能源及環境學院
SCHOOL OF ENERGY AND ENVIRONMENT

SEE 1003
Introduction to Sustainable Energy and Environmental Engineering

Dr. Shauhrat Chopra
School of Energy and Environment

02 – Energy and Electricity; Lighting and its implications

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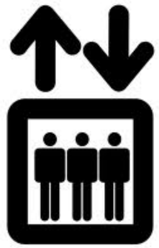
SEE 1003 class overview

Week	Topics	Assignment issued	Key dates
Week 1	Course introduction; Climate Change and the Engineering approach		**Quiz 1**
Week 2	**MODULE I** Introduction to Sustainability Energy, Natural Resources and pollution, Electromagnetic energy; Electrical energy – Lighting, Light pollution, Policy	**Semester-long Project**	
Week 3		**Project deliverable 1.1**	
Week 4	**MODULE II** Motor, Generator – Transportation Air Pollution and Energy Consumption; Policy		
Week 5		**Project deliverable 1.2**	**Project deliverable 1.1**
Week 6	**MODULE III** Noise Pollution in Urban Environment	**Project deliverable 1.3**	**Quiz2**
Week 7	**MODULE IV** Urban Sustainability; Water and Energy Nexus		**Project deliverable 1.2**
Week 8	**MODULE V** Tools: Systems Analysis for Sustainability Cost-Benefit Analysis, Material Flow Analysis, Life Cycle Assessment		
Week 9			
Week 10	**MODULE VI** Advances in Environmental and Energy Engineering	**Project deliverable 1.4**	**Project deliverable 1.3; Quiz3**
Week 11	**MODULE VII** Waste management and Waste-to-Energy		
Week 12	**MODULE VIII** Economics and Policy of Energy and Environment	**Project deliverable 1.5**	**Quiz4** **Project deliverable 1.4**
Week 13	**Individual Presentations (5-mins)**		**Final Project Report**

What is energy? What are the types of energy?

Energy – the capacity of a physical system to do work

Kinetic energy



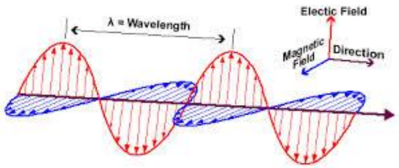
Potential energy

Thermal energy

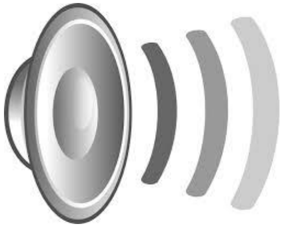
Chemical energy

Electrical energy

Electrochemical energy

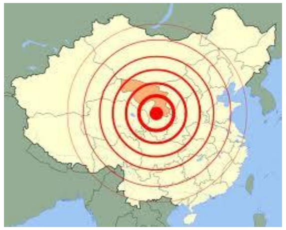


Electromagnetic energy

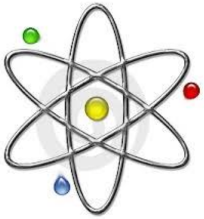


Sound energy

Vibrational energy

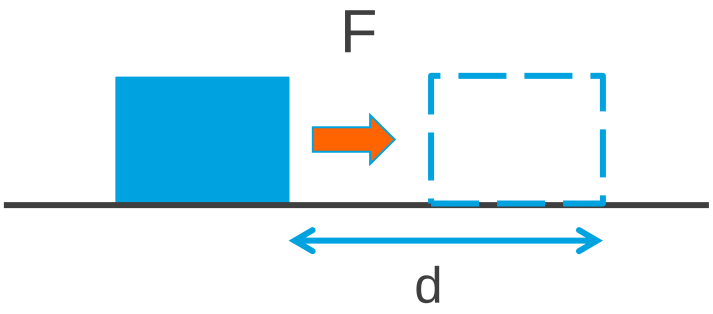


Nuclear energy



Force, energy and power

Force (F) – interaction that will change the motion of an object
Energy (E) – work done by a given force
Power (P) – rate of doing work



$F = ma$

kg is not a force
N = kg m/s^2 is

Related words:
Thrust
Drag
Torque (r x F)
Pressure (F/area)

$E = F \cdot d$

1 Joule = 1 Nm
Also as kg m^2/s^2

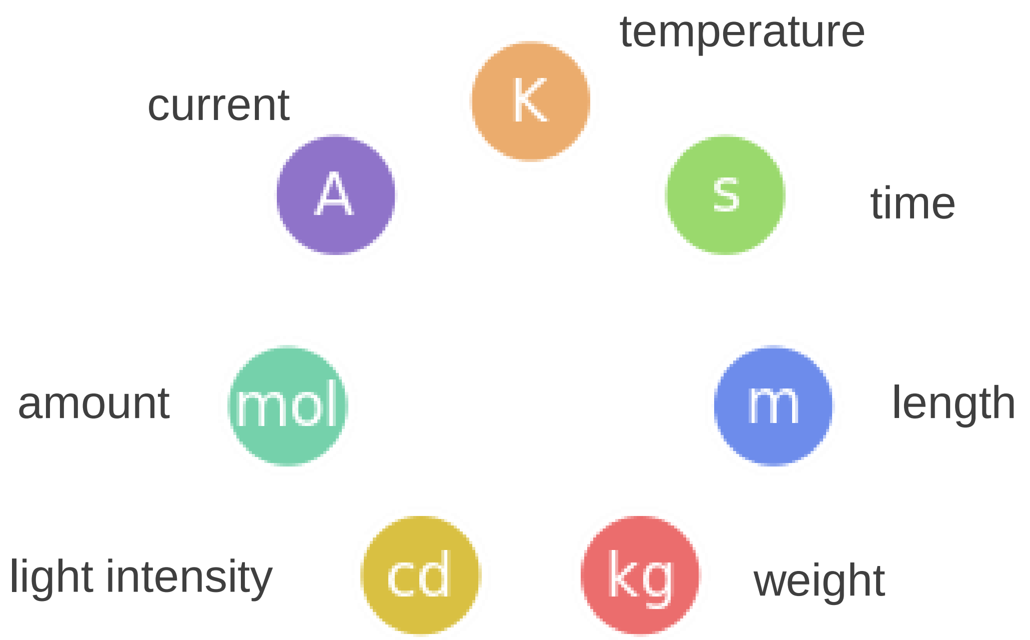
Related words:
Calorie
BTU
Wh
eV

$P = E/t$

1 W = 1 J/s
Also as kg m^2/s^3

Related words:
horsepower

SI unit



Quantity	SI unit	
Force	N	kg m s^{-2}
Energy	J = F x d	kg m^2 s^{-2}
Power	W = E/t	kg m^2 s^{-3}
Pressure	Pa = N/area	kg m^{-1} s^{-2}

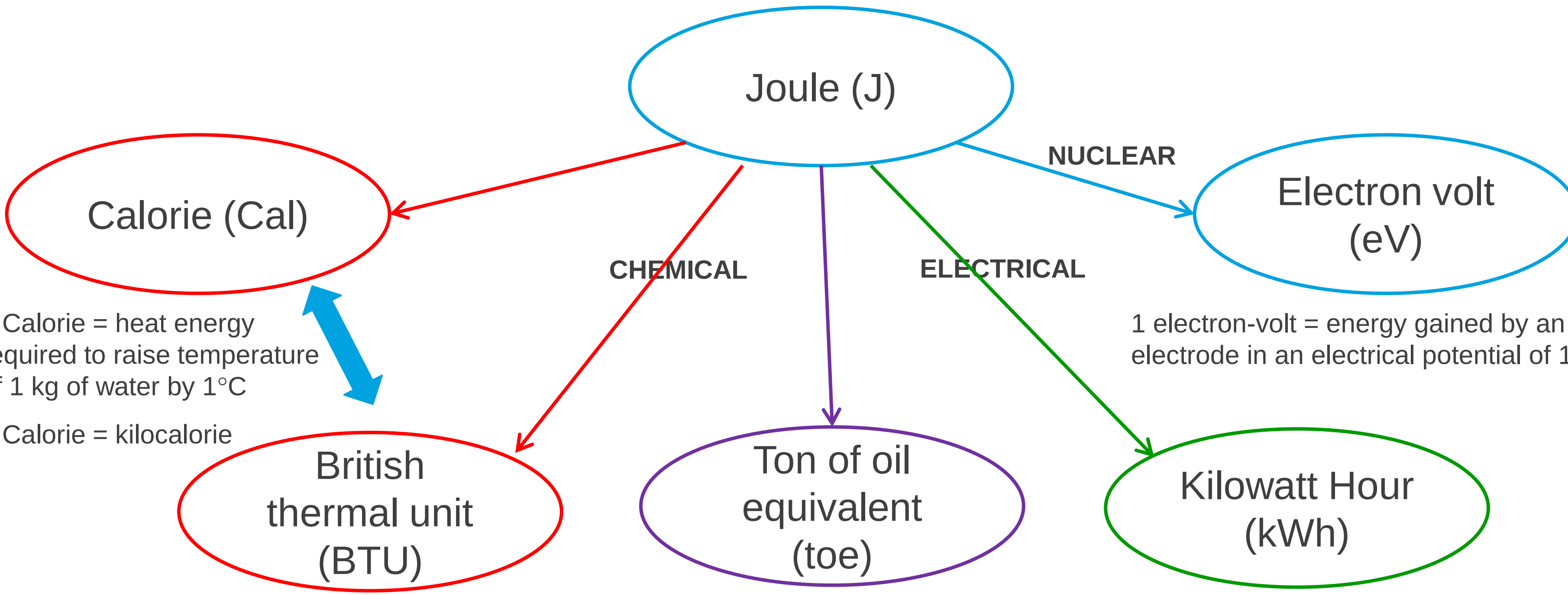
Unit of energy

Joule (J) – SI unit for energy

$1\ J = 1\ N\ m = 1\ kgm^2/s^2$

Power: Watt (W) – Joule/second

1 Joule = Energy required for
Moving an object by 1 meter with a force of 1 Newton
Moving 1 coulomb of charge through 1 volt



