John Andrews & Nick Jelley

Lecture 12:

Energy and Society

Milankovich cycles

CO$_2$ concentration, ppmv

Temperature change from present, °C

Year before present (present = 1950)
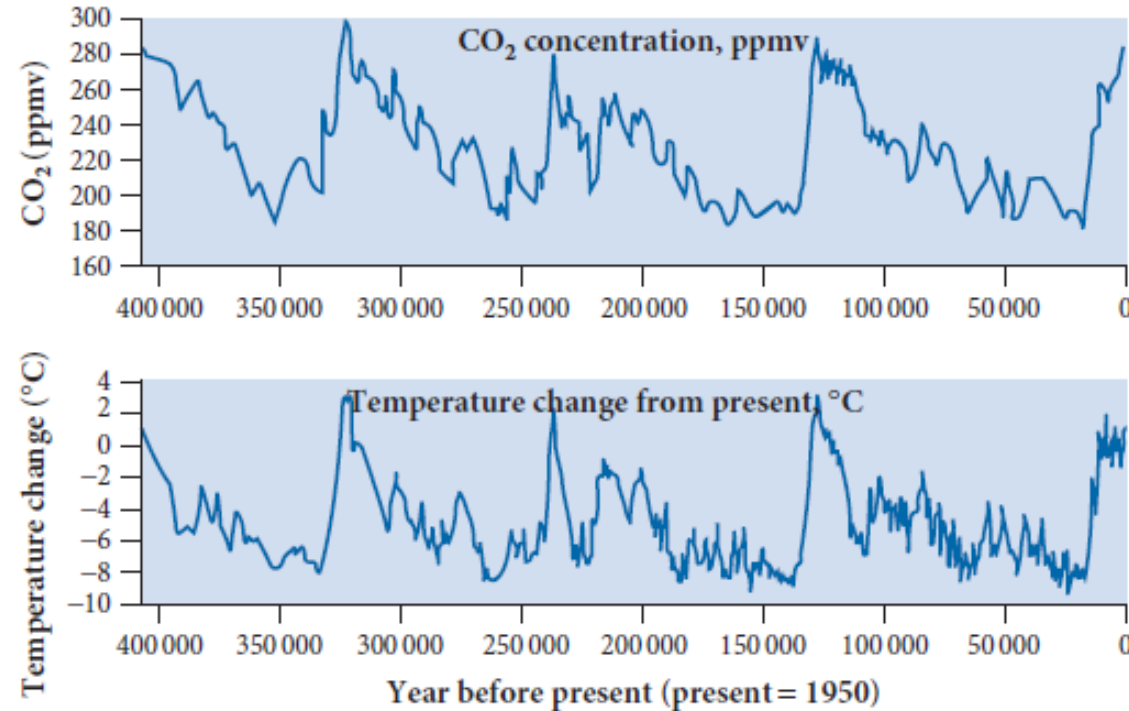
Ice core samples show large fluctuations in CO$_2$ concentration over last 400 000 years, called **Milankovich cycles**

- Periods ~ 26, 40, and 100 thousand years

- Caused by **roughly periodic variations in Earth's orbit and tilt**

- Leads to variations in distribution of solar irradiation, and to **ice ages**

- End of last ice age caused Antarctic to warm, releasing CO$_2$ and raised global temperature.

There is a **good correlation** between global temperature and atmospheric CO$_2$ concentration. However, this does not prove a causal connection between the two effects.

