUs)
  - Joules or Exajoules (EJ or $10^{18}$J)
  - Sometimes primary, sometime final energy
- Oil-oriented lens
  - BOE (barrels of oil equivalent) or TOE (tons oil equivalent)
- Coal-oriented lens
  - TCE (tons coal equivalent)
Getting a Feel for the Numbers …

1 BTU = 1055 joules = 252 calories
1 Watt = joule/second = 3.41 BTU/hr
1 hp = 550 ft-lbs/sec = 746 watts

burning 1 match = 1000j

1 bbl = barrel of oil = 42 gallons
= 5.6 x 10^6 BTU = 5.9 x 10^9 joules

1 Quad = 10^{15} BTU = 10^{18} joules (EJ)
1 EJ = 4 days of US energy use

Dan Kammen, ER100/200 lecture (2007)

1 microcentury = 10^{-6} century = 52 min, 36 seconds,
introduced by Enrico Fermi as the standard duration of a lecture period
# Energy Rate Scaling

- **Food** - 250 kcal/candy bar
- **Average daily requirement** - 2000-3000 kcal/day = 100 W
- **Human heart** - 2 W
- **Running** - 500 W
- **1 horsepower** - 750 W
- **747 jet plane** - 250 MW
- **Automobile** - 100 kW
- **Space shuttle (with boosters)** - 1 (14) GW
- **Typical electric generating plant** - 1000 MW
- **1 wind turbine** - 1-3 MW
- **Laptop computer** - 10 W
- **Cell phone** - 2 W

**US energy consumption per year** -----
100,000,000,000,000,000,000,000 J or 3.5 TW

**Worldwide energy consumption per year** -----
400,000,000,000,000,000,000,000,000,000 J or 15 TW
Emission Factors of Fossil Fuels

Figure 8.5. Carbon Content of Fossil Fuels

<table>
<thead>
<tr>
<th></th>
<th>Tons of Carbon per TJ Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>26.8</td>
</tr>
<tr>
<td>Oil</td>
<td>20.0</td>
</tr>
<tr>
<td>Gas</td>
<td>15.3</td>
</tr>
</tbody>
</table>

Sources & Notes: IPCC, 1997. The carbon emissions factor for coal is based on anthracite coal. There are slightly different carbon contents for other grades of coal, such as coking (25.8), bituminous (25.8), and lignite (27.6).
More sophisticated approaches take into account fuel characteristics, technologies, oxidation factor, actual operation, etc. (e.g. IPCC guidelines, USEPA tools, GHG Protocol) – Full fuel (of life) cycle emission factors can be important to consider (esp. liquid fuels)

Metric units are the standard: metric tons (1.1 US short tons) more common (tCO2, MtCO2…), grams more precise (MgCO2, TgCO2….MgCO2 = tCO2)

Be careful to note the difference between average and marginal emissions rates!
– average electricity emission rates (for power plant, utility, region) used to characterize emissions
– marginal electricity emission rates used to estimate emission reductions (what is avoided
– same average vs. marginal concept can apply in other sectors

<table>
<thead>
<tr>
<th>Activity Level</th>
<th>Emission Factor</th>
<th>Selected Data Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Fuel Use</td>
<td>Fuel combusted (GJ, Btu, etc.)</td>
<td>Fuel carbon content (tCO2/GJ, tCO2/Btu…)</td>
</tr>
<tr>
<td>Electricity</td>
<td>Energy generated or delivered (MWh)</td>
<td>Emission rate (tCO2/MWh) OR Heat rate/efficiency (Btu/kWh or MJ/kWh) times fuel carbon content</td>
</tr>
<tr>
<td>Other sources &amp; gases</td>
<td>Cement produced (tons), Rice production (acres flooded), etc.</td>
<td>Various factors: tCO2/t cement, tCO2e/acre flooded (methane) etc.</td>
</tr>
</tbody>
</table>

\[
\text{Emissions} = \text{Activity Level} \times \text{Emission Factor}
\]
A few tricks of the trade

• Law of 70 (see Koomey, 2001 reading)
  – recall that exponential growth rarely lasts forever

• Average coal power plant (33% efficient) –
  – GHG emissions $\approx 1.0$ tCO2e/MWh
  – $10/\text{tCO2} \approx 1\text{c/kWh}$

• Efficient natural gas power (50% efficient)
  – GHG emissions $\approx 0.4$ tCO2e/MWh
  – $10/\text{tCO2} \approx 0.4\text{c/kWh}$

• Gasoline/diesel fuel
  – 1 barrel = 42 gallons, so,
  – $100/\text{barrel} = \sim$ $2.50/\text{gallon}$
  – $1/\text{gallon} \approx 100/\text{tCO2}$
Addressing multiple GHGs

