Climate Change Economics

Edwin Cox
OLLI

Outline of today's discussion

Signaling the desired behavior

- Taxes, specifically carbon tax

Mitigation cost

- Determining the "social cost of carbon"
- Optimum tax is set at the SCC
- Mitigation cost calculation
- Mitigation cost of specific energy tradeoffs

Putting it all together – can it work?

Externalities

Externality

- In economics, a cost imposed on a party by a party who did not choose to incur that cost or benefit from it

Examples

- Persons who die prematurely as a result of fine particle pollution from coal-fired power plants
  - Estimated at 30,000 per year in the U.S. alone
  - Loss of life-years as a result estimated to be > $100B / year
- Damages due to climate change
- Health consequences to bystanders from cigarette smokers
- People killed by drunk drivers

Taxes

Obvious objective of taxation

- To raise money to pay for the services of the government

Less obvious but useful objective of tax

- Promote desired and suppress undesired behaviors
- Promote desired behavior through tax rebates
- Suppress undesired behavior through tax on the undesired activity
  - Taxes on cigarettes and alcohol
- Social programming use of taxation to correct externalities promulgated by English economist Arthur Pigou

Slippery slope of taxation

Tax policies tend to get enshrined, especially if benefiting parties are effective lobbyists

- Oil depletion allowances still in effect, though their usefulness has long since passed

Politicians tend to find new uses for extra money that comes in

- Government becomes bloated, inefficient
- Tax load inhibits private expenditures that promote economic growth

Carbon tax

Many economists favor a carbon tax to address climate change

- Tax is levied on fossil fuels – anywhere along the supply chain will work – e.g., $25 per tonne carbon dioxide per unit fuel
- Tax set equal to the marginal damages expected from carbon emissions is maximally efficient
- Other taxes (income, payroll) are reduced by the same amount → revenue neutral
- Potentially regressive tax → deliberate redistribution to lower income individuals to balance that effect

Carbon tax - issues

Very little empirical evidence on which to judge whether it will work as theorized

- British Columbia experiment – Dr. Murray

Scaling to global extent

- Enforcement
- Free riders
- Leakage
- Equity – developed vs. developing nations

Carbon tax - advantages

Simplicity - example

- Deciding whether to make a trip with my family from Durham to Nashville to see relatives by air or auto
- Taking into account environmental impact
  - Will I emit more CO_2 by driving or flying? Did I take into account driving to the airport, whether the plane was full or empty, …
- With a carbon tax, all of that is automatically priced in to the cost of the ticket, gasoline, etc, to simplify the decision

Mitigation cost

How much does it cost, in $/tC, to change from an existing polluting energy source to a less-polluting energy source?

- $(\$/kWh_a - \$/kWh_b)/(Emiss/kWh_b - Emiss/kWh_a)$

Example: Coal plant vs. wind turbine

- ($0.094-$0.116)/(0-0.00026tC)
- $85.84/tC

Of tons & tonnes

Much potential (and actual) confusion over the multiple ways of expressing carbon emissions – whether as tons or tonnes

Ton & tonnes

- Tonne = metric ton = 1000 kg = 2204.6 lb – international use
  - But often spelled ton in informal uses (e.g., Guiness Book)
- Imperial ton, or long ton = 2240 lb – UK, displaced by tonne
- Ton = short ton = 2000 lb - US
- Tonne = 1.1 ton

Unless otherwise specified, tC is tonnes carbon

Of C & CO_2

Equally, if not more confusing than tons is CO_2 (carbon dioxide) vs C (carbon)

- One molecule of CO_2 has mass of 44u (12u for the C, 16u for each O)
- The C part of the CO_2 molecule is 12u
- A tonne of CO_2 (tCO_2) is only 12/44 ton of C (tC)
- 44 tCO_2 = 12 tC
- \$100/tC = \$27.27/tCO_2

Energy- the nexus of CC

Climate change is largely a consequence of how we get our energy

- Burn coal and natural gas to generate electricity
- Burn petroleum to power transportation
- Burn fuels to heat our buildings
- Burn fuels for industrial processes

Avoiding CC will require reducing fossil fuel consumption

- Use energy more efficiently
- Use energy sources that don't produce greenhouse gas emissions

Concepts of Energy

Force = mass x acceleration (F=ma)

- Newton's Second Law
- Acceleration: the acceleration due to Earth's gravity, $g = 9.8\ m/s^2$
- Mass: A 2 liter bottle of pop (2 kg)
- Then the force require to lift that mass is 2 x 9.8 $kg\text{-}m/s^2$, or 19.6 N (N=newton)
- Let's call it 20 N (close enough!)

