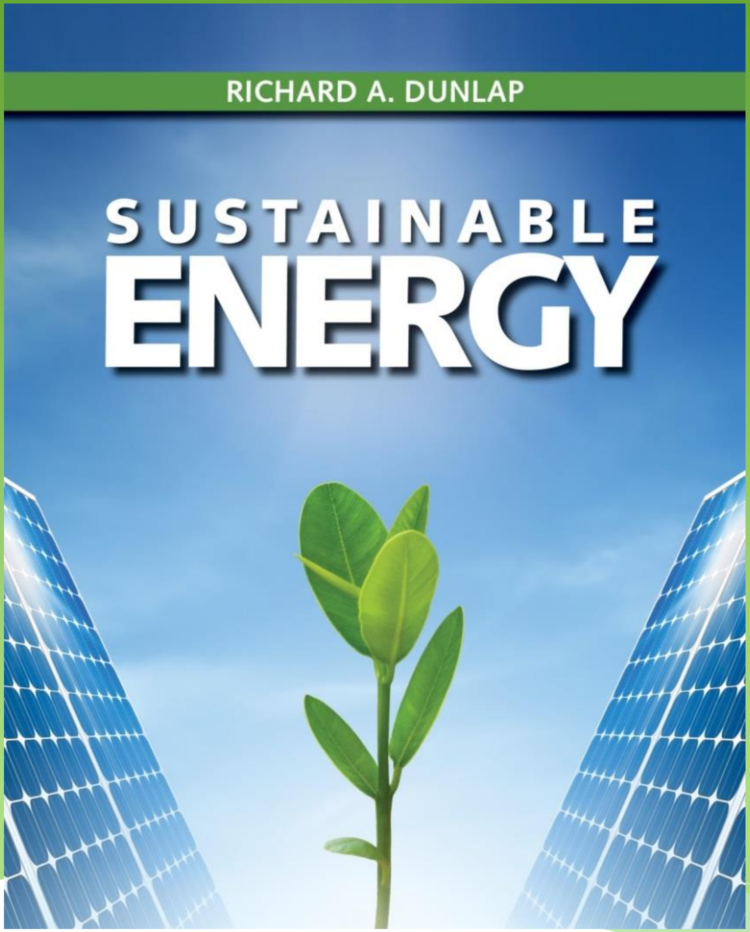
Sustainable Energy



Chapter 2

- Past, Present and Future World Energy Use

CENGAGE Learning

Learning Objectives

- The energy needs of humanity throughout history.
- The current energy distribution and relationship to economic, geographical, climate, and industrial factors.
- The principles of exponential growth.
- The Hubbert model of resource utilization.
- Resource limitations to energy production and use.
- Limits of technology on energy production and use.
- Economic factors that limit energy use.
- Social factors affecting energy production.
- Environmental aspects of energy use.
- Political factors affecting energy use.
- The integration of new energy technologies with existing technology.

Average power consumption per capita

Table 2.1: Estimated average power used per person as a function of the stage of human development (worldwide) or as a function of year (for the United States, 1850–2000). The power values are calculated from the primary energy use.

society	power consumption (W)
hunter	100
use of fire	200
domestication of animals	500
Renaissance	1160
1850	4880
1900	5340
1950	7300
1960	8180
1970	11,000
1980	11,250
1990	11,000
2000	11,730

Source: Data adapted from G. J. Aubrecht II. *Energy: Physical, Environmental, and Social Impact* (3rd ed.). Pearson Prentice Hall, Upper Saddle River, NJ (2006).