Anthropogenic effect

Since the **Industrial Revolution** atmospheric CO_2 concentration has increased sharply:
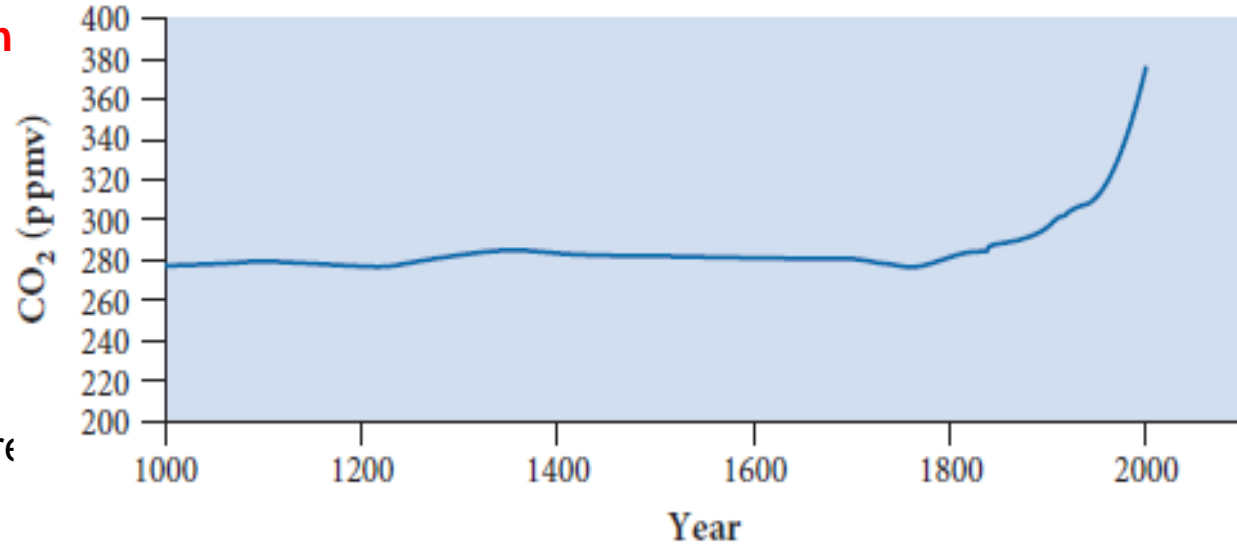
1750 ~ **280 ppm**
1955 ~ **312 ppm**
2015 ~ **405 ppm**

and the global mean temperature has increased by **~ 0.5 °C**

15 of the warmest years on record have occurred in the 21st century.

The significant rise in temperature since ~1750 and in particular over the last **50 years** is known as **'global warming'**.

The rise in temperature over the period 1970-2000 can only be explained by **anthropogenic causes.**

The predicted temperature variation due to **natural causes** over this period shows no rise.

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Andrews & Jelley: Energy Science, 3rd edition

Existing evidence of global warming

There is already a huge amount of corroborating evidence for global warming, including

- Shrinking of Arctic and Greenland **ice sheets**

- Retreating of **glaciers**

- Movement of **plankton** to cooler waters

- Dying of **coral reefs**

- Rise in **sea water level** of 20 cm over last 100 years

- An increase in the severity and frequency of **heat waves** and of **heavy rainfalls**

(a) Polar bear habitat ©Howard Perry/istock
(b)Flooding in Asia: 1000 Words/shutterstock

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Future scenarios

1-2 °C rise

- Loss of small glaciers in Andes
- Major water shortages in S Africa & S America
- 10 million people affected by coastal flooding

3 °C rise

- Severe drought in Southern Europe every decade
- Major water shortages for 1-4 billion people
- 150–550 million people at risk from lack of food
- 170 million people affected by coastal flooding
- 20-50% of animal species face extinction

4 °C rise

- Up to 50% less water available in S Europe
- Agricultural yields in Africa down 15-35%
- Half of Arctic tundra lost
- 300 million people affected by coastal flooding

>5 °C rise

- Loss of most Himalayan glaciers and loss of water for hundreds of millions of Chinese and Indians
- Flooding of major coastal cities
- Increase in ocean salinity
- CO_2 release from soils and methane from melting permafrost – possible **tipping point**

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Discounted cash flow analysis

Energy technologies

1. need **capital** to build plant

2. money to **operate and maintain** plant (O&M)

3. obtain **revenue** from selling the energy generated

Investing and discounting

Money invested today at a fixed annual interest rate increases in value each year.

Conversely, revenue received in the future is worth less than revenue received today.

Reducing future revenue to its **present value** is called **discounted cash flow analysis**.