Concepts of Energy

Energy (aka Work) = force x distance (E=Fd)

- Lift the soda bottle one meter
- Energy = 20 kg-m^2/s^2 = 20 N x 1 m = 20 N-m = 20 J (J=Joule)
- 1 J = 1 N-m
- James Joule (along with Lord Kelvin) demonstrated the equivalence of heat and mechanical energy

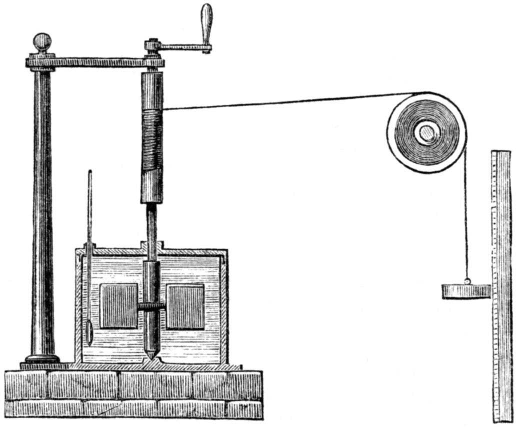
Joule's Heat Experiment

A falling weight pulled a cord wrapped round an axle

The axle spun paddles in an insulated fluid chamber

A thermometer revealed the temperature change due to the energy transferred to the fluid by paddle / fluid interaction

Results published in 1843-45 were received with skepticism



Concepts of Energy

Power = Energy / time

- Power is the rate of performing work
- If we raise the 2 liter pop bottle one meter in one second, we are expending power at 20 J/s, or 20 W (W = Watt)
- James Watt was the Scottish instrument maker who make the first practical steam engine

Energy is Interconvertible

Energy is the capacity for doing work

Types of energy

- Electrical, chemical, thermal, electromagnetic, gravitational potential, mechanical (kinetic)

In theory, any type of energy can be converted into any other (though not necessarily directly)

There is always a reduction in the quantity and/or quality of usable energy when it is converted; the lost fraction becomes thermal energy, the least valuable

Efficiency is useful energy out / energy in

Scientific notation

Numbers get very big or very small

Example: 3,600,000,000 J

- 3 billion, 600 million J
- Same as 3.6 x 1 billion J
- 1 billion is 10 raised to the 9th power (10^9), so we can write this 3.6×10^9 J
- Rather than say "10 raised to the 9", we have a convenient shorthand – *Giga* – to add to the unit
- 3.6 Gigajoule, or 3.6 GJ

Scientific notation

Prefixes for scientific numbers

- Go by thousands (10^3, 10^6, 10^9, 10^{-3})
- K (kilo), M (mega), G (giga), T (tera), P (peta)
- m (milli), µ (micro), n (nano), p (pico), f (femto)

Energy Units

Joule - the SI (International System) unit

British thermal unit (Btu) – the Imperial/U.S. unit

- Quantity of heat raising one lb of water one degree F

Calorie (cal)

- Heat raising one gram of water one degree C

Food Calorie, or kilocalorie (Cal)

- 1000 cal

Watt-hour (Wh)

- A watt used/produced over the course of an hour (3,600 sec)