Breakdown of primary energy sources in the United States

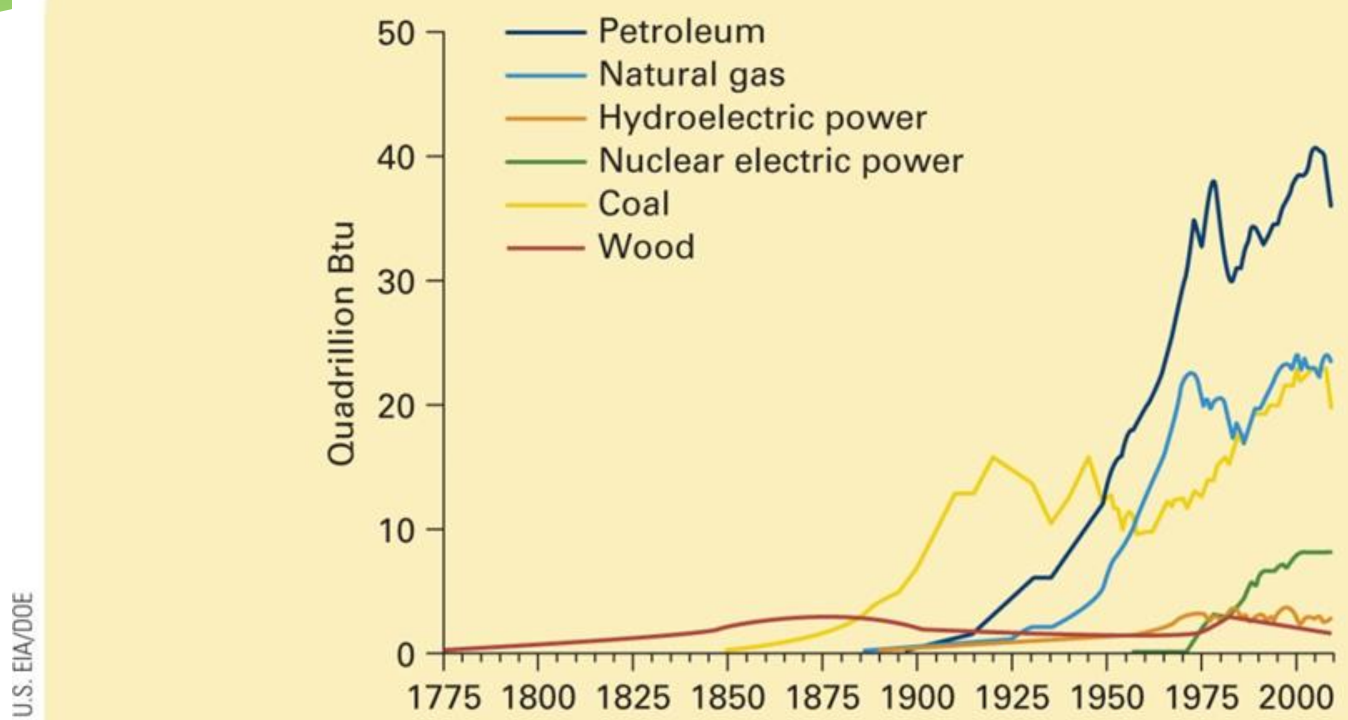


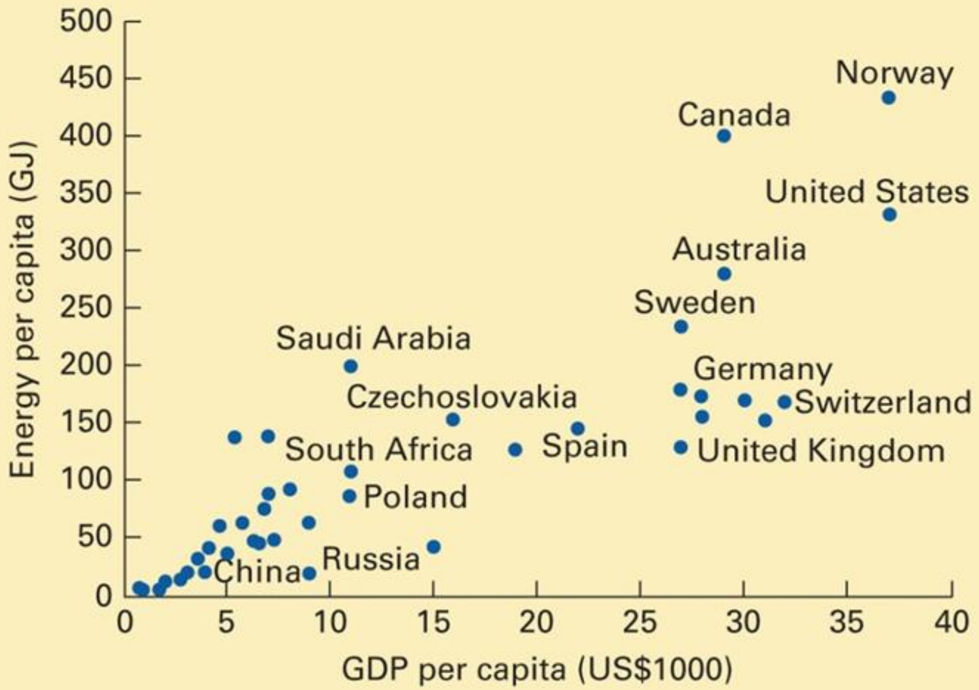
Figure 2.1: Annual energy use in the United States from different sources, 1775–2009 [1 quadrillion Btu = 1 quad = 10^{15} Btu = 1.055 EJ (EJ = 10^{18} J; see Appendix I)].

Primary U.S. energy sources

Major energy source

- Wood until late 1800s
- Coal late 1800s to about 1950
- Petroleum since 1950

Energy use per capita in different countries



Based on R. Hinrichs and M. Kleinbach, Energy: Its Use and the Environment 4th ed, Brooks-Cole, Belmont (2006) p. 55

Figure 2.4: Relationship of annual per-capita energy use and per-capita gross domestic product (GDP) for different nations.

Factors affecting energy use

Direct relationship between per capita GDP and per capita energy use

Other factors affecting per capita energy use

- Climate
- Population density
- Types of industry

Annual energy use in the United States

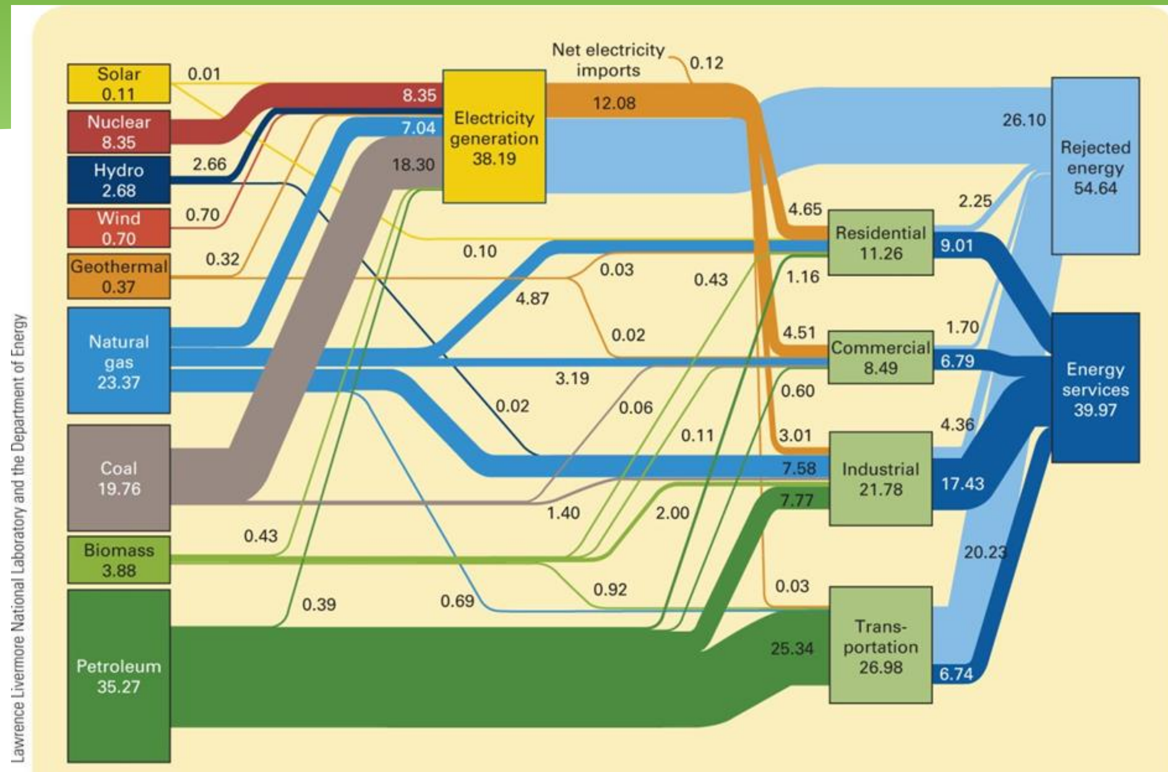


Figure 2.5: Annual energy use (in 2009) in the United States (~94.6 quads), showing sources, end use, and conversion losses. Units are quads (quad = 1.055 EJ).

Breakdown of primary energy sources and end use
Note: almost 60% of primary energy is lost due in conversion processes (mostly due to efficiency of heat engines)

Per capita primary energy use

Typical single family (two individuals) primary energy use (typical of Northern United States)

gasoline for transportation 9.8×10^{10} J
oil for residential heating 1.04×10^{11} J
electricity (at 40% efficiency) 1.1×10^{11} J

This gives a total average power consumption per person of 5.0 kW

This is less than 1/2 of the actual number

Remainder is used by industry/business/government etc.

Growth

In order to extrapolate energy use into the future we need to understand how to model growth.