Formula for present value of future revenue

Suppose that a fixed revenue A is obtained each year. The present value V_p of the revenue obtained over N years, is given by

$$V_p = A [1 - (1+R)^{-N}]/R$$

where R is the discount rate.

Example

$R = 5\%$, $N = 30$, $A = \$100,000$, yields

$$V_p = 100,000 [1-(1.05)^{-30}]/0.05 = \textbf{\$1,537,245}$$

[Note: ignoring discounting gives a value of

30 x \$100,000 = **\$3,000,000**]

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Levelized Cost of Energy

The **net present value** is the return after subtracting the initial capital from the present value of the revenue:

$$V_{NP} = V_P - C_{capital}$$

e.g. If $C_{capital} = \$1,000,000$, in the earlier example, then the present value is given by

$$V_{NP} = 1,537,245 - 1,000,000 = \$537,245$$

In order to compare the economics of different energy technologies 'on a level playing field', we first calculate the annual revenue that would give zero net present value, by putting

$$V_{NP} = A_{cost} \, [1 - (1+R)^{-N}]/R - C_{capital} = 0$$

Hence,

$$A_{cost} = C_{capital} \; R/[1 - (1+R)^{-N}]$$

We then define **levelized cost of energy LCOE** as

$$LCOE = A_{cost} \, /E$$

where E = energy produced per year

$$LCOE = \left(CRF \times C_{capital} + O\&M_f \right) \Big/ \left(8760 \times CF \right)$$
$$+ O\&M_v + Fuel$$

$$CRF = R \Big/ \left[1 - \left(1 + R \right)^{-N} \right]$$

CRF is capital recovery factor and **CF** is capacity factor

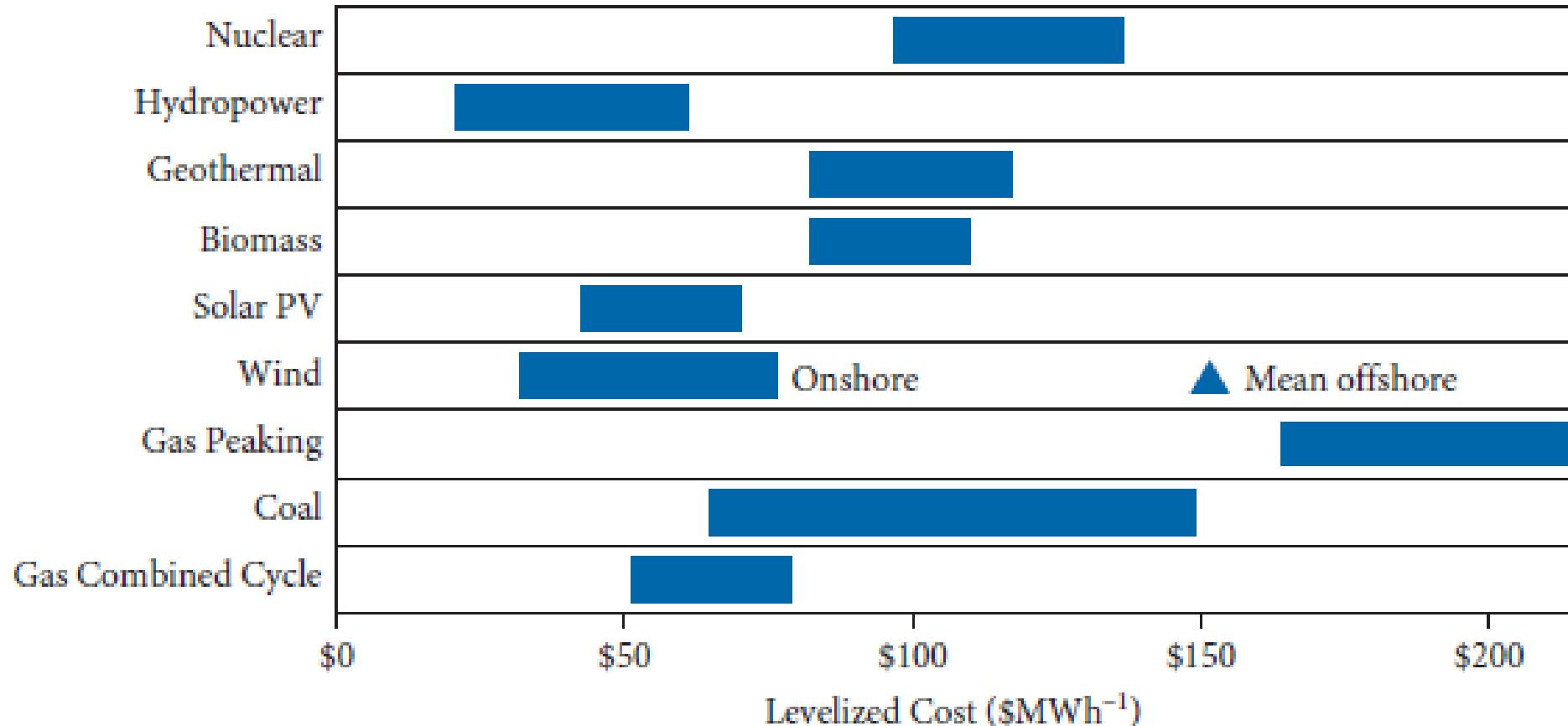# Comparison of LCOE's for various energy technologies