1 Calorie = heat energy required to raise temperature of 1 kg of water by 1°C

1 Calorie = kilocalorie

1 electron-volt = energy gained by an electrode in an electrical potential of 1V

1 BTU = heat energy required to raise temperature of 1 pound of water by 1°F

1 toe = energy generated by burning 1000kg of oil

1 kWh = electricity used in 1 hour at 1000W

Unit conversion – important to choose the correct conversion

Joule vs.
calorie
BTU
toe
eV

Conversion of Energy Units:	
1 x calorie (cal.)	= 4.1868 joules
1 x British Thermal Unit (BTU)	= 1,055 joules
	= 252 cal.
1 x kilowatt-hour	= 3.6 x 10^{6} joules
1 x megawatt-hour	= 3.6 x 10^{9} joules
1 x gigawatt-hour	= 3.6 x 10^{12} joules
1 x ton of oil equivalent (toe)	= 4.1868 x 10^{10} joules
1 x million tons of oil equivalent (Mtoe)	= 4.1868 x 10^{16} joules

Other energy units and conversions

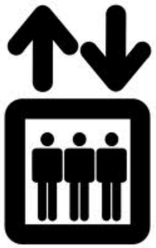
US unit (foot-pounds-force)	1 ft lbf = 1.3558 J
Horsepower hour	1 hp h = 2.6845 MJ
Nuclear	1 eV = 1.602 x 10^{-19} J

How big are the energies? – class tutorial

1. How much kinetic energy (in J) is in a car (1000kg) moving at 60km/h?

Assume car of 1000kg moving at 60km/h,
kinetic energy $E = \frac{1}{2} mv^2 = 139kJ$

2. How much potential energy (in J) is needed to move one person (70kg) up one floor in an elevator?



Assume a person 70kg moving up one floor (about 3 meters)
potential energy $E = mgh = 2.1kJ$

3. How much thermal energy (in J) is in a cup of coffee at 100°C?

A cup of starbucks coffee 250g at 100°C
Heat capacity of water $Q = 4.19$ J/g K
Thermal energy $E = m\,Q\,\Delta T = 78.6kJ$

4. How much chemical energy (in J) is in a large MacDonald french fries?

A large MacDonald french fries
380 Calorie = 1588 kJ

How big are the energies?

5. How much thermal energy is produced from 10g of charcoal

During BBQ?

10g coal gives 293 kJ of energy

6. How much electrical energy is consumed for a 60W light bulb in one hour?

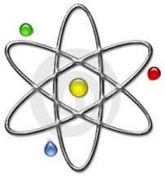
60W light bulb turned on for 1 hour
Energy = Power x time = 60Wh = 216kJ

7. How much electrochemical energy is stored in a AA alkaline battery?

Capacity ~2500 mAh
Voltage = 1.5V

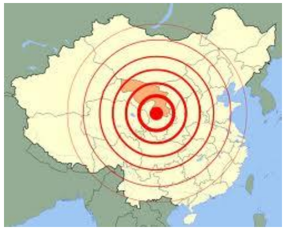
Energy = 2.5 x 1.5 = 3.75Wh = 13.5kJ

8. How much nuclear energy is produced from nuclear fission of 1g of uranium?



^{235}U + neutron $\rightarrow$ ^{141}Ba + ^{92}Kr + 3 neutrons
about 200MeV (per atom) = 3.2×10^{-11} J/atom
1g U-235 gives 8.2×10^{10} J = 82 GJ

How big are the energies?



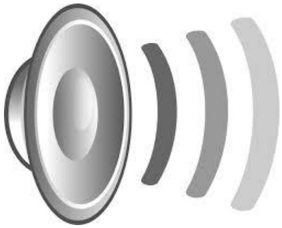
9. How much vibrational energy is produced in M6.8 earthquake?

Earthquake with magnitude in Richter scale
(6.8 Great Hanshin Earthquake, Kobe, Japan 1995)

$E \sim 6.3 \times 10^4 \times 10^{3M/2}$

Energy = 1.0×10^{15} J = 1.0×10^{12} kJ

10. How much vibrational energy is in a 80dB sound?

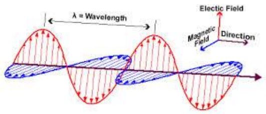


Construction site = 80dB

$L(E) = 10 \log_{10} (E_1/E_o)$ in dB $E_o = 10^{-12}$ J/m^3

$E_1 = 10^{-4}$ J/m^3

11. How much energy is in a photon coming out from a red laser pointer?



Energy of individual photon depends on frequency ($E = h\nu = hc/\lambda$)

RTHK FM radio (92.6-94.4MHz)

Red laser pointer (635nm)

Chest x-ray (7×10^8 Hz, typical wavelength 0.02nm)

Total energy depends on the power of the source

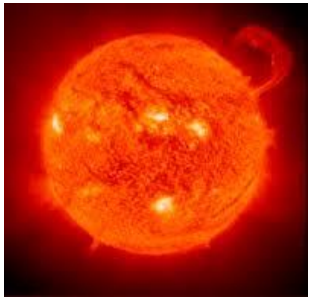
$h = 6.626 \times 10^{-34}$ Js

$c = 3 \times 10^8$ m/s

$\lambda = 635\text{nm} = 6.35 \times 10^{-7}$m

$E = 3.13 \times 10^{-19}$ J

How big are the energies?



12. How much daily solar energy does Earth receive on average per square meter?

Direct sunlight at noon is about 1000 W/m^2
Daily average irradiance (over entire day) ~ 250 W/m^2
In 1 day (24 h), energy = 250x24 = 6000 Wh = 2.16 x 10^7 J = 2.16 x 10^4 kJ

13. How much energy is released during the formation of a 1 km^3 cloud?

Density of cumulus cloud = 0.5 g/m^3
1 km^3 cloud = 5 x 10^8 g = 5 x 10^5 kg
Heat of vaporization of water ~ 2260 kJ/kg

Heat released from cloud formation ~ 1 x 10^9 kJ

Order of magnitude

world energy consumption (10^{20}/year)

Diameter of solar system (10^{13})

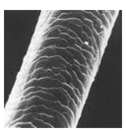
Distance from earth to sun (10^{11})

Diameter of earth (10^{7})

Stratosphere (10^{4})

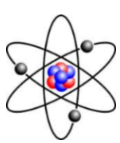
Football field (10^{2})

Height of human (10^{0})



Diameter of hair (10^{-4})

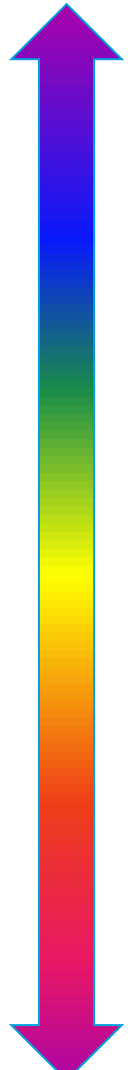
PM 2.5 (10^{-6})



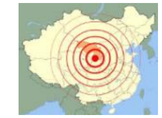
Atoms (10^{-9})

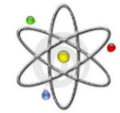
Proton, neutron (10^{-12})

meter		Joule
10^{12}		10^{12}
10^{10}		10^{10}
10^{8} (Gm)		10^{8}
10^{6} (Mm)		10^{6}
10^{4}		10^{4}
10^{2} (km)		10^{2}
1 meter		1
10^{-2} (cm)		10^{-2}
10^{-4} (mm)		10^{-4}
10^{-6} (µm)		10^{-6}
10^{-8}		10^{-8}
10^{-10} (nm) (Å)		10^{-10}



Earthquake (10^{15})



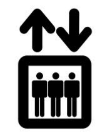


1g U235 (10^{11})

1kg coal (10^{7})

Moving car (10^{5})

Elevator (10^{3})



Sound (10^{-4})

http://rt.com/news/3d-japan-objects-levitation-102/ 2:20mins
https://www.youtube.com/watch?v=A0YsytN_ylU 2:29mins

one U-235 atom (10^{-11})