Linear growth

Linear growth is described as

$$N(t) = N_0 + \frac{dN}{dt}\,t \qquad (2.2)$$

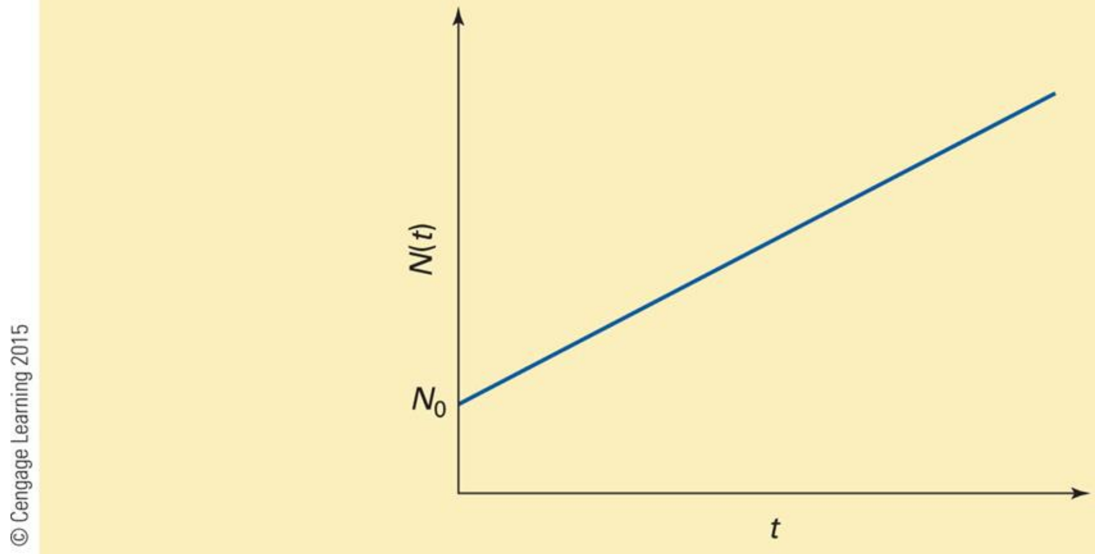


Figure 2.7: Quantity characterized by linear growth.

Exponential growth

Exponential growth is described as

$$\frac{dN}{dt} = aN \tag{2.3}$$

This may be integrated to give

$$N(t) = N_0 \exp(at) \tag{2.4}$$

Exponential growth

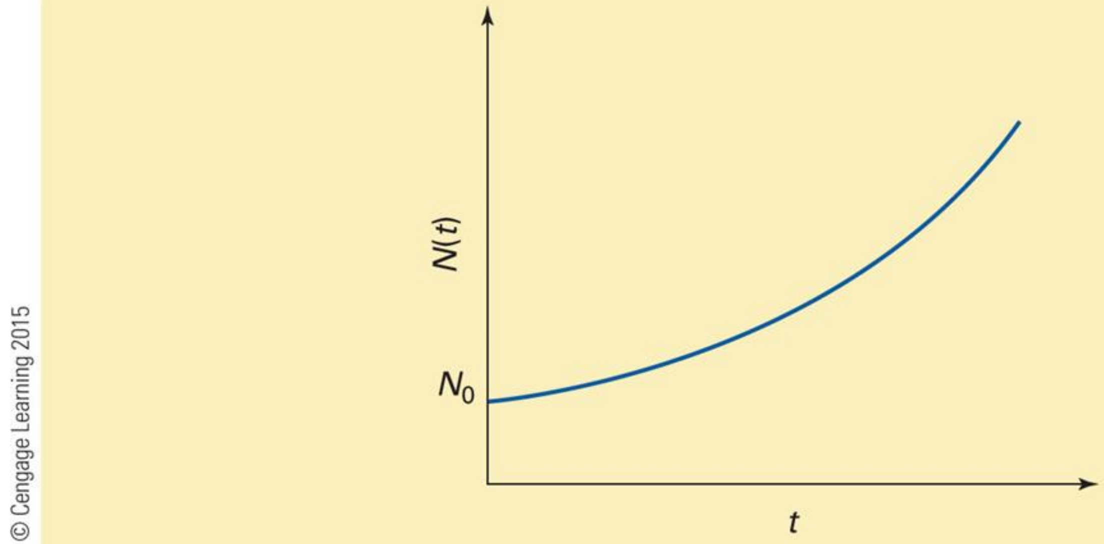


Figure 2.8: Quantity characterized by exponential growth shown on a linear plot.

Semi-log plot of exponential growth

It is often convenient to present a quantity that grows exponentially on a semi-log plot

$$\log[N(t)] = \log(N_0) + at\log(e) \quad (2.6)$$

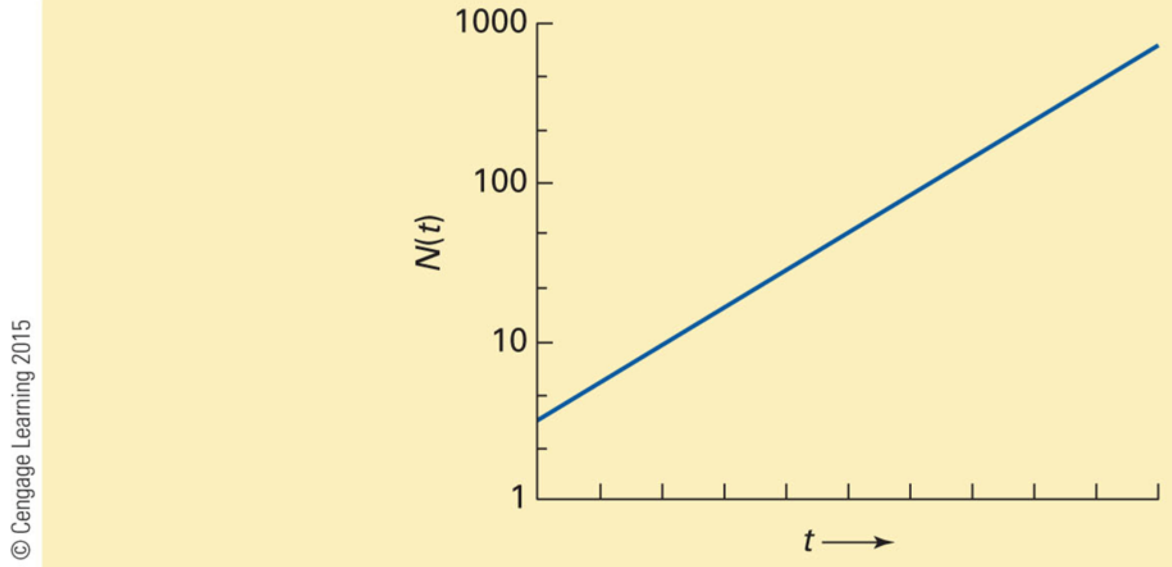


Figure 2.9: Quantity characterized by exponential growth shown on a semilog plot.

Doubling time

For exponential growth the doubling time is expressed as

$$t_D = \frac{\ln(2)}{a} \qquad (2.7)$$

For small growth rates the growth rate (in % per unit time) may be expressed as

$$R = 100\frac{\ln(2)}{t_D} \qquad (2.9)$$

Examples of growth rates and doubling times

Table 2.2: Annual growth rates and corresponding doubling times.