Others

- Ergs, lbs of TNT, electron-volts, horsepower-hours, foot-pounds

Conversion of energy units

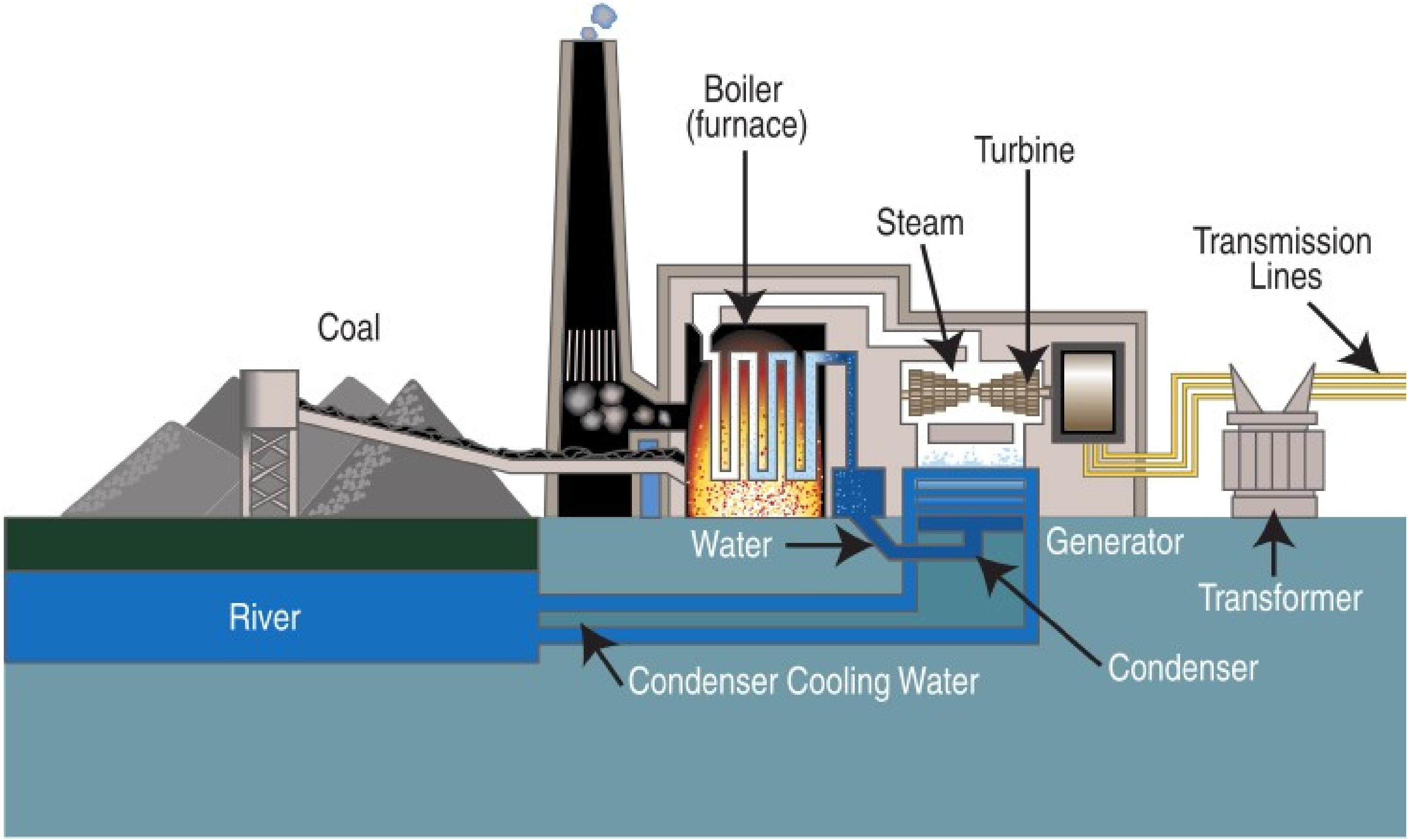
1 Btu = 1055 J = 1.055 kJ

1 Wh = 1 W x h = 1 J/s x 3600 s = 3600 J

1 W = 3600 J/h

1 W = 3600 J/h x 1 Btu/1055 J = 3.412 Btu/h

Steam power plant



Steam power plant

React fossil fuel and oxygen at sufficient temperature to convert chemical energy to heat (combustion)

- Chemical energy to thermal energy

Heat water to produce steam (boiler)

- Thermal energy to latent thermal energy

Process steam to produce mechanical energy (turbine)

- Latent thermal energy to mechanical energy

Mechanical energy varies magnetic field across loops of wire to produce electric current (generator)

- Mechanical energy to electrical energy

Power plant cost inputs

Plant construction ($/kW)

Plant operation and maintenance – fixed ($/kW/yr)

- Administration
- Land, buildings

Plant operation and maintenance – variable ($/kW/yr)

- Proportional to the amount of energy generated
- Wear and tear

Fuel cost ($/kW/yr)

- Proportional to the amount of energy generated

Capacity factor

- Hours generating / 8760

LCOE (levelized cost of electricity) = Total annual cost / kWh of electricity gen