Prefix

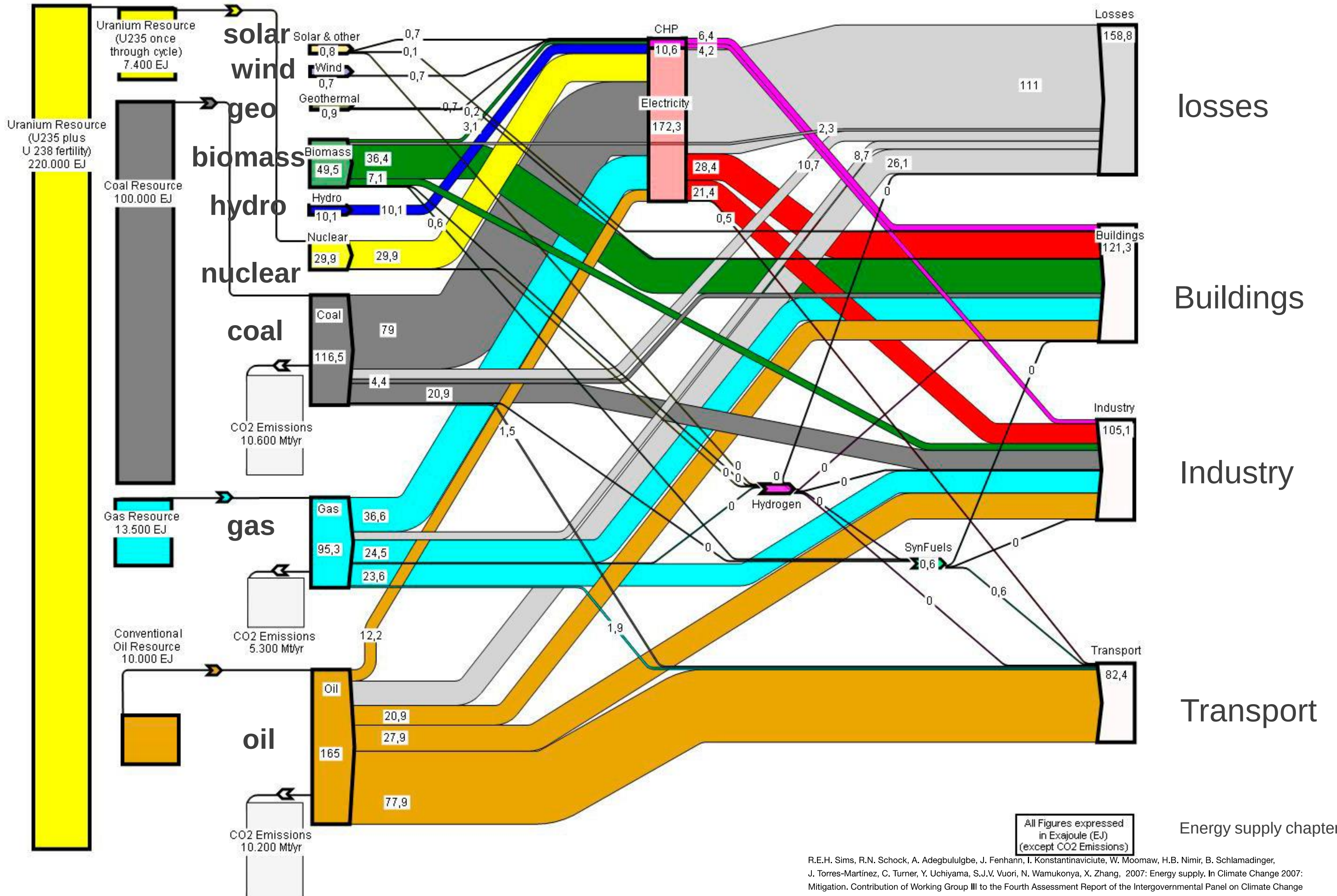
World energy consumption
5.56 x 10^{20} J/year
= 556 EJ/year in 2020

Metric prefixes

Prefix	Symbol	1000^m	10^n	Decimal	English word[n 1]	Since[n 2]
yotta	Y	1000^8	10^{24}	1 000 000 000 000 000 000 000 000	septillion	1991
zetta	Z	1000^7	10^{21}	1 000 000 000 000 000 000 000	sextillion	1991
exa	E	1000^6	10^{18}	1 000 000 000 000 000 000	quintillion	1975
peta	P	1000^5	10^{15}	1 000 000 000 000 000	quadrillion	1975
tera	T	1000^4	10^{12}	1 000 000 000 000	trillion	1960
giga	G	1000^3	10^9	1 000 000 000	billion	1960
mega	M	1000^2	10^6	1 000 000	million	1960
kilo	k	1000^1	10^3	1 000	thousand	1795
hecto	h	$1000^{2/3}$	10^2	100	hundred	1795
deca	da	$1000^{1/3}$	10^1	10	ten	1795
		1000^0	10^0	1	one	–
deci	d	$1000^{-1/3}$	10^{-1}	0.1	tenth	1795
centi	c	$1000^{-2/3}$	10^{-2}	0.01	hundredth	1795
milli	m	1000^{-1}	10^{-3}	0.001	thousandth	1795
micro	μ	1000^{-2}	10^{-6}	0.000 001	millionth	1960
nano	n	1000^{-3}	10^{-9}	0.000 000 001	billionth	1960
pico	p	1000^{-4}	10^{-12}	0.000 000 000 001	trillionth	1960
femto	f	1000^{-5}	10^{-15}	0.000 000 000 000 001	quadrillionth	1964
atto	a	1000^{-6}	10^{-18}	0.000 000 000 000 000 001	quintillionth	1964
zepto	z	1000^{-7}	10^{-21}	0.000 000 000 000 000 000 001	sextillionth	1991
yocto	y	1000^{-8}	10^{-24}	0.000 000 000 000 000 000 000 001	septillionth	1991

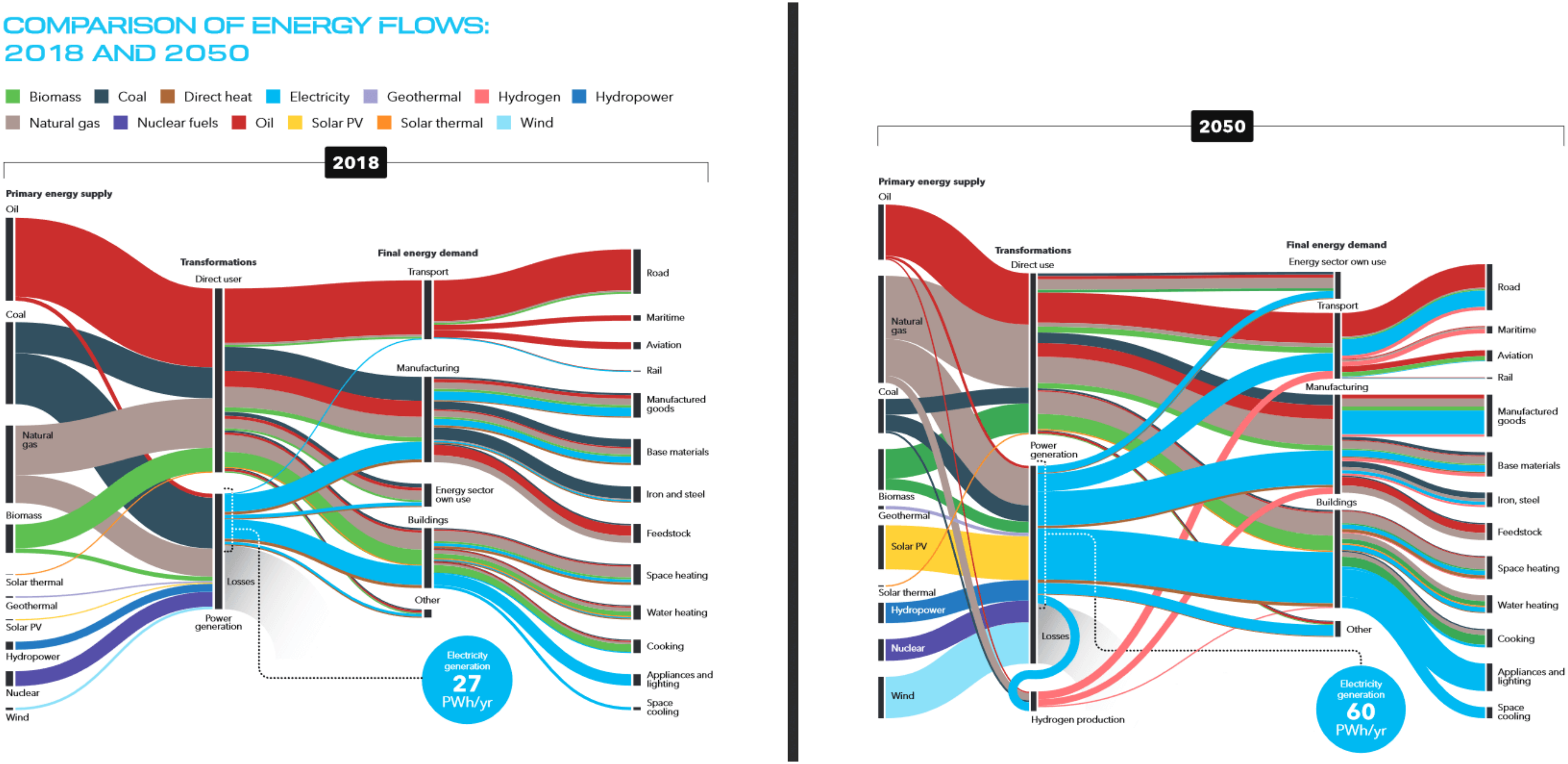
1. ^ This table uses the short scale.
2. ^ The metric system was introduced in 1795 with six prefixes. The other dates relate to recognition by a resolution of the CGPM.