% growth per year	t_D (y)
1	69.7
2	35.0
3	23.4
4	17.7
5	14.2
6	11.9
7	10.2
8	9.0
9	8.0
10	7.3
20	3.8
50	1.7
100	1.0

Some examples of growth

World population since year 1000

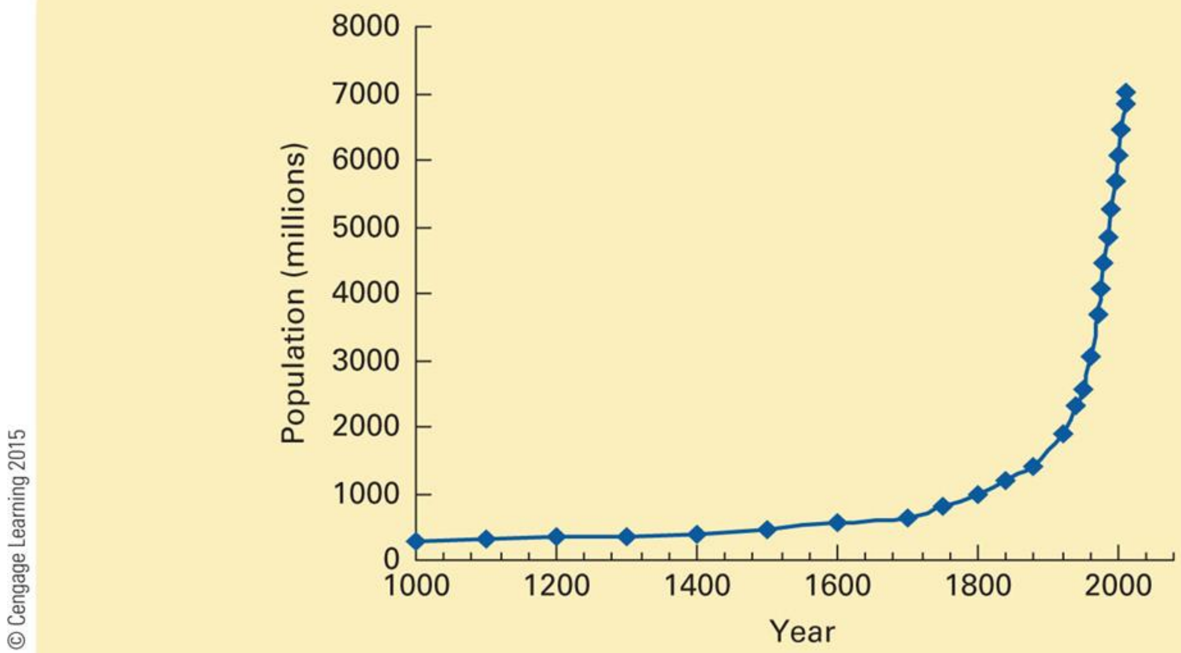


Figure 2.10: Population of the world for the past 1000 years.

Extrapolation of world population

Assuming exponential growth at 1.6% per year

Table 2.3: World population and mass of humanity as a function of year for 1.6% annual growth.

year	population	mass (kg)
2012	7.00×10^{9}	4.90×10^{11}
2200	1.42×10^{11}	9.92×10^{12}
2400	3.48×10^{12}	2.43×10^{14}
2600	8.53×10^{13}	5.97×10^{15}
2800	2.09×10^{15}	1.46×10^{17}
3000	5.13×10^{16}	3.59×10^{18}
3200	1.26×10^{18}	8.82×10^{19}
3400	3.09×10^{19}	2.16×10^{21}
3600	7.58×10^{20}	5.31×10^{22}
3800	1.86×10^{22}	1.30×10^{24}
4000	4.56×10^{23}	3.19×10^{25}

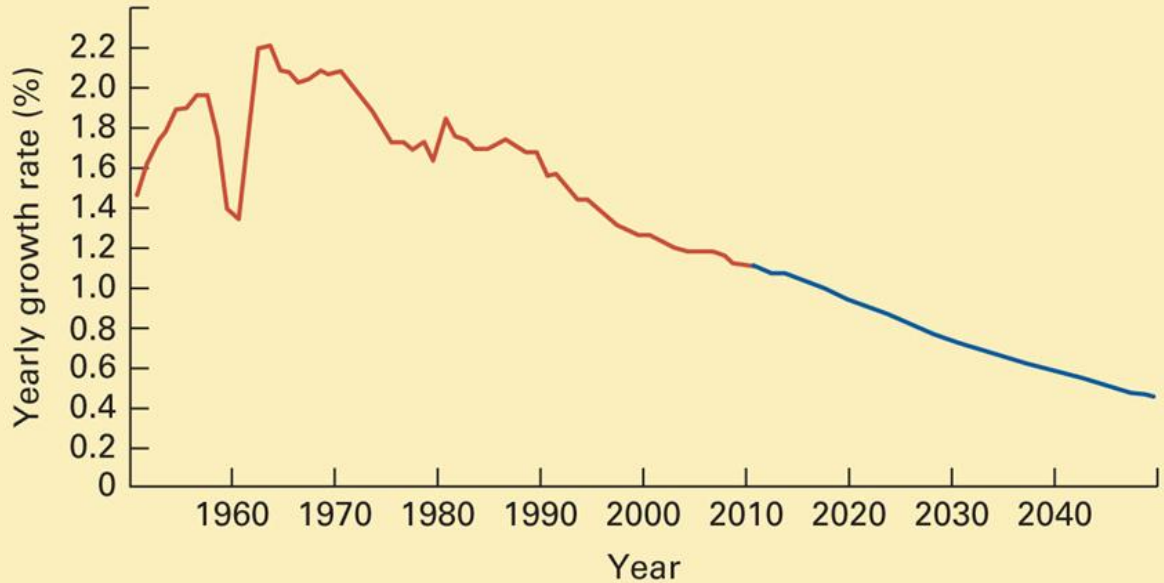
Sustainable world population

Current world population is about 7 billion

Estimates of sustainable world population, probably not much more than 10 billion

Current growth rate cannot continue for very long

Actual population growth



Based on the U.S. Census Bureau, http://www.census.gov/population/international/

Figure 2.11: Trends in the annual growth rate of the world population in recent years and projected future growth.

Future world energy use

Increase in world energy use is due to

- increase in world population
- increased per capita energy use

Exponential growth of world population cannot continue at the same rate.

Increased per capita energy use is due mostly to increase in developing countries.