Fig. 12.2 Levelized cost of energy.
Source: Lazard (2015).

Comparison of Fossil and Renewable Technologies

Table 12.1 Lowest-cost estimates for some fossil fuel and renewable technologies

Technology	LCOE ($/MWh)	Life (y)	Capital ($/kW)	Capacity factor	Fuel ($/MWh)	O&M$_f$ ($/kWy)	O&M$_v$ ($/MWh)
Coal	65	40	3800	0.9	18	40	2
Gas CC	52	20	1200	0.7	23	6	3.5
Nuclear	85	40	5400	0.9	9	140	0.5
Wind onshore	37	20	1250	0.5	0	35	0
PV utility	58	30	1600	0.3	0	11	0
CSP storage	119	35	9000	0.85	0	115	0
PV home	184	20	3800	0.25	0	16	0

Source: Based on Lazard (2015) estimates for the lowest LCOE for each technology.

Learning curve estimation

There is a global trend for most technologies that **costs fall as production increases**.

On a **log-log-scale**, the rate of fall in cost is roughly linear. (See learning curve for onshore wind opposite).

It provides a means of estimating how the cost of particular technology will evolve in the **future**.

Example: Photovoltaic cells

Present cost of PV panels ~ **6 cents kWh^{-1}**. Learning rate during period 2009-2015 was 15%.

Assuming learning rate remains constant (helped by technical advances e.g. perovskite + silicon double layer cells with increased efficiency to ~ 30%), then PV cost in 2050 **~ 2 cents kWh^{-1}**.
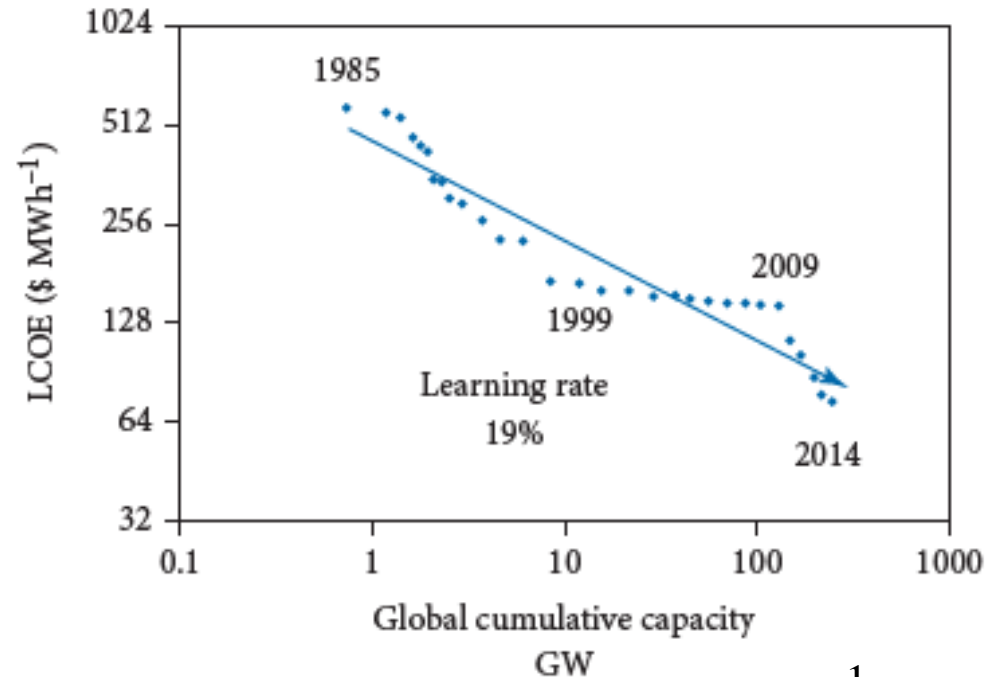
Number of years before the LCOE is $\frac{1}{x}$ what it is today