Global energy flow (EJ in 2004)



R.E.H. Sims, R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martinez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang, 2007: Energy supply. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Figure 4.4: *Global energy flows (EJ in 2004) from primary energy through carriers to end-uses and losses. Related carbon dioxide emissions from coal, gas and oil combus-*

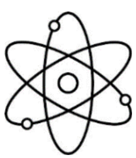


ENERGY TRANSITION OUTLOOK 2020. POWER SUPPLY AND USE REPORT.
https://eto.dnv.com/2020/power-supply-use/

Law of conservation of energy

Energy cannot be created or destroyed, but only changed from one form into another

Energy sources → Conversion method → Work done



Fossil fuels
Biofuel
Nuclear
Geothermal
Wind
Water
Solar

→

Heat engines

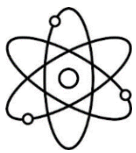
Turbine (mechanical)

→

Transport
Motion
Electricity

Energy flow

Energy generation	→	Energy transmission	→	Energy use

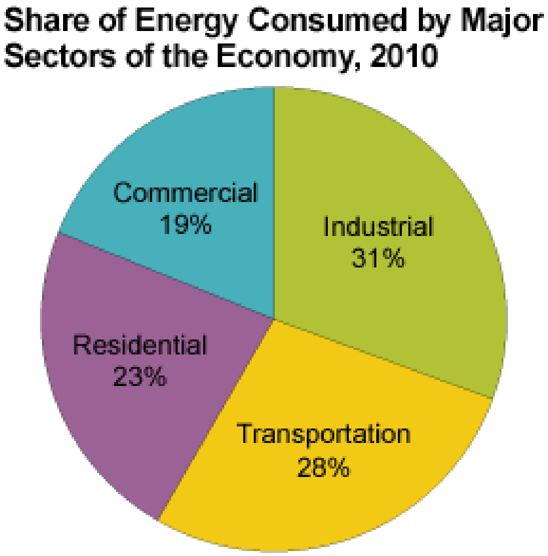


Fossil fuels
Biofuel
Nuclear
Geothermal
Wind
Water
Solar

$\eta_{generation}$?

Cable
Pipeline
Trucks
Ships


$\eta_{transmission}$?

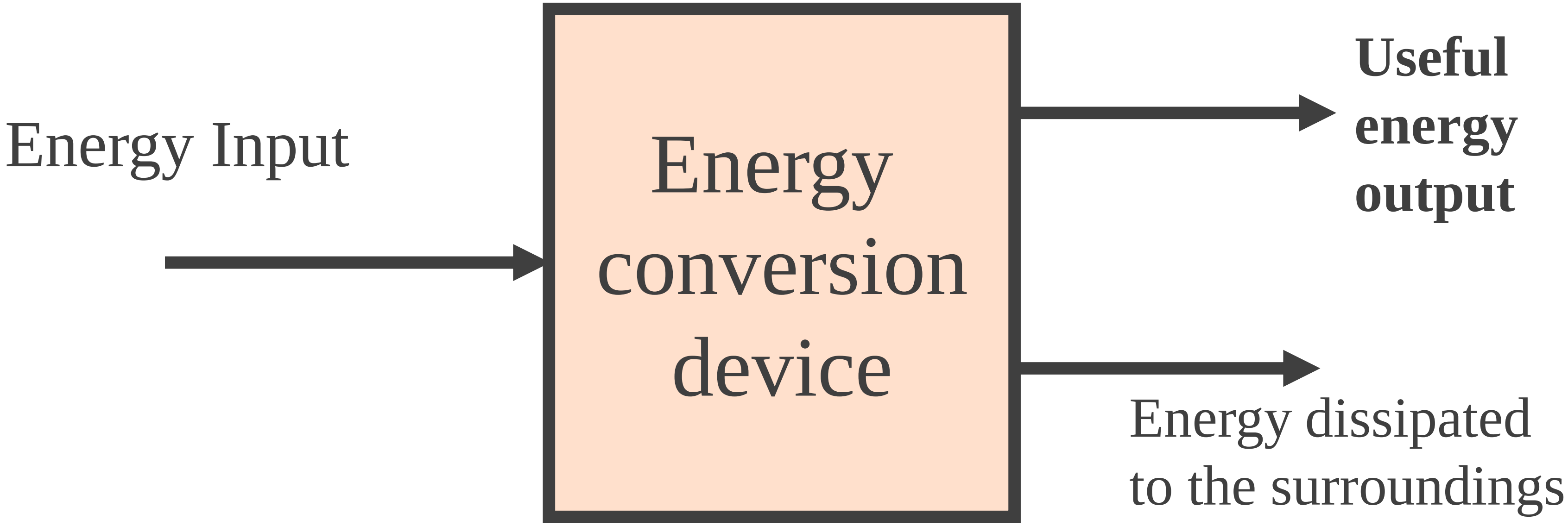


Source: U.S. Energy Information Administration, *Annual Energy Review 2009*, and *Monthly Energy Review* (June 2011), preliminary 2010 data.

Losses? η_{usage}?

- **Supply-side efficiency (energy extraction, conversion, distribution)**
- **Demand-side or End-use efficiency (useful energy in industry, service, agriculture, households, transportation, etc.)**

Definition of energy efficiency



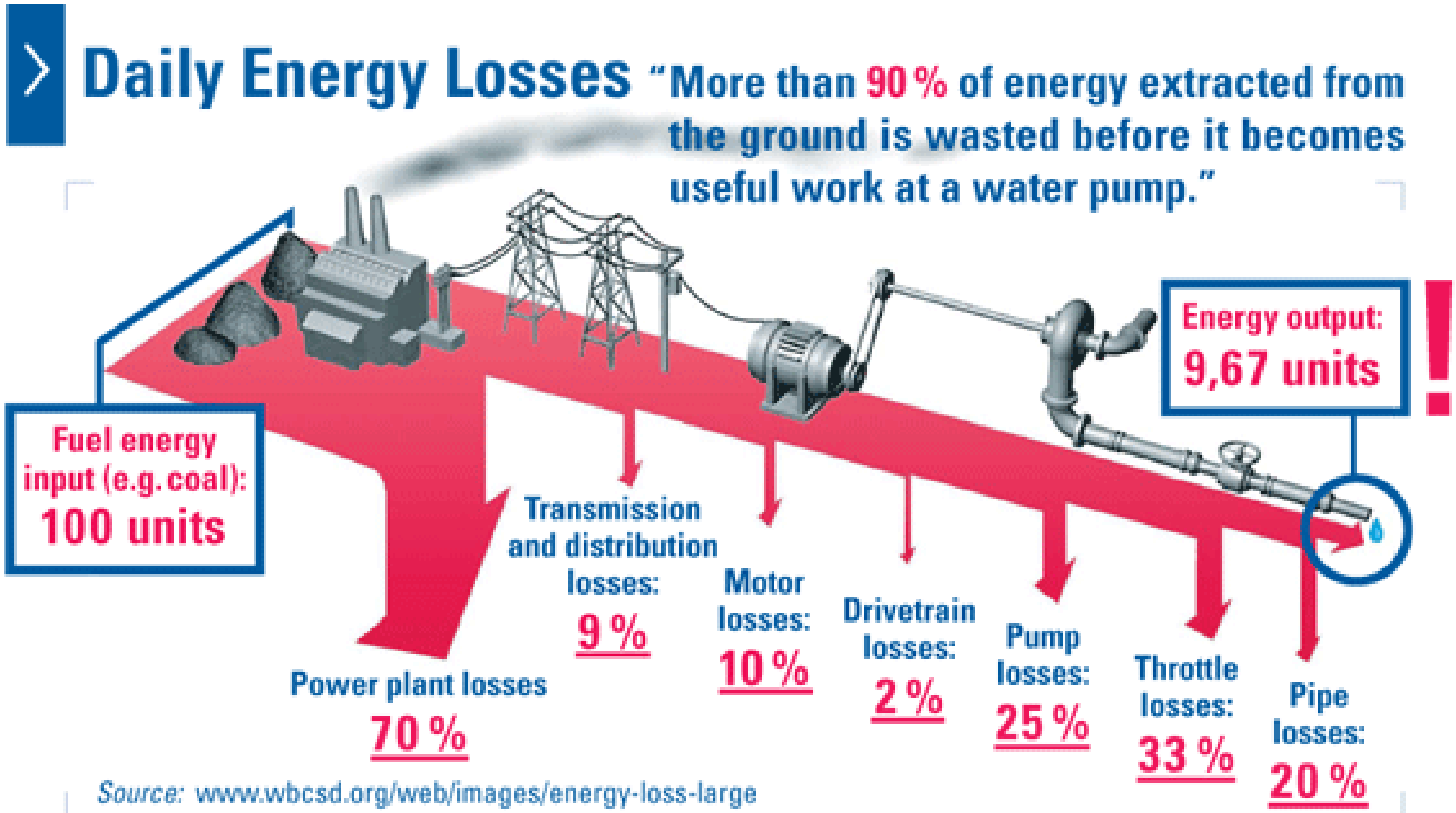
$$\boxed{Efficiency = \frac{Useful\ Energy\ Output}{Total\ Energy\ Input}}$$

Efficiency of some common devices

Device	Efficiency (%)
Electric motor	90
Steam boiler (power plant)	89
Home oil furnace	65
Home coal furnace	55
Power plant (thermal)	36
Automobile engine	25
Light bulb – fluorescent	20
Light bulb - incandescent	5

More energy loss

Propagation of efficiencies (water pump)