Predicted energy trends in some countries

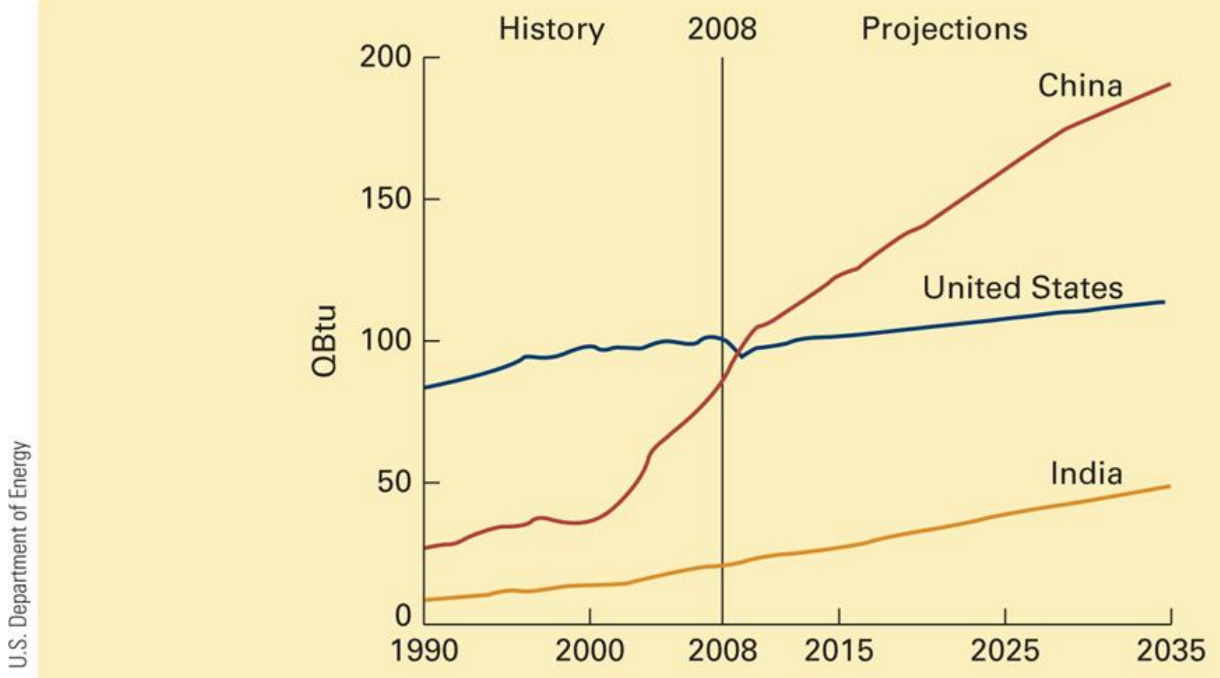


Figure 2.12: Historical and predicted energy use in different components of the world population,1990–2035 (quadrillion Btu). OECD = Organisation for Economic Co-operation and Development

Energy use in OECD and non-OECD countries

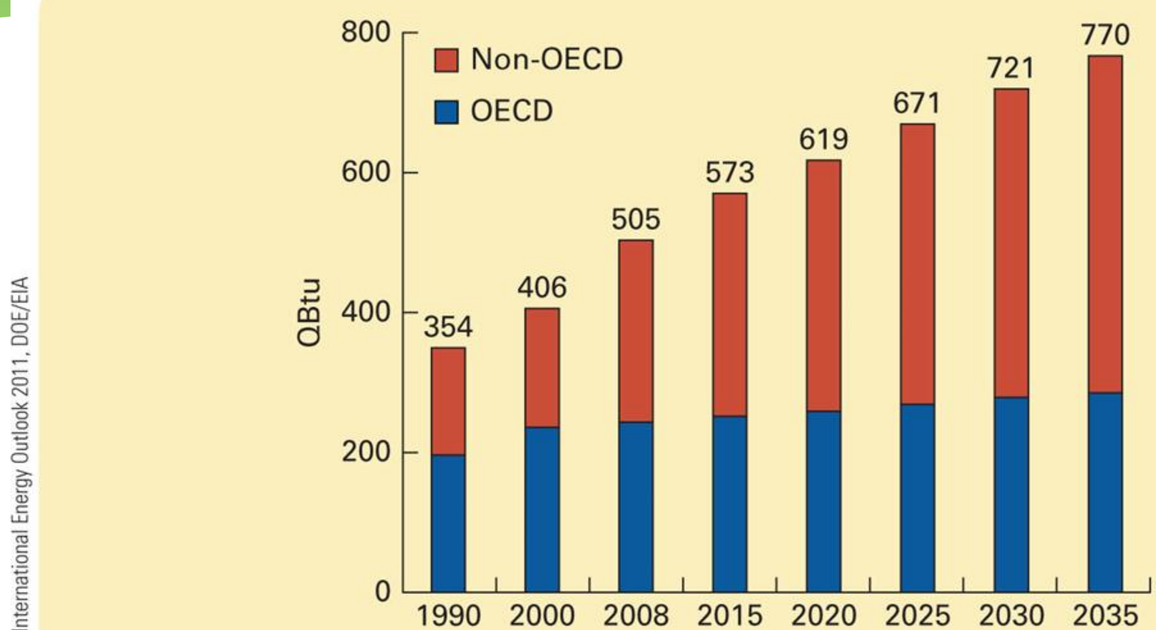


Figure 2.13: Previous and predicted total world energy use up to the year 2035 (quadrillion Btu).

OECD includes (U.S., Canada, U.K, Japan, France, Germany, etc.)
non-OECD includes (China, India, Russia, Brazil, etc.)

Hubbert model

Developed by M. King Hubbert in 1956

General assumptions

- When it is first realized that a resource is useful, the utilization of that resource begins slowly. This is because efficient procedures for utilizing the resource and an appropriate infrastructure need to be developed.
- Once the appropriate infrastructure has been developed, resource utilization increases.
- When the resource becomes scarce, utilization decreases and eventually stops.

Quantity if resource used per unit time

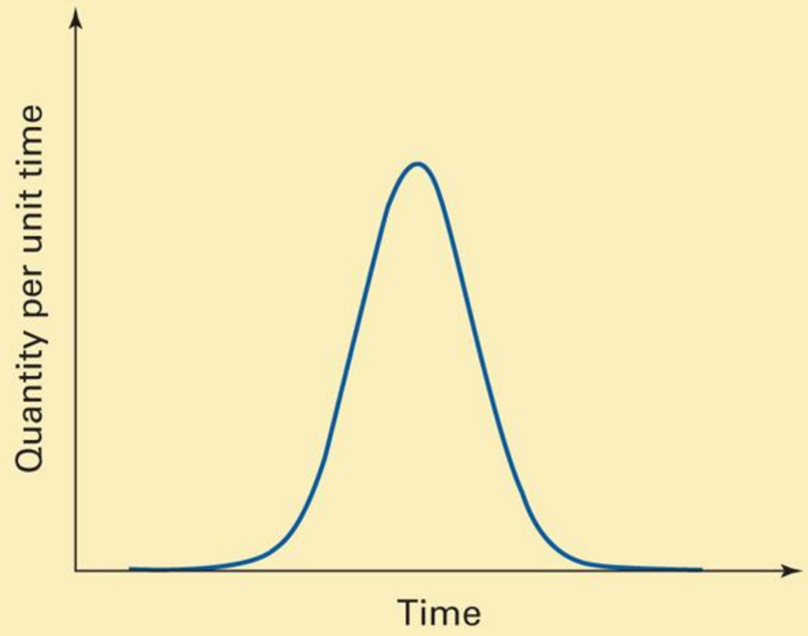


Figure 2.14: Quantity of a resource used per unit time as a function of time.