$$n\left(\frac{1}{x}\right) = \frac{6930\ln(x)}{r_p g_p} \quad \text{e.g.} \quad n\left(\frac{1}{2}\right) = \frac{4800}{r_p g_p}$$

r_p and g_p % learning and growth rates

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Risk assessment: the dread factor

Experts tend to make risk assessments based on the probability of an accident occurring, whereas the **public perception** of risk tends to be affected by the nature of the accident.

Risks are perceived to be greater if the are involuntary, controllable, and potentially catastrophic.

This is known as the **dread factor**.

Fig. 12.4 Perceived risks versus actual risks.
Source: Psychol.

Conversely, risks are perceived to be lower if they are voluntary, controllable and limited.

Hence, **nuclear accidents** have a high dread factor but **car crashes** have a low dread factor.
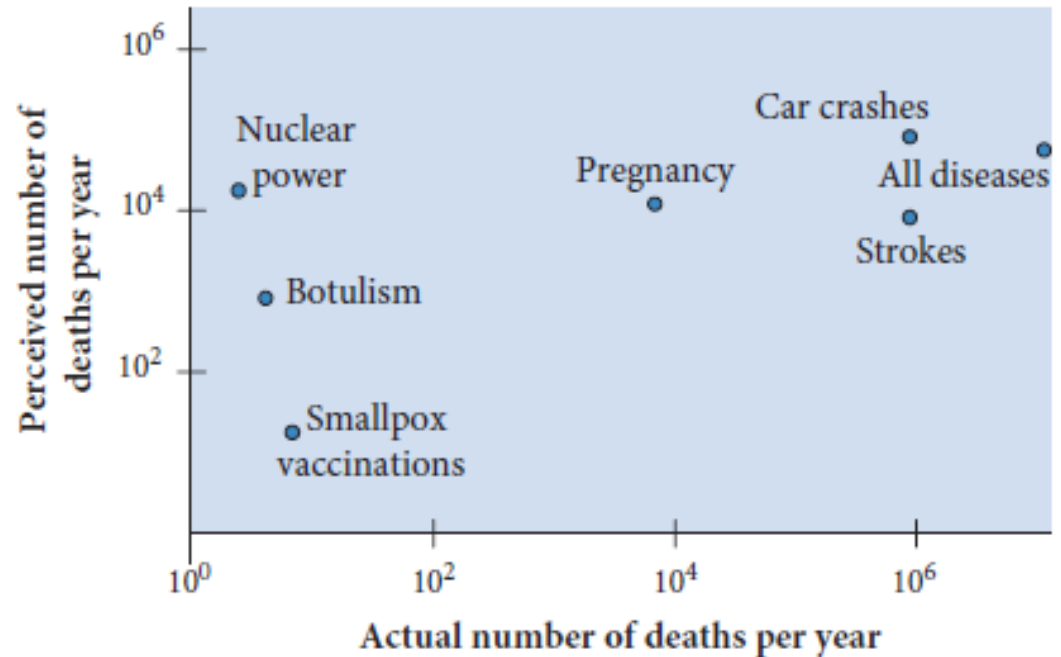
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Designing safe systems

Systems can be made safer by adding **redundancy.**

If component has a probability of failure q, then its **reliability $r_1 = (1 - q)$** (= probability of not failing).