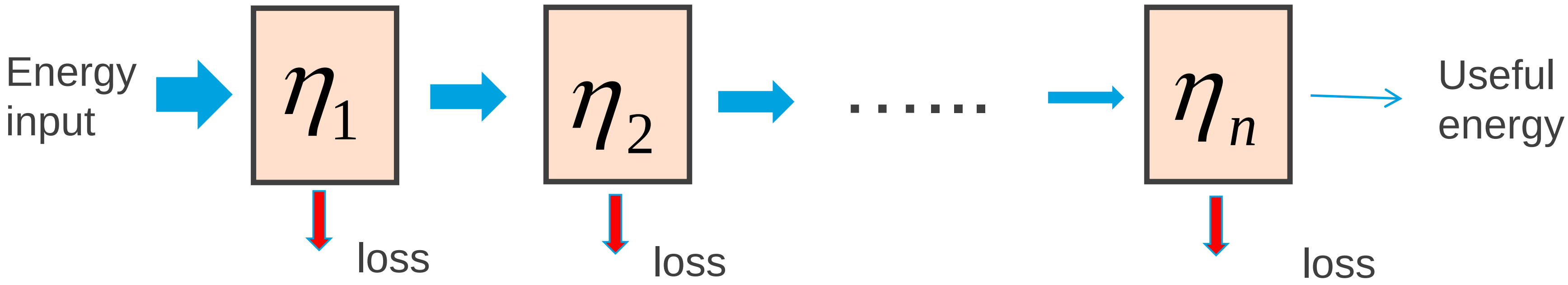


Every step counts

http://en.wikipedia.org/wiki/Electric_power_transmission

http://www.bsharp.org/physics/transmission

Propagation of efficiencies



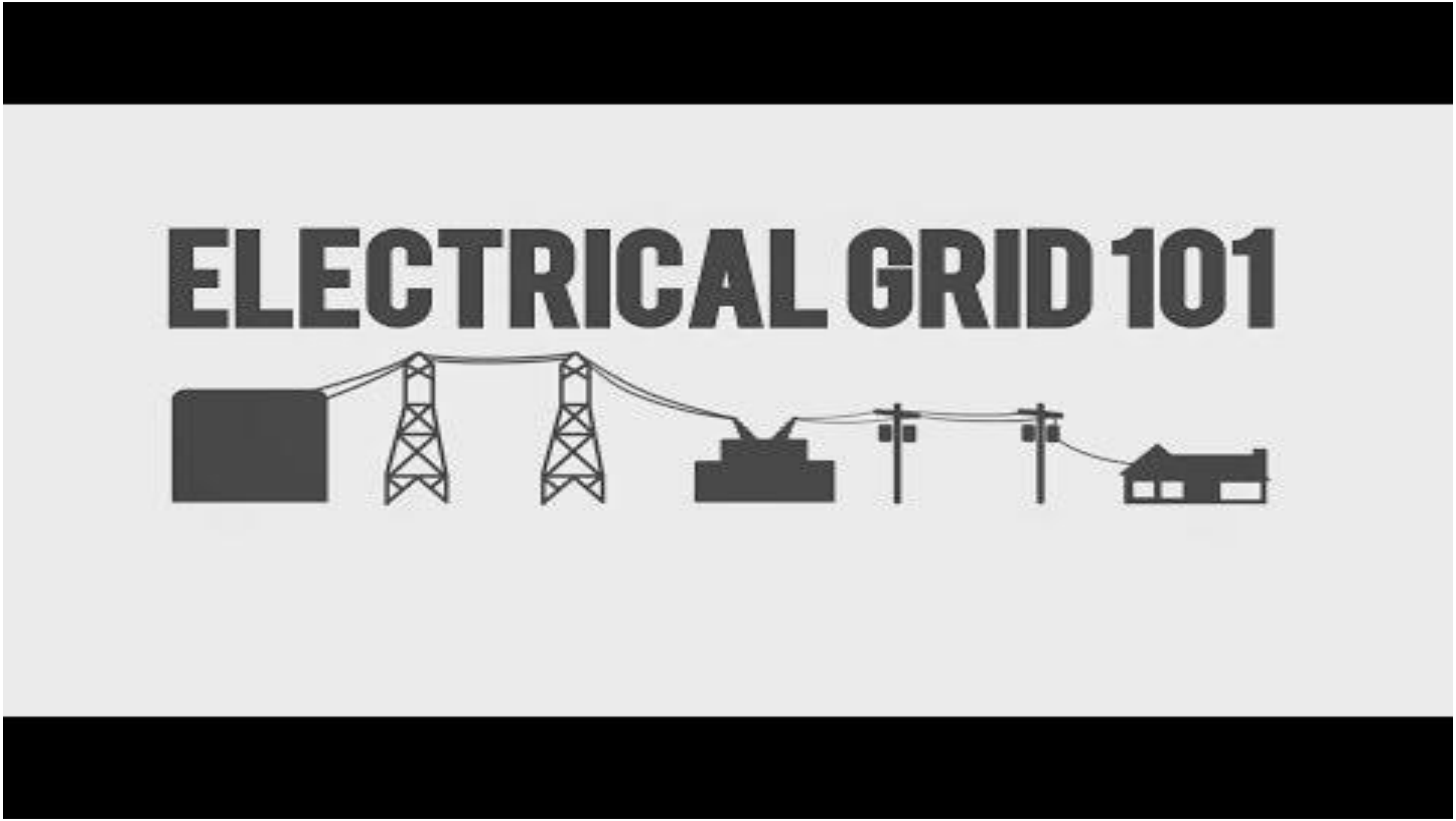
$$\eta_{overall} = \eta_1 \times \eta_2 \times \cdots \times \eta_n = \prod_n \eta_n$$

Step	Step efficiency	Cumulative efficiency
Extraction of coal	96%	96%
Transportation	98%	94%
Electricity generation	38%	36%
Electricity distribution	91%	33%
Lighting (incandescent)	5%	1.7%

Power Grid

Simple Power System

- Every large-scale power system has three major components:
  – **generation**: source of power, ideally with a specified voltage and frequency
  – **load** or **demand**: consumes power; ideally with a constant resistive value
  – **transmission system**: transmits power; ideally as a perfect conductor
- Additional components include:
  – **distribution system**: local reticulation of power (may be in place of transmission system in case of microgrid),
  – **control equipment**: coordinate supply with load.


ELECTRICAL GRID 101

Power System Examples

- **Interconnected Systems**: can range from quite small, such as an island, to one covering half the continent:
  - there are four major interconnected ac power systems in North America (five, if you count Alaska), each operating at 60 Hz AC; 50 Hz is used in China, the Post-Soviet states, India, Europe, Australia and Africa.
  - *Microgrid vs. Nation-wide Electric Grid*
- **Airplanes and Spaceships**: reduction in weight is primary consideration; frequency is 400 Hz.
- **Ships and submarines.**
- **Automobiles:** dc with 12 volts standard and higher voltages used in electric vehicles.
- **Battery operated portable systems**.

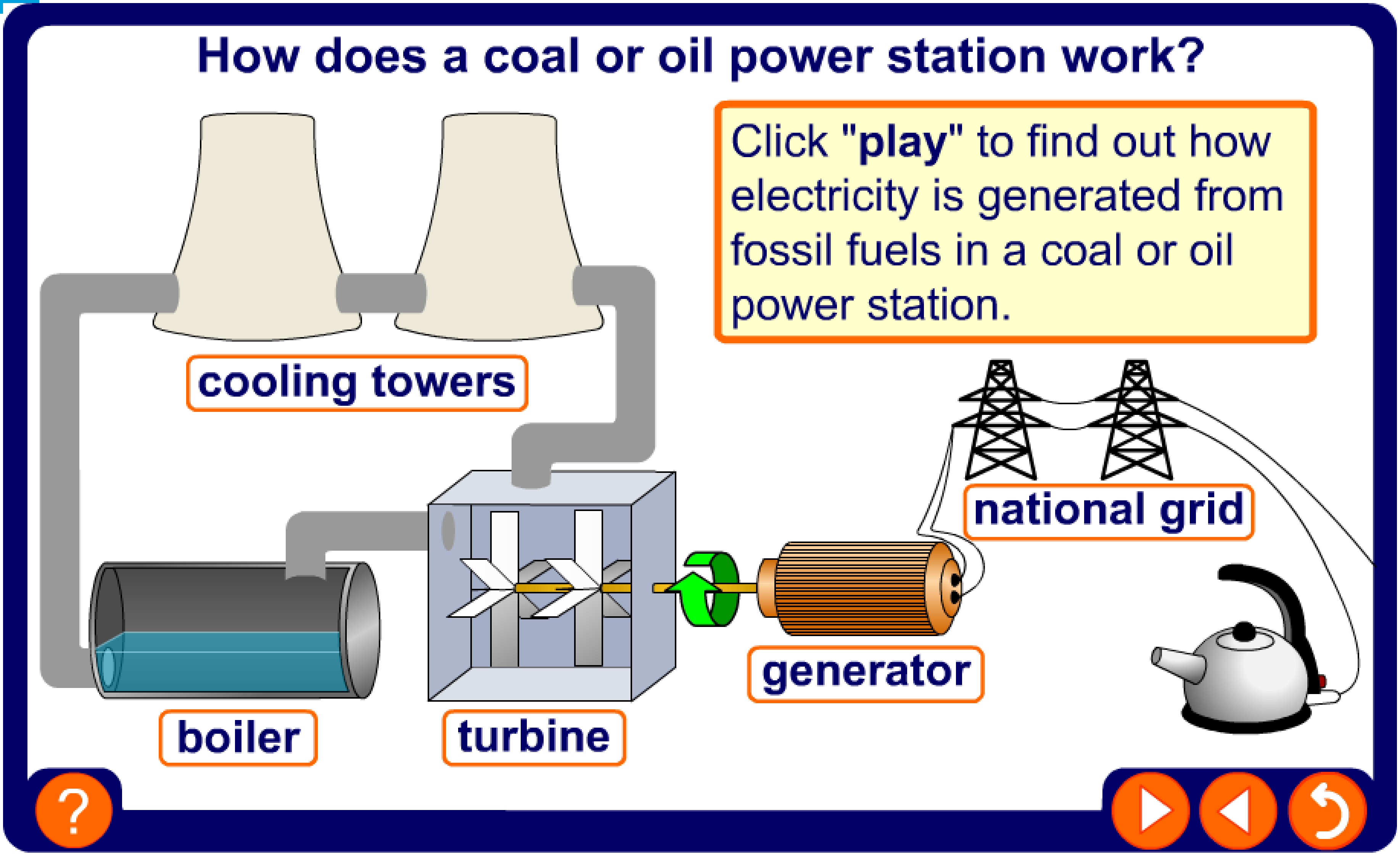
Stages in a coal power station – activity

What is the order of generating electricity from coal?