The table above shows the gases that together with CO2 form the “Kyoto six-gas basket” used for most GHG reporting. Source: WRI, 2005 [pdf.wri.org/navigating_numbers.pdf]

Global Warming Potential (GWP) and “tons CO2 equivalent”

- A common numeraire for all Kyoto gases that:
  - Compares their ability to trap heat in the atmosphere relative to CO2
  - Reflects the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of CO2
- Common practice is to use IPCC Second Assessment Report, 100 year integration (as shown here)
- Unit: CO2 equivalents (gCO2e or gCO2eq).

\[ Mg \ CO_2 \ Eq = (Mg \ of \ gas) \times (GWP) \]
Cost-effectiveness and bottom-up cost curves

- Combine cost-effectiveness and emissions reduction potential
- Area under curve yields total cost of avoided emissions.
- Options below x-axis (0) have “net cost savings”

U.S. MID-RANGE ABATEMENT CURVE – 2030

The McKinsey Cost Curve v2.0 identifies 19 Gt of abatements by 2020 making it technically feasible to achieve 450ppm.

Global abatement cost curve, 2020
(up to costs of €60/t)

Average cost of opportunities up to 17 Gt = €0/t (if benefits of left hand side fully captured)

Breakdown by abatement type
- 10 Gt for terrestrial carbon (forestry and agriculture)
- 5 Gt for energy efficiency
- 4 Gt for low carbon energy supply
Calculating Bottom-up Mitigation Cost or Cost-Effectiveness

\[
\text{CostEff} \left[ \frac{\$}{tCO_2} \right] = \frac{\Delta NPV_i [\$]}{\Delta NPE_j [tCO_2]}
\]

NPV – cumulative net present value of option at discount rate \(i\), through future year \(t\)

NPE – cumulative discounted sum of emissions (E) at discount rate \(j\) (discount rate \(j\) makes big difference, commonly \(j = 0\), choice generally undocumented)

\(\Delta\) - difference between mitigation and reference (baseline) option
Cost Curves

- Bottom-up methods tend to produce “step-wise” cost curves (with some negative cost options); top-down methods tend to produce smoothly increasing ones (with no negative cost options).
- Step-wise curves provide a technique for screening and ranking GHG mitigation options, but limitations should be recognized.
- Care should be taken to consider interdependencies among options (e.g. benefits of fuel switching in power sector may be reduced by end-use efficiency programs).
Cost curve from WA CAT process

Note: Strategies quantified in terms of emissions reductions but not cost:

- Bar width represents cumulative 2008-2020 anticipated GHG reductions for individual options (not counting overlap)
- Bar height represents cumulative 2008-2020 anticipated cost per ton of GHG reduced for individual options (not counting overlap)

Cumulative Emissions Reductions 2008-2020
Cost and barrier considerations help identify opportunities and interventions

Technical mitigation options grouped by estimated mitigation costs

Group 1 – Remove non-market barriers to achieve economic benefit
- Transport efficiency
- Building efficiency
- Appliance efficiency
- Industry efficiency
- Urban design

Group 2 – Establish carbon price/regulation and remove non-market barriers
- Some CCS (e.g., ecbm)
- Other methane (waste, fuel)
- Some wind, hydro, biomass
- Agriculture (soil carbon)
- Some forestry
- Some biofuels
- Fuel switch
- Power plant efficiency
- Non-CO₂ GHG (industry)

Group 3 – Accelerate tech and institutional development
- CCS
- "Safe" nuclear
- Hydrogen/electric vehicles and infrastructure
- Biomass (with CCS)
- Advanced renewables (solar, wind with storage)
- Advanced biofuels (cellulosic)
- Avoided deforestation
- Advanced industrial processes

Unidentified

Costs may decline over time due to R&D, learning, etc.
From cost curve to wedges

Source: https://solutions.mckinsey.com/ClimateDesk/default.aspx
How much is enough?

Emissions relative to different GHG concentration pathways

Source: https://solutions.mckinsey.com/ClimateDesk/default.aspx
Box SPM.2: Mitigation potential and analytical approaches

The concept of “mitigation potential” has been developed to assess the scale of GHG reductions that could be made, relative to emission baselines, for a given level of carbon price (expressed in cost per unit of carbon dioxide equivalent emissions avoided or reduced). Mitigation potential is further differentiated in terms of “market potential” and “economic potential”.

Market potential is the mitigation potential based on private costs and private discount rates, which might be expected to occur under forecast market conditions, including policies and measures currently in place, noting that barriers limit actual uptake [2.4].