By adding a second component on stand-by, the probability of both components failing is q^2, so the reliability increases to **$r_2 = (1 - q^2)$**

e.g. if $q = 0.1$, then **$r_1 = 0.9$** and **$r_2 = 0.99$**

It is essential that the failures of the two components are **independent**.

For example, if the event which caused one component to fail also caused the other to fail, then we would have **common-mode failure**.

The safety of large systems is often calculated using **probabilistic risk assessment**, by assigning a failure probability to every component. Vulnerable parts of the system are then found using **fault-tree analysis.**

A system is said to be **fail-safe** if it puts itself in a safe condition in the event of a fault.

e.g. **control rods** in a nuclear reactor which will automatically drop due to **gravity** in the event of a power failure and close the reactor down.

Human factors also need to taken into account in systems requiring operator intervention (e.g. that operators of nuclear plant can make wrong judgements, as in the Three-Mile-Island accident).

International agreements on climate change

United Nations Framework Convention on Climate Change (UNFCCC)

First summit (Rio de Janeiro) 1992

Kyoto Protocol 1997

- industrialized countries agreed to limit GHG emissions by 5.5% compared with 1990 levels for period 2008-2012

- Emissions trading between countries

- India, China & other developing countries were not required to reduce emissions.

- Over 160 countries ratified the agreement, but not USA, which thought that limiting GHG emissions would damage its economy.

Result of Kyoto Protocol

- Reductions agreed were largely met

- Failed to slow growth in global emissions

Copenhagen Accord 2009

- No agreement on emissions targets

- Resolved to keep global temperature rise to below 2 $^{\circ}$C since pre-industrial times

Paris Agreement 2015

- Reaffirmation to keep global temperature rise to below 2 $^{\circ}$C since pre-industrial times

- Emissions to fall as soon as possible

- Carbon neutrality (sinks to balance sources) towards end of this century

Cost neutral carbon price is when cost of savings in CO_2 equals cost of project. Stern report 2006 – spending ~1% annually of GDP by 2050 on mitigation could avoid 5-20% reduction in consumption under BAU.

Policy issues concerning carbon abatement

Energy security - the ability of a country to meet its own energy demand. However, this can mean subsidizing fossil fuels. Globally, the cost of such subsidies is much greater than that for low-carbon energy.

Sustainable development – needs policies that cater for present generation without compromising future generations, e.g. subsidizing PV farms rather than building more fossil-fuel power stations.

Emissions trading – a country which exceed its emissions limit can buy from a country, which is below its limit, their surplus, or can receive credits by creating CO_2 sinks (e.g. forests). Requires tight caps for a high carbon price, and accurate records and monitoring.

Carbon tax – based on amount of carbon emitted, so tax on coal would be higher than tax on gas. Tends to damage competitiveness of countries with high emissions per unit of GDP.

Regulations – e.g. minimum fuel efficiency, buildings insulation. Market forces to meet standards most cost-effectively, but no market incentive to innovate.

Feed-in tariffs (FITs) – guaranteed price for producer of renewable energy – provides incentive over conventional generation, and extra cost generally shared by all consumers

Tradable green certificates (TGCs) – schemes which requires electricity suppliers to obtain specified % of their energy from renewable energy sources.

Kaya identity

Kaya identity:

$$CO_2 \text{ emissions} = \text{population} \times \frac{\text{GDP}}{\text{population}} \times \frac{\text{energy}}{\text{GDP}} \times \frac{CO_2 \text{ emissions}}{\text{energy}}$$

To reduce CO2 emissions, we need to reduce the factors on the right hand side.

population — expected to stabilize at around **10 billion after 2050**

$\dfrac{\text{GDP}}{\text{population}}$ — reducing this ratio can mean lowering standard-of-living which is **undesirable**

$\dfrac{\text{energy}}{\text{GDP}}$ — reduce by **better energy efficiency** and by **energy savings**

$\dfrac{CO_2 \text{ emissions}}{\text{energy}}$ — reduce by **switching to low-carbon** sources of energy

Rebound effect: lower costs of energy arising through efficiency improvements result in additional activities whose emissions offset those saved through improved efficiency.