1. Powdered coal is blown into the furnace.
2. The coal burns, heating up water in the boiler.
3. The high pressure steam turns the turbine.
4. The turbine turns a shaft connected to the generator.
5. The generator turns and electricity is produced.
6. The water in the boiler becomes high pressure steam.

? C solve

What happens in a coal/oil power station?



How do fossil fuels produce electricity?

- Power stations that are fuelled by coal and oil, operate on the same basic principle.

- The fuel is burned and the heat produced is used to boil water. This creates high-pressure, superheated steam, which is then used to turn a turbine.

- The turbine turns a generator and so generates electricity.

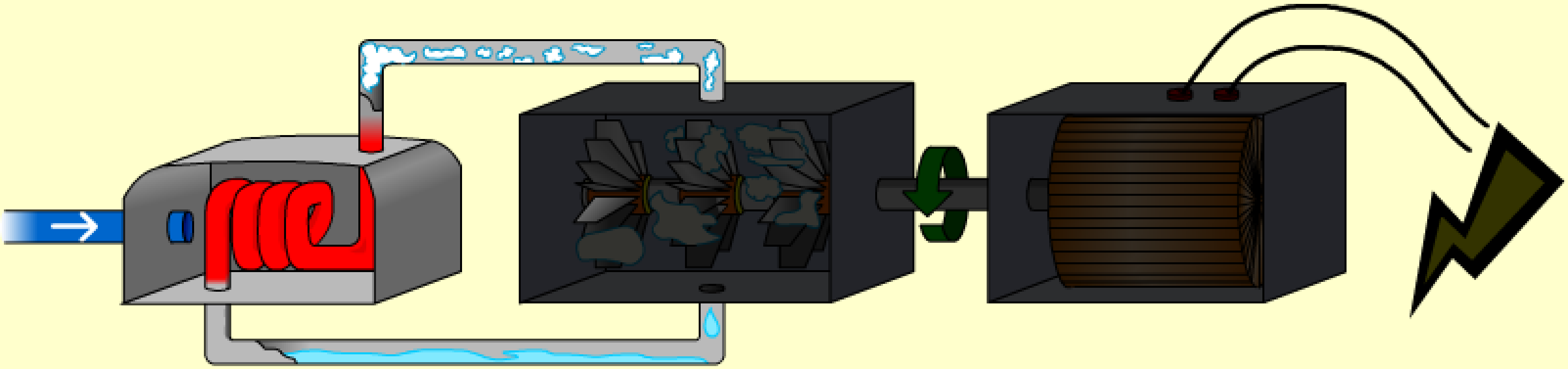
- The cooling towers cool the steam, which condenses as water and can then be recycled in the power station.

- Natural-gas-fired power stations do not use steam. The natural gas is burnt and the hot gases produced are used directly to turn the turbine.

Energy changes in a coal/oil power station

What are the energy changes in a coal or oil power station?

1. The boiler: fuel is added and burnt to turn water into steam.



Input energy ? → ? Output energy

chemical | kinetic | electrical | heat

? | C | solve

What waste do fossil fuels produce?

Burning fossil fuels creates waste products that can act as pollutants and have harmful environmental effects.

- **Carbon dioxide** – This **greenhouse gas** is the main waste product of burning fossil fuels. Increased levels of carbon dioxide due to human activities are thought to be connected with global warming.
- **Sulfur dioxide and nitric oxides** – These gaseous pollutants contribute to the formation of smog and acid rain.
- **Ash** – This waste solid is disposed of in landfill sites.

What can be done to reduce the problems caused by burning fossil fuels?

What is nuclear fuel?

Nuclear fuel is used to generate electricity but, unlike fossil fuels, it does not burn.

Guangdong Daya Bay Nuclear Power Station

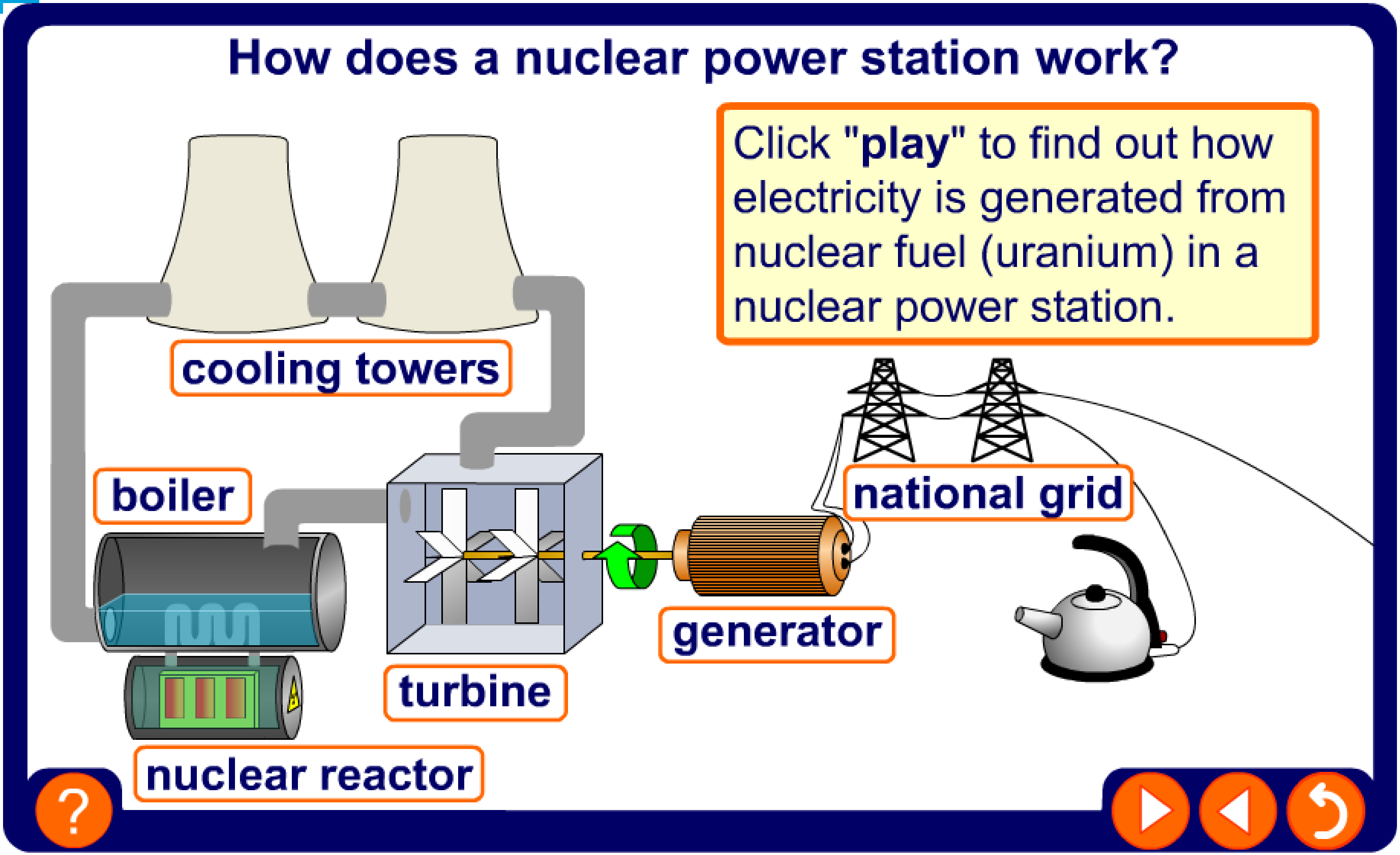
In a nuclear fuel, such as uranium, reactions take place that split the atoms and release huge amounts of heat energy.

This is called **nuclear fission**.

In a nuclear power station, the heat released from nuclear fission reactions is used to change water into steam. As in other types of power station, the steam then turns a turbine, which turns a generator and produces electricity.

Nuclear power stations do not release any greenhouse gases such as carbon dioxide or gases which cause acid rain.

What happens in nuclear power station?



What waste does nuclear power produce?

Nuclear power stations produce radioactive waste.

The used nuclear fuel contains some uranium, which can be separated from the waste and reused.

It also contains plutonium, which is a highly-radioactive product of the fission reactions that occur in uranium nuclear fuel.