Total quantity of resource used

Total quantity used is the integral of the quantity per unit time

$$Q(t) = \int_0^t \frac{dQ}{dt} dt \quad (2.10)$$

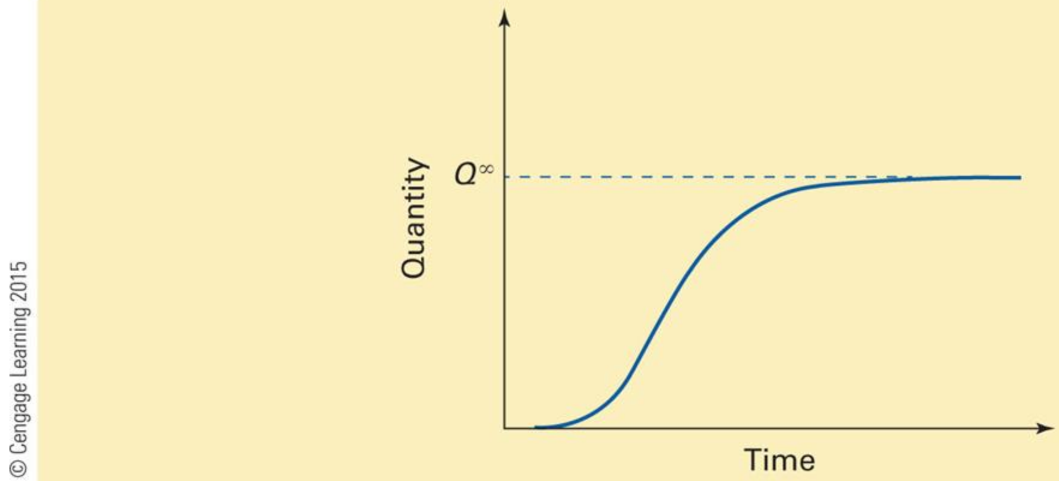


Figure 2.15: Amount of a resource used up to a time, *t*.

Challenges for sustainable energy development

- Availability of the necessary resources.
- Availability of the necessary technology.
- Consideration of economic factors.
- Consideration of social factors.
- Environmental impact.
- Consideration of political factors.
- Ability to integrate new technology with existing technology.

Availability of the necessary resources

A number of alternative energy technologies require materials with limited availability.

Some examples of materials that may be a concern are

- Lithium for fusion energy
- Lithium for rechargeable batteries
- Rare earth elements for generators
- Indium, gallium and selenium for photovoltaic cells

Materials production for photovoltaics

Comparison of current annual production of some materials of relevance to photovoltaic cells and requirements to fulfill world energy needs

Table 2.4: In, Ga, and Se needed to produce copper-indium-gallium-selenide photovoltaic cells required to generate an average of 1 GW electricity and power sufficient to meet total global needs (about 18 TW). Also given is the 2008 total world production of these elements. (t = tonne = 10^3 kg = 2205 lb).

element	to produce 1 GW (t)	to fulfill world energy needs (t)	2008 world production (t)
indium	90	3.8×10^6	140
gallium	30	4.2×10^5	111
selenium	180	7.5×10^6	3000

Data adapted from "Byproduct Mineral Commodities Used for the Production of Photovoltaic Cells" U.S. Geological Survey, Circular 1365.

Availability of the necessary technology

Development of high temperature superconductors for generators and power distribution lines is an example of a new technology that is important for alternative energy technologies.

High temperature superconductors

High temperature superconducting wire for power distribution or superconducting magnet use

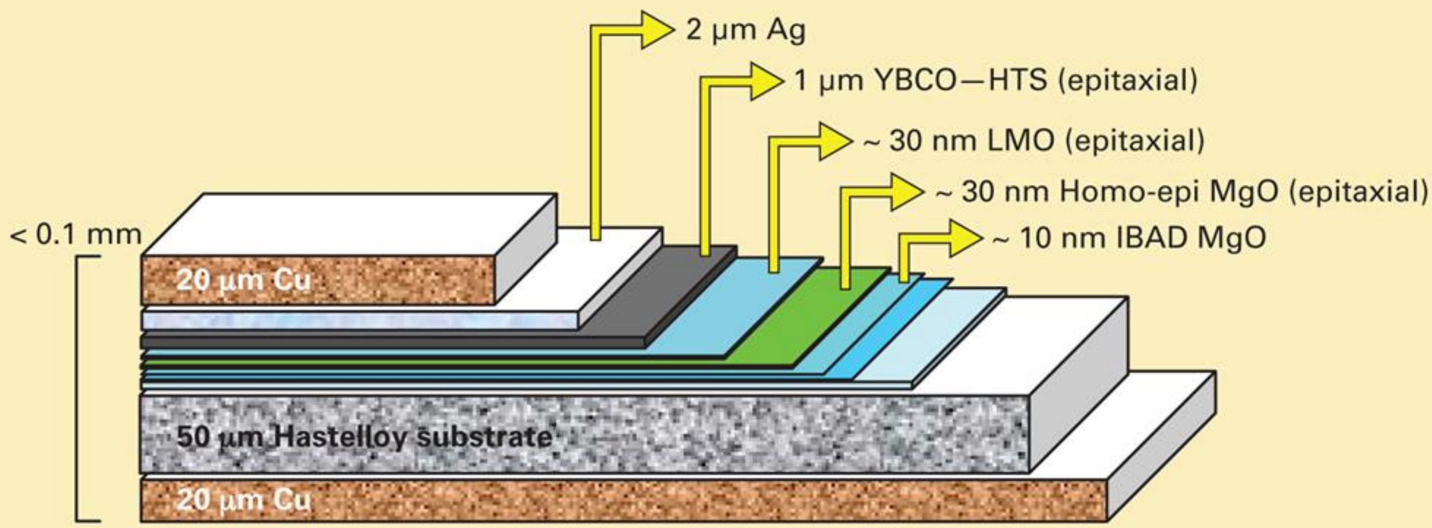


Figure 2.16: Structure of second-generation high-temperature superconducting wire.

Based on V. Selvamanickam, "Coated Conductors: From R&D to Manufacturing to Commercial Applications," EUCAS | ISEC | ICMC Superconductivity Centennial Conference, September 19-23, 2011, Den Haag, The Netherlands, http://www.superpower-inc.com/system/files/2011_0225+Barcelona+Wind+Seminar_Selva.pdf and http://www.superpower-inc.com/content/2g-hts-wire

Some technological challenges for alternative energy production

- New organic photovoltaic cells that are reasonably efficient and are much more cost-effective than conventional semiconductor based materials (Chapter 9).
- Suitable economical membranes for the exploitation of salinity gradient or osmotic energy (Chapter 14).
- Methods for production of cellulosic ethanol (Chapter 16).
- Efficient non-lithium-based secondary batteries that will provide a cost-effective basis for widespread electric vehicle development (Chapter 19).
- Economical and efficient methods for direct hydrogen production (e.g., solar hydrogen, Chapter 20).

Consideration of economic factors

Commercialization of energy technologies requires a consideration of economics.

Ultimately technologies must be competitive in order to be attractive to producers and consumers.

Cost per unit electricity generated must include three components

- Cost of fuel
- Cost of infrastructure operation and maintenance
- Initial infrastructure cost amortized over its lifetime

Fuel and operating costs

Fuel and operating cost are more significant for some technologies than others.

For example: fuel cost is important for coal, natural gas and nuclear but is not a factor for hydroelectric, wind and solar.

Operating costs are relatively low for technologies such as hydroelectric but can be significant for example for nuclear (where waste disposal is an important factor).

Infrastructure costs

Table 2.5: Typical capital system costs in the United States in dollars per kilowatt ($/kW) for large electric generating stations using different energy technologies.

energy resource	infrastructure cost ($/kW capacity)
coal	500
wind	800
natural gas	1000
hydroelectric	1000
geothermal	2500
nuclear (fission)	3000
solar (photovoltaics)	4000

Overall cost per kWh

Table 2.6: Typical cost of electricity per kilowatt-hour in the United States in dollars per kilowatt-hour (US$/kWh), as generated by different technologies.

energy resource	electricity cost (US$/kWh)
coal	0.025
natural gas	0.04
hydroelectric	0.05
wind	0.06
nuclear (fission)	0.065
geothermal	0.08
solar (photovoltaics)	0.30

Electricity cost in some countries

Variations between countries can result from different generating methods and also from national economics.