Power plant capital costs

Referred to as total plant investment (TPI) or overnight cost

Amortized over the lifetime of the plant ("mortgage")

Financed through combination of equity (shareholder) and fixed rate (bonds, bank) investments

Equity interest rate (10-15%) reflects risk of being second in line for repayment

Fixed interest rate (5-10%) reflects lower risk of being first in line for repayment ("senior debt")

Weighted average cost of capital (WACC) is fraction equity-financed x equity rate plus fraction fixed-financed x fixed rate

Running costs

Fixed O&M

- Operations and maintenance labor
- Supplies other than fuel
- Independent of amount of electricity generated

Variable O&M

- Wear and tear
- Consumables such as chemicals to remove pollutants
- Proportional to hours of operation, amount of electricity generated

Fuel consumption

Proportional to the amount of electricity generated

Heat rate is the amount of thermal energy required from fuel to generate one kWh of electricity, given in Btu

Heat rate differs by fuel, by type of plant, efficiency of plant

Efficiency and heat rate are related

- 1 kWh_{el} = 3412 Btu_{el} = Power Out (electrical)
- Heat rate = Power In (thermal)
- Efficiency η = Power Out / Power In
- Efficiency η = 3412 / Heat rate

Fuel consumption - coal

Fuel heat content of coal

- 19.2 million Btu per 2000 lb – typical
- Varies based on type of coal (anthracite, bituminous, sub-bit., lignite)

Fuel cost

- \$50 per 2000 lb, \$2.60 per million Btu, \$2.46/GJ

Heat rate

- 10089 Btu/kWh

Fuel cost / kWh

- \$0.026 = \$2.60 x 10089 / 1000000

Fuel consumption - NG

Fuel heat content of natural gas

- 1.025 million Btu (mmBtu) per 1000 cu. ft. (mcf)
- 1.081 GJ per mcf

Fuel cost

- \$5.19 per mcf, \$4.80 per GJ, \$5.06 per mmBtu

Heat rate

- 10354 Btu/kWh

Fuel consumption

- 10354 Btu/kWh x 1 mcf / 1.025 mmBtu = 0.0101 mcf/kWh

Fuel cost / kWh

- \$0.052/kWh = \$5.19/mcf x 0.0101 mcf/kWh

Putting it all together: coal

Capacity factor 90%, production 7884 kWh

Capital cost $2917 / kW

- Amortized at 15% over 20 years, $466/kW-yr

Fixed O&M - $31/kW-yr

Variable O&M - $35/kW-yr

Fuel - $206/kW-yr

Total annual cost - $739/kW-yr

LCOE = $739/7884 kWh = $0.094/kWh

Putting it all together: NG

Capacity factor 90%, production 7884 kWh

Capital cost $968 / kW

- Amortized at 15% over 20 years, $155/kW-yr

Fixed O&M - $7/kW-yr

Variable O&M - $128/kW-yr

Fuel - $454/kW-yr (@$5.19/mcf)

Total annual cost - $745/kW-yr

LCOE = $745/7884 kWh = $0.089/kWh

Carbon Emissions

Coal

- Emissions = 207 lb CO_2 / mmBtu
- Heat rate = 10089 Btu/kWh
- 207*10089/1000000/2200 = 0.00095 tCO_2 / kWh

NG

- Emissions = 121 lb CO_2 / mcf
- Heat rate = 10254 Btu/kWh
- Fuel energy = 1025000 Btu /mcf
- 121*10354/1025000/2200=0.00055 tCO_2 / kWh

Putting it all together: wind

Capacity factor 35%, production 3066 kWh

Capital cost $1980 / kW

- Amortized at 15% over 20 years, $316/kW-yr

Fixed O&M - $40/kW-yr

Variable O&M - $0/kW-yr

Fuel - $0/kW-yr

Total annual cost - $356/kW-yr

LCOE = $356/3066 kWh = $0.116/kWh

Mitigation cost

How much does it cost, in \$/tC, to change from an existing polluting energy source to a less-polluting energy source?

- $(\$/kWh_a - \$/kWh_b)/(Emiss/kWh_b - Emiss/kWh_a)$

Example: Coal plant vs. wind turbine

- (\$0.094-\$0.116)/(0-0.00026tC)
- \$85.84/tC