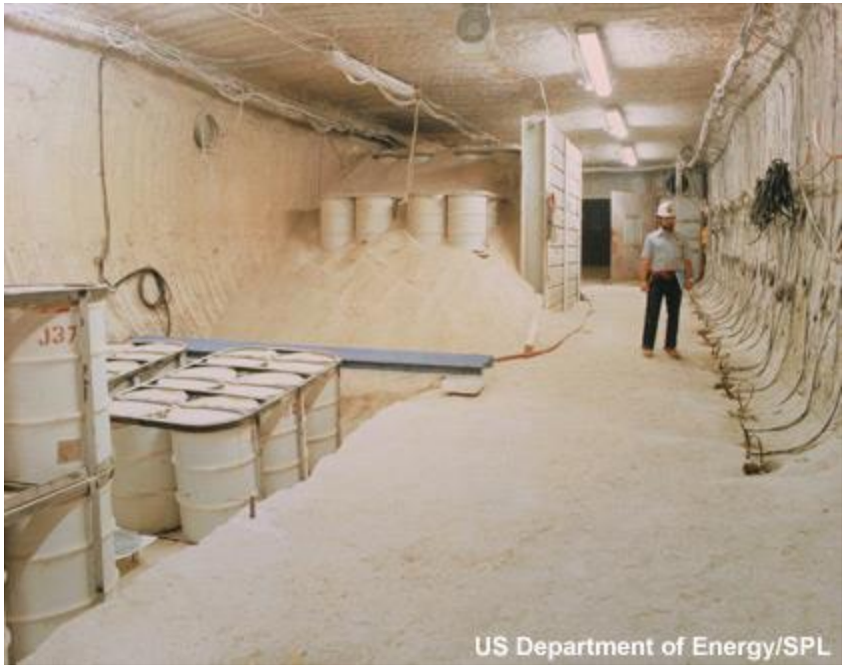
New reactors that use this waste product as a fuel have been built.

However, plutonium is also used in the construction of nuclear bombs and poses a very serious threat if it gets into the wrong hands.

Where can nuclear waste be stored?

Nuclear waste that cannot be reused poses serious problems as it can remain radioactive for thousands of years.

Highly radioactive waste can be turned into glass to help stabilize it and prevent leaks during storage.



One solution is to bury the waste deep underground.
This must be in a geologically stable environment, so there are few suitable sites.

Another suggested solution is to dump radioactive waste at the bottom of the sea. Dealing with nuclear waste is expensive and any solution has to be long term.

How quickly can electricity be produced?

The demand for electricity varies depending on the time of day and time of year. Power stations have to cope with this.

Power stations cannot be turned on at the flick of a switch. These are typical start-up times for power stations that use non-renewable energy resources.

Type of fuel	Start-up time
natural gas	1 hour
oil	4 hours
coal	7 hours
nuclear power	48 hours

Natural gas power stations produce electricity quickly.

Nuclear power stations take about two days to reach full power. They are only shut down for maintenance.

Which type of power is useful when extra power is needed for a short time?

Renewable Energy Sources

- Wind energy
- Hydro energy
- Geothermal energy
  - Power plants, direct use, heat pumps
- Ocean energy
  - Tidal; salinity-driven

→ **Principle of electricity generation same as coal-fired power plant**
Conversion of Mechanical energy into Electrical energy

- Biomass energy
  Direct: combustion of biomass
  Indirect: chemical conversion to biofuel

→ **Sparingly used for electricity generation**

Radiant solar energy

- **Solar heating (passive and active), solar power plants, photovoltaic cells**

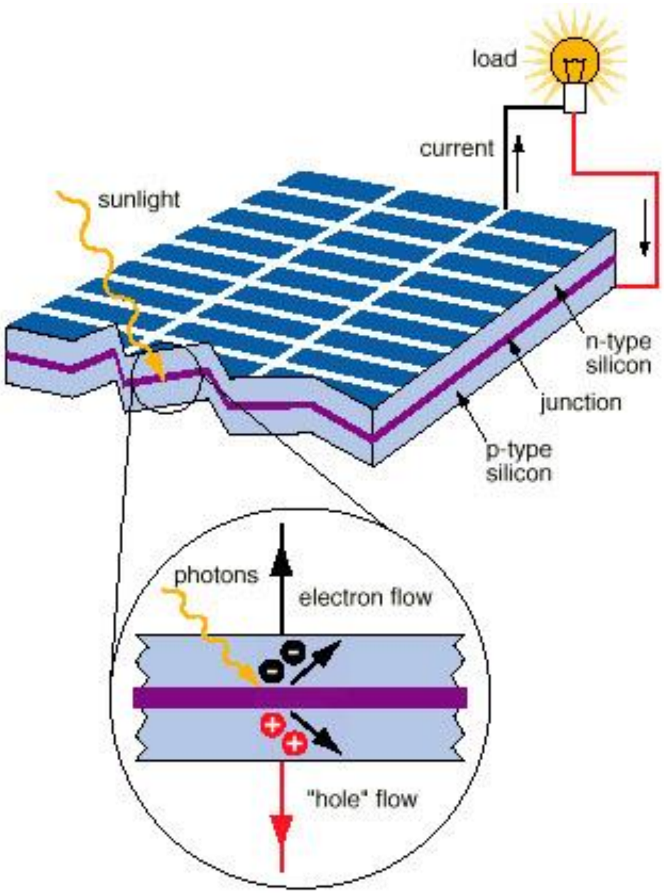
What is Photovoltaic

- A method of generating electrical power by converting solar radiation into direct current electricity through some materials (such as semiconductors) that exhibit the photovoltaic effect.

Photovoltaic

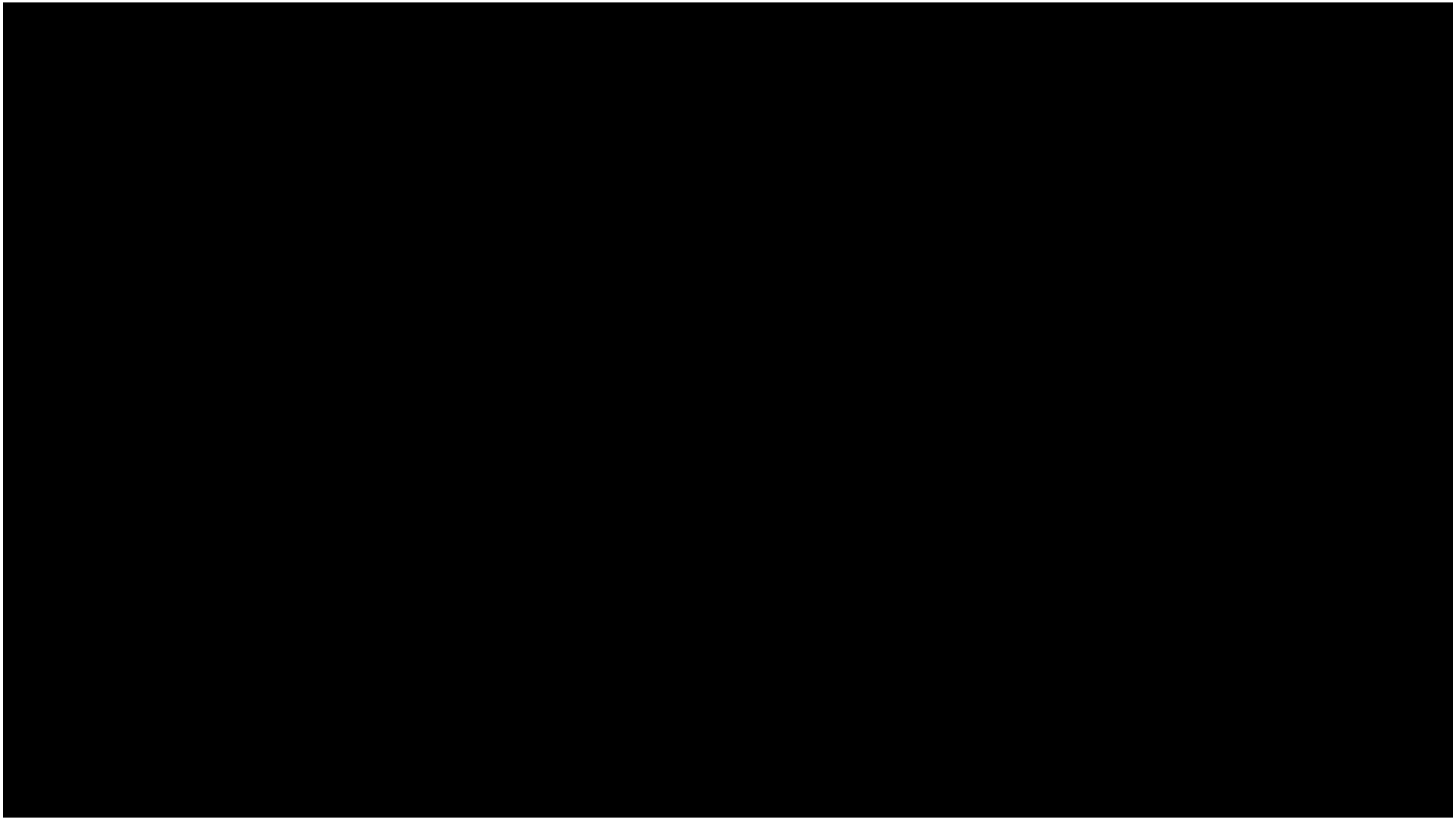
Solar Cell

Photovoltaic



- Sun light of certain wavelengths is able to ionize the atoms in the silicon
- The internal field produced by the junction separates some of the positive charges ("holes") from the negative charges (electrons).
- If a circuit is made, power can be produced from the cells under illumination, since the free electrons have to pass through the junction to recombine with the positive holes.