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Global energy-related emissions and Final energy demand in 2014

Building, industry & transport sectors accounted for **88%** of energy-related CO_2 emissions in 2014.

Final demand = 400 EJ ~ 2/3 of primary energy consumption

200 EJ heat not used ~ 140 EJ rejected in electricity generation ~ 60 EJ rejected in other processes

Sector	$GtCO_2$	EJ	% CO_2	% Final
Industry (heat)	5.5	80	40	29
Industry (electricity)	6	35		
Industry (process)	2.5			
Transport (heat)	7	100	20	25
Buildings (heat)	3.5	50	28	35
Buildings (electricity)	6	35		
Buildings (biomass)		55		
Other demand (heat)	2.5	35	12	11
Other demand (electricity)	1.5	10		
Totals	34.5	400	100	100

Need to decarbonize **heat** as well as **electricity**

To restrict **global warming to < 2°C,** energy-related emissions need to be **zero by ~2100** and in **2050 to be about half of those in 2015**

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IEA future emissions scenarios

International Energy Agency (IEA) has produced various scenarios of global warming according to the amount of GHGs emitted.

6DS scenario = extension of current trends (BAU).

4DS scenario = constant emissions up to 2050 (current pledges + improving efficiency)

2DS scenario = CO_2 emissions from 2015 < 1200 $GtCO_2$ ($\equiv$ 450 ppmv)

Global mean temperature rise is proportional to **cumulative CO_2 emissions** to a good approximation. Amount is ~ 0.5 °C per 1000 $GtCO_2$ cumulative emissions.

Scenario	CO_2 ppmv by 2100	CO_2eq ppmv by 2100	Prob < 2 °C by 2100	ΔT pre-indus by 2100	ΔT pre-indus equilibrium*
6DS	770	890	0%	3.7	6.0
4DS	630	690	5%	2.8	4.3
2DS	440	460	80%	1.7	2.1

*Based on stabilizing concentrations by 2150.