Table 2.7: Average 2011–2012 residential cost of electricity per kilowatt-hour in equivalent U.S. dollars (US$/kWh) in different countries.

country	average cost (US$/kWh)
United States	0.10[1]
Canada	0.108[2]
France	0.194[3]
United Kingdom	0.22[3]
Australia	0.25[4]
Sweden	0.27[3]
The Netherlands	0.289[3]
Brazil	0.342[5]
Germany	0.365[3]
Denmark	0.404[3]
Japan	0.262[6]
China(Beijing)	0.078[7]
India (Delhi)	0.103[8]

[1] http://www.eia.gov/electricity/monthly/
[2] http://www.electricity.ca/media/Presentations/Electricity%20Pricing%20Presentation_June%202nd_2011.pdf
[3] http://www.energy.eu/#domestic
[4] http://www.abc.net.au/news/2012-03-21/australians-pay-highest-power-prices-says-study/3904024?section=nsw
[5] http://www.aneel.gov.br/area.cfm?idArea=550.
[6] http://thisbluemarble.com/showthread.php?t=36342
[7] http://english.sz.gov.cn/ln/201205/t20120517_1914423.htm
[8] http://www.bsesdelhi.com/docs/pdf/Delhi_Tariff_Economics.pdf

Consideration of social factors

Public opinion can influence the development of certain technologies and government energy policy.

Nuclear energy has generated more public interest than most other energy approaches.

Public approval of nuclear power in the U.S.

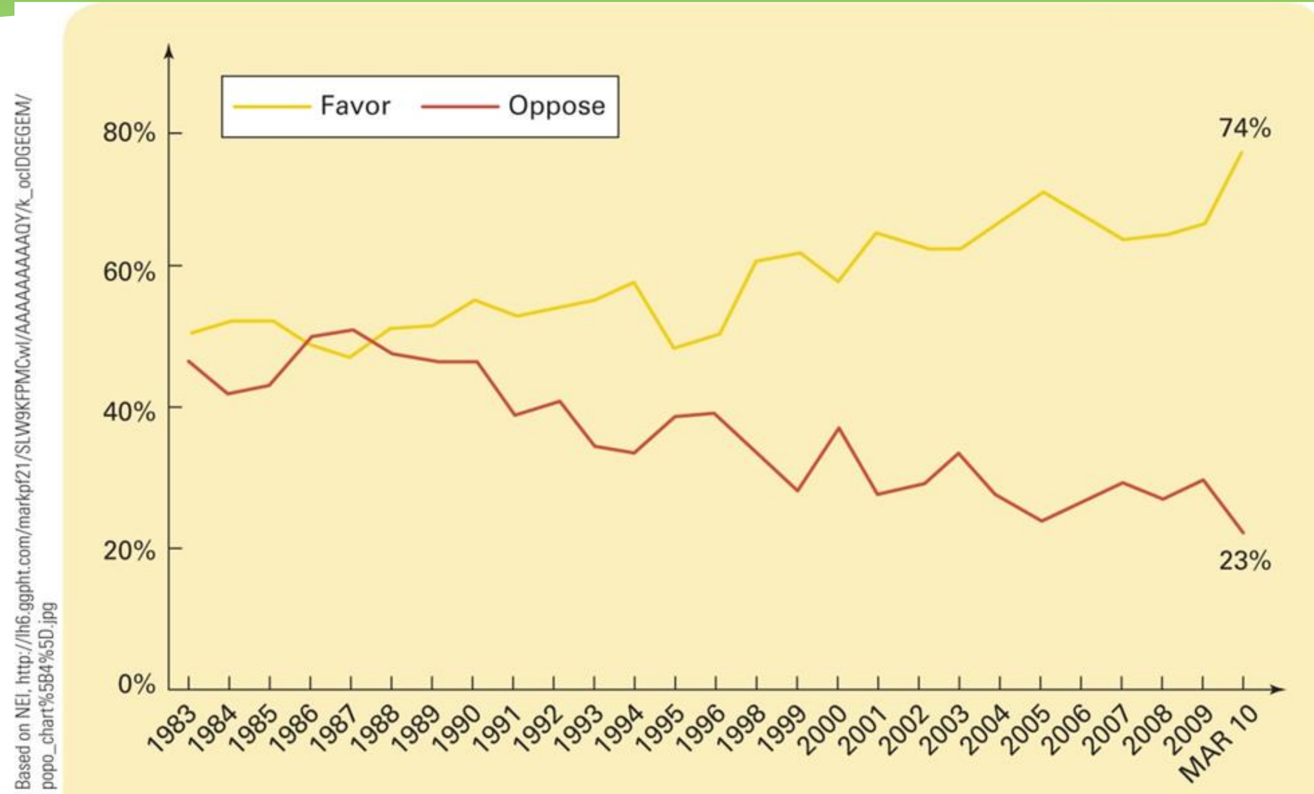


Figure 2.19: Result of polls in the United States concerning public approval or disapproval of nuclear energy.

Effects of nuclear incidents on public opinion

Public approval of nuclear power generally diminishes after an incident

Based on http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS02_1312778417P.pdf

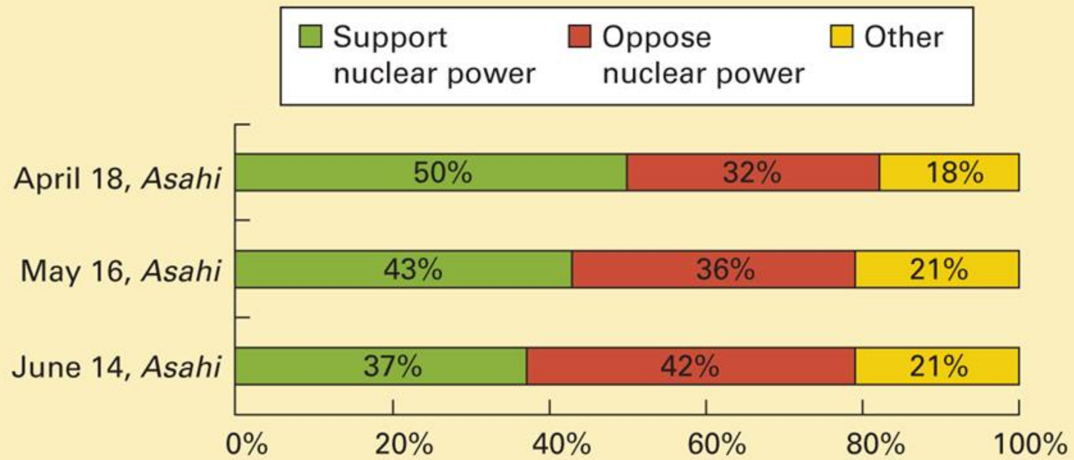


Figure 2.20: Results of polls in Japan concerning approval of nuclear energy following the March 11, 2011 earthquake/tsunami and subsequent nuclear reactor incident.