Emission reductions in the 2DS, 4DS, 6DS scenarios
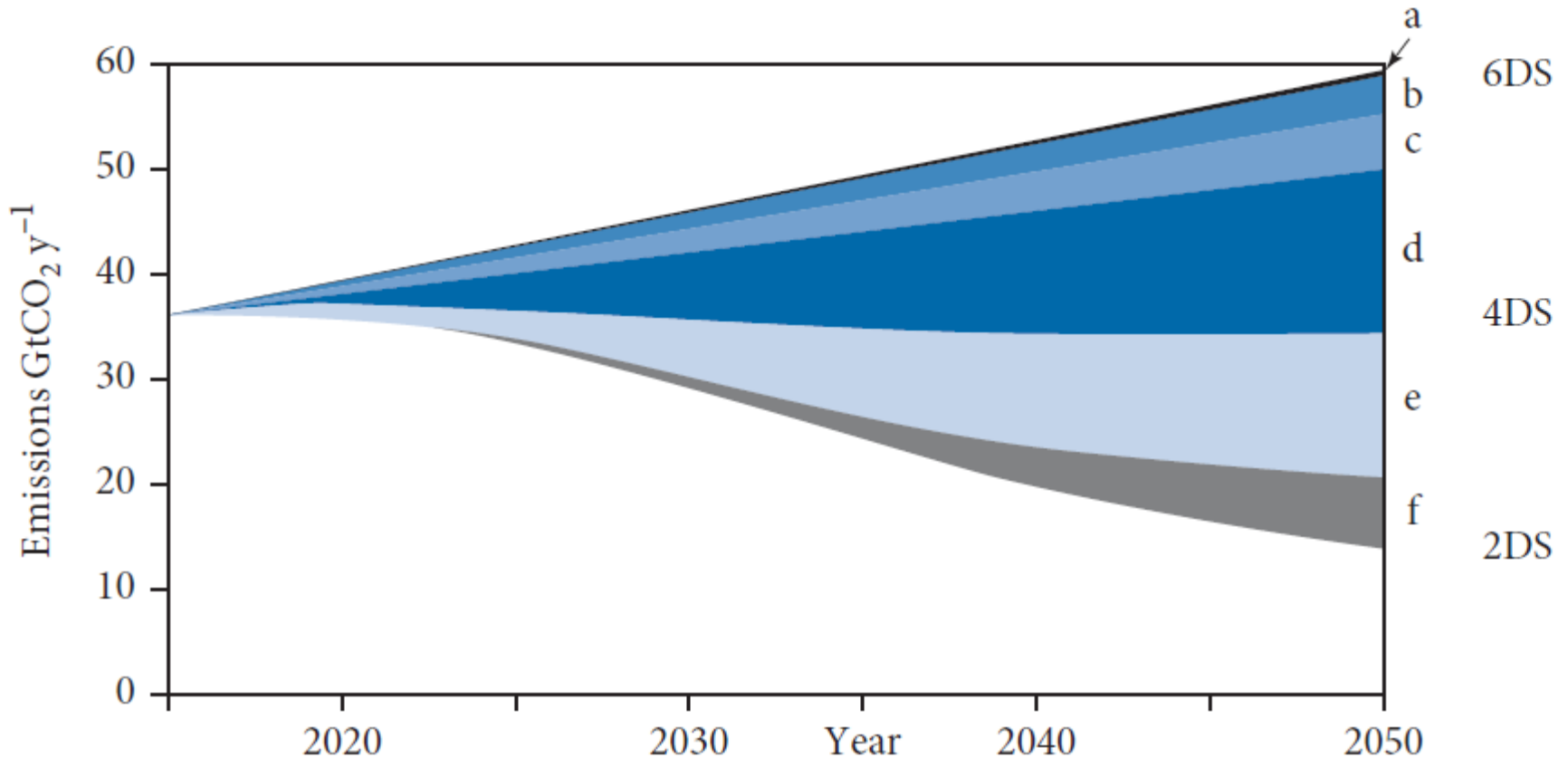
a Power generation efficiency and FS 1%   d End use fuel and electricity efficiency 38%
b Nuclear 8%   e Renewables 30%
c End use FS 10%   f CCS 13%

Accessible potential and actions required

Source	Potential (GWe)	Source	Potential (GWe)
CCS*	~750	Solar PV	~2000-5000
Hydro	~800	Solar CSP	~300
Marine**	~100	Biomass*	~200
Geothermal	~200	Nuclear	~1000
Wind	~1000-2000	**Total**	**> 6000**

*Power generation; **tidal and wave   1000 GWe for a year ≈ 30 EJ

To realise the above potential, continued support is needed

- to increase demand and production from **low-carbon sources**

- to drive down costs through the **learning effect** to compete with fossil-fuel technologies

- to support **research and development** of the energy technologies of the future

Renewables are the answer for a better world

Fig. 12.6 Solar-powered lamps being used in a refugee camp near Chikwawa, Malawi.
Credit: Ashley Cooper/ Science Photo Library

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Key Points

- There is strong evidence that **anthropogenic emissions of CO_2** have caused the global temperature to rise of 0.5 ^{o}C over the last 50 years.

- IPCC predicts that, under the **BAU scenario**, the global temperature could exceed **4 ^{o}C** relative to 1861-1880.

- IPCC predicts that, even if all countries were to comply with the Paris Agreement, the global temperature would still rise by **2.7 ^{o}C by 2100**.

- Wind power and solar PV are already **competitive with fossil fuels** in many regions.

- **Smart grids, interconnectors** and **cheap energy storage** are needed for significant penetration of renewables.

- **Many different carbon mitigation strategies** are required in parallel to keep the atmospheric concentration of CO_2 as low as possible. (Air-capture of CO_2 is a possibility)

- **End-use energy savings** and **low-carbon sources** of energy (for **heat and electricity**) are essential to provide the energy needed to raise the standard-of-living in developing countries and avoid excessive global warming.