Importance of different factors in forming public opinion

Cost is a major factor for public opinion

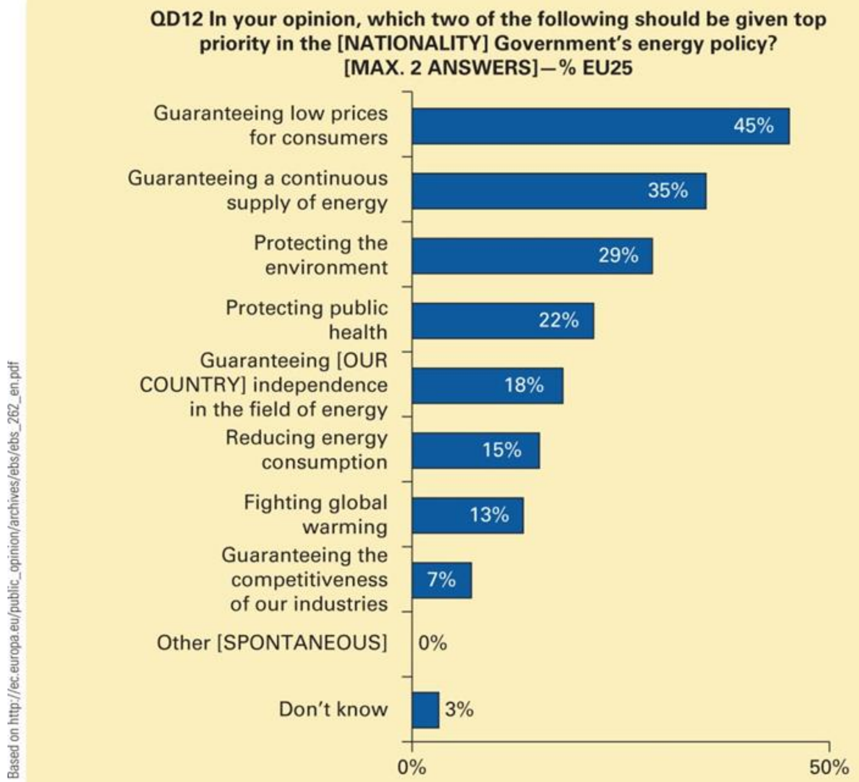


Figure 2.21: Results of a recent European Union poll concerning public priorities on energy-related matters.

Public preference for energy technologies

Despite the importance of cost, public opinion favors solar energy

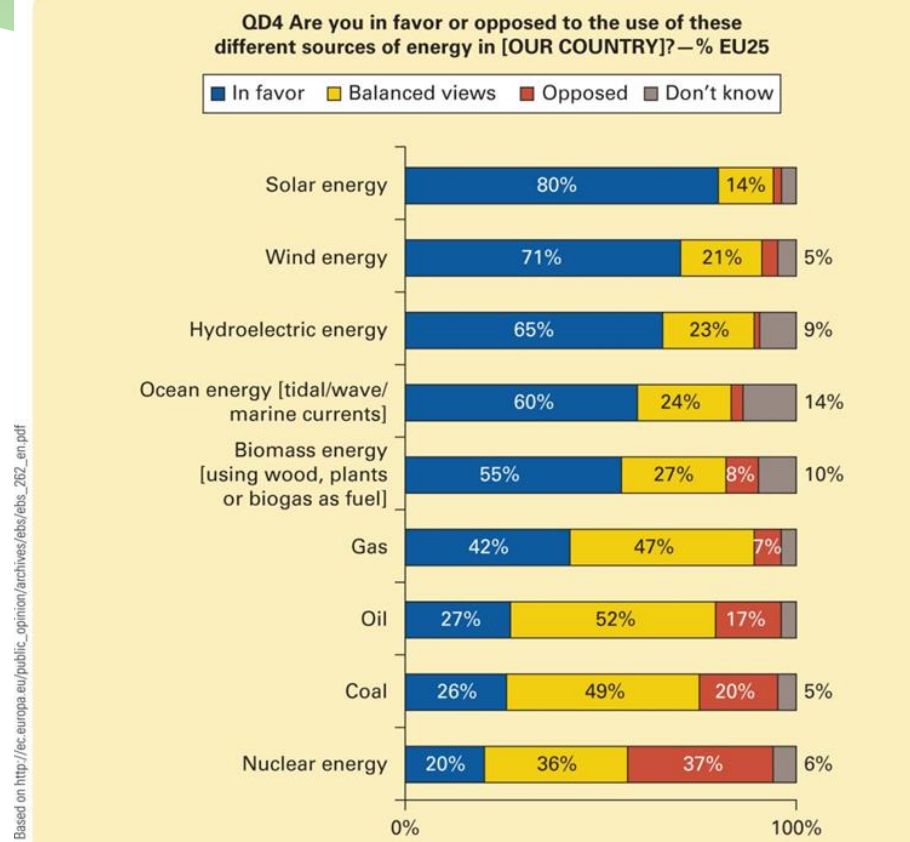


Figure 2.22: Results of a recent European Union poll concerning public opinion on the development of renewable energy.

Environmental impact

Renewable energy sources can contribute to greenhouse gas emissions in two ways

- During the processing of materials and manufacture of the infrastructure. This can be substantial because of the low energy density of most renewable sources.
- During the operation of the facility. This is usually small.

Greenhouse gas (CO_2) emissions from different energy sources

Table 2.9: Greenhouse gas emissions (CO_2) per unit electrical energy generated for some fossil fuels and renewable resources.

resource	CO_2 (kg/MWh)
coal	955
natural gas	430
solar (photovoltaic)	98–167
wind	7–9
geothermal	7–9
hydroelectric (high head)	3.6–11.6

Based on data from International Energy Agency "Benign energy? The environmental implications of renewables," Paris: OECD (1998)

Consideration of political factors

National energy policies generally deal with issues such as

- A description of national policies concerning energy generation, transmission and use
- The establishment of energy efficiency and environmental standards related to energy use
- The specification of energy-related fiscal policies, including subsidies, incentives, tax exemptions, and the like, to promote improved energy utilization
- The participation in funding programs for energy-related research and development
- The development of energy-related treaties and agreements with other countries

Factors influencing energy policy

Details of energy policies depend on such factors as

- Economy.
- Climate.
- Geography.
- Natural resources.
- Population.

Ability to integrate new technology with existing technology

Development of new technologies requires development of new infrastructure.

Transitions between technologies need to avoid disruptions.

Distribution infrastructure

Particularly important for transportation technologies

- Electric vehicles require charging stations
- Hydrogen vehicles require hydrogen fueling stations

Summary

- Human energy use has increased over the years
- Traditionally wood was the source of energy and this was replaced first by coal and then by petroleum
- Per capita energy consumption is directly related to per capita GDP
- About 60% of primary energy is rejected as waste heat
- Human population has grown exponentially but the growth rate is declining
- The greatest increase in energy use at present is in developing countries
- The Hubbert model describes the utilization of a limited resource
- Development of new energy sources needs to consider
  - Resource limitations
  - Technological limitations
  - Economic factors
  - Social factors
  - Environmental factors
  - Political factors
  - Integration with existing technology