Electricity generation through PV



Electricity Grid in Hong Kong: Generation

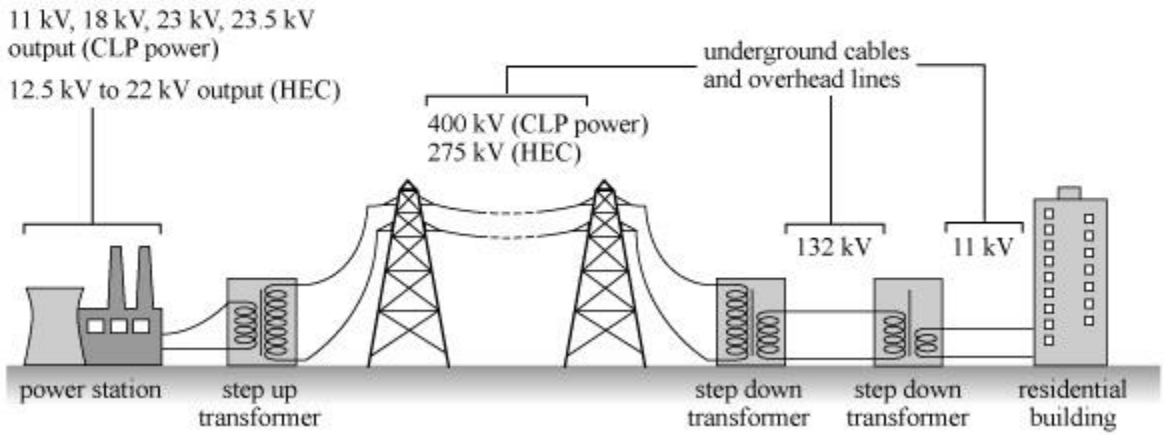
- **Lamma Power Station** of The Hongkong Electric Co., Ltd. (HEC) and the **Castle Peak Power Station** of CLP Power Hong Kong Limited (CLP Power) are the two coal power plants.

Fig. 1 Lamma Power Station of HEC (photo courtesy of HEC)

Fig. 2 Castle Peak Power Station of CLP Power (photo courtesy of CLP Power)

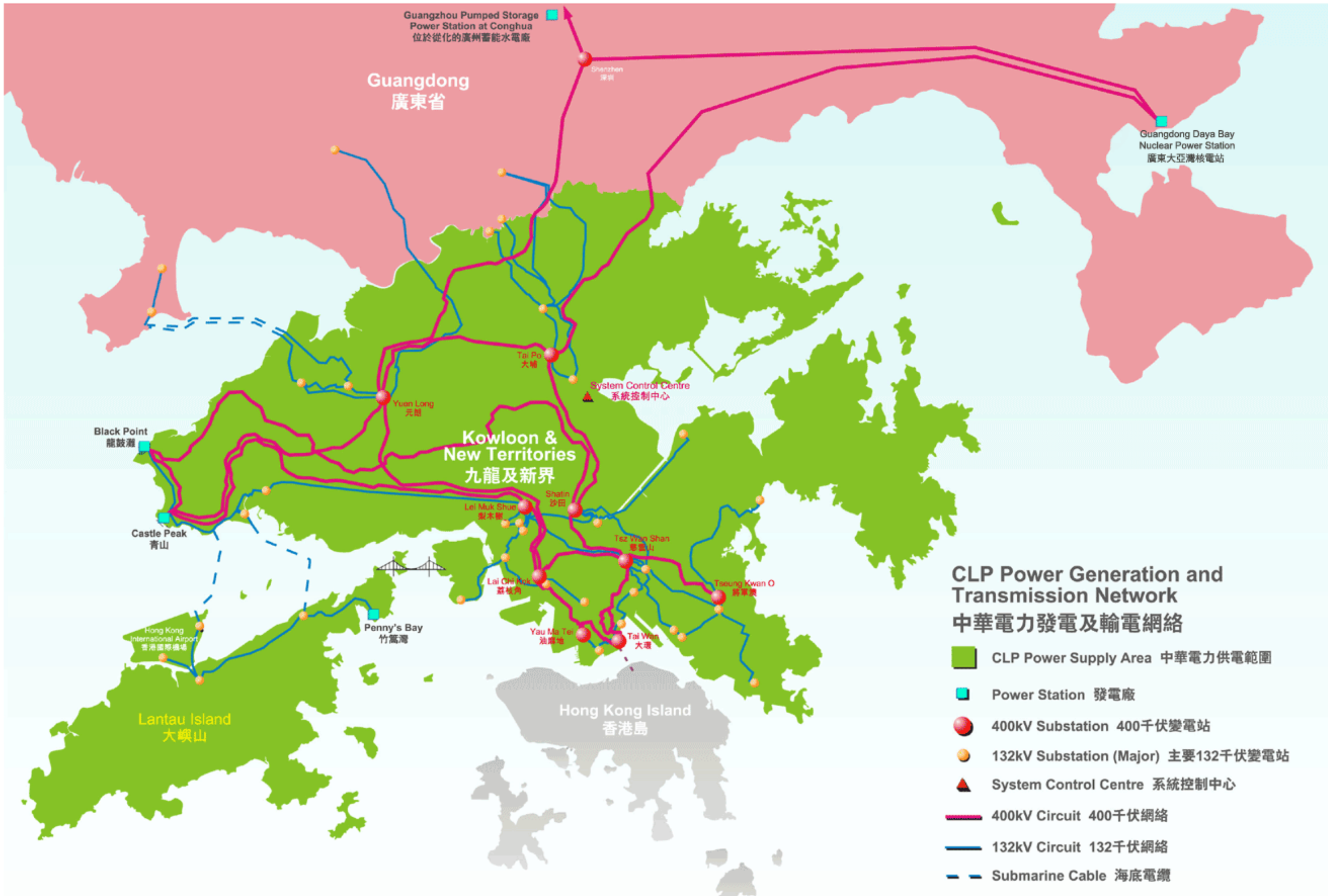
- Hong Kong also gets its electricity from a nuclear power plant, the Guangdong Daya Bay Nuclear Power Station.

Electricity Grid in Hong Kong: Transmission and distribution



- Voltage for transmitting electricity over large distance is very high.
  - highest transmission voltage for CLP Power and HEC are 400 kV and 275 kV respectively
- These voltages are hundreds of thousands times higher than the voltage of a dry cell

Hong Kong: Transmission and distribution



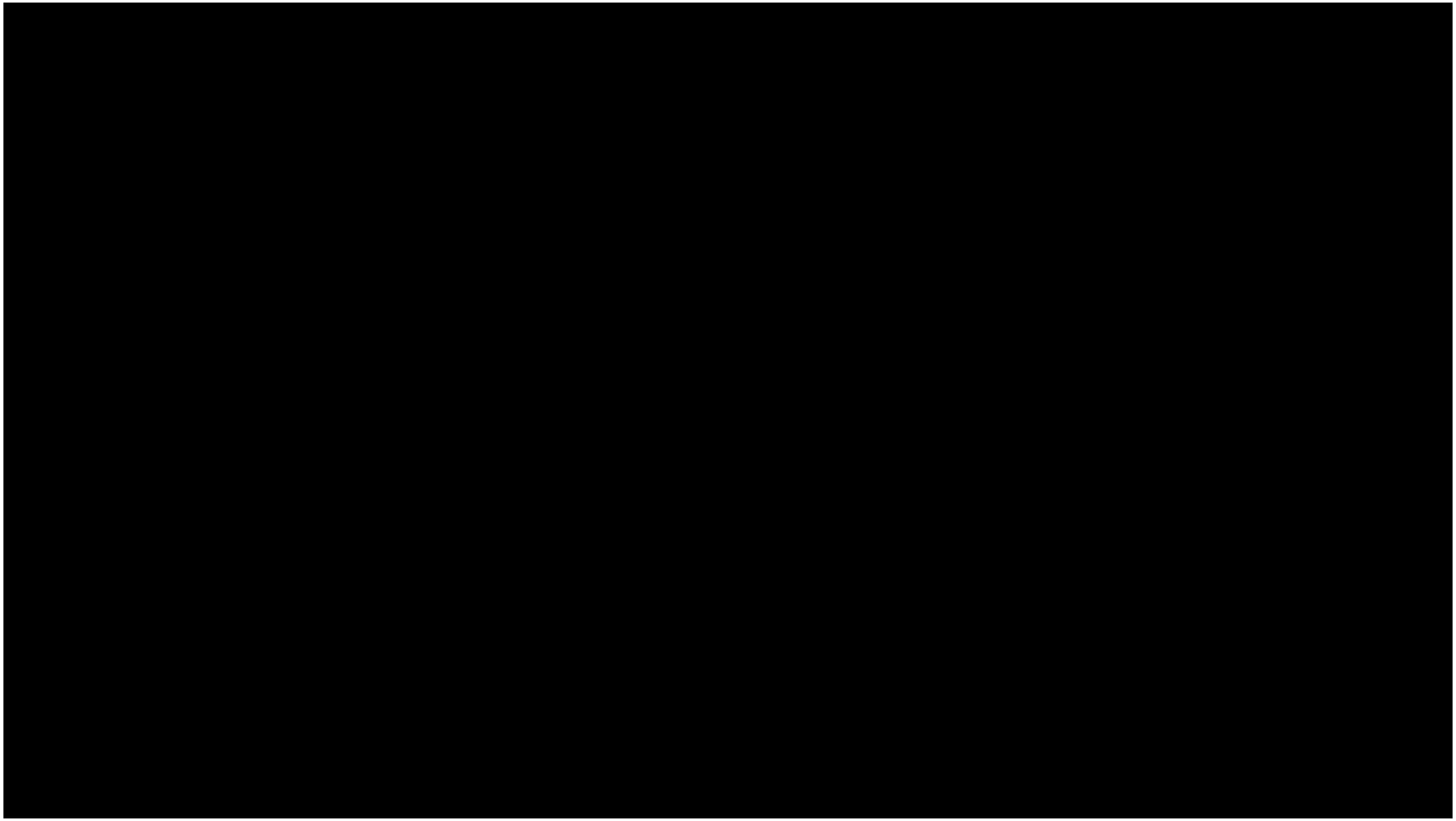
The high voltage reduces the current flowing through the transmission cables and thus reduces the power transmission loss due to the current's heating effect.

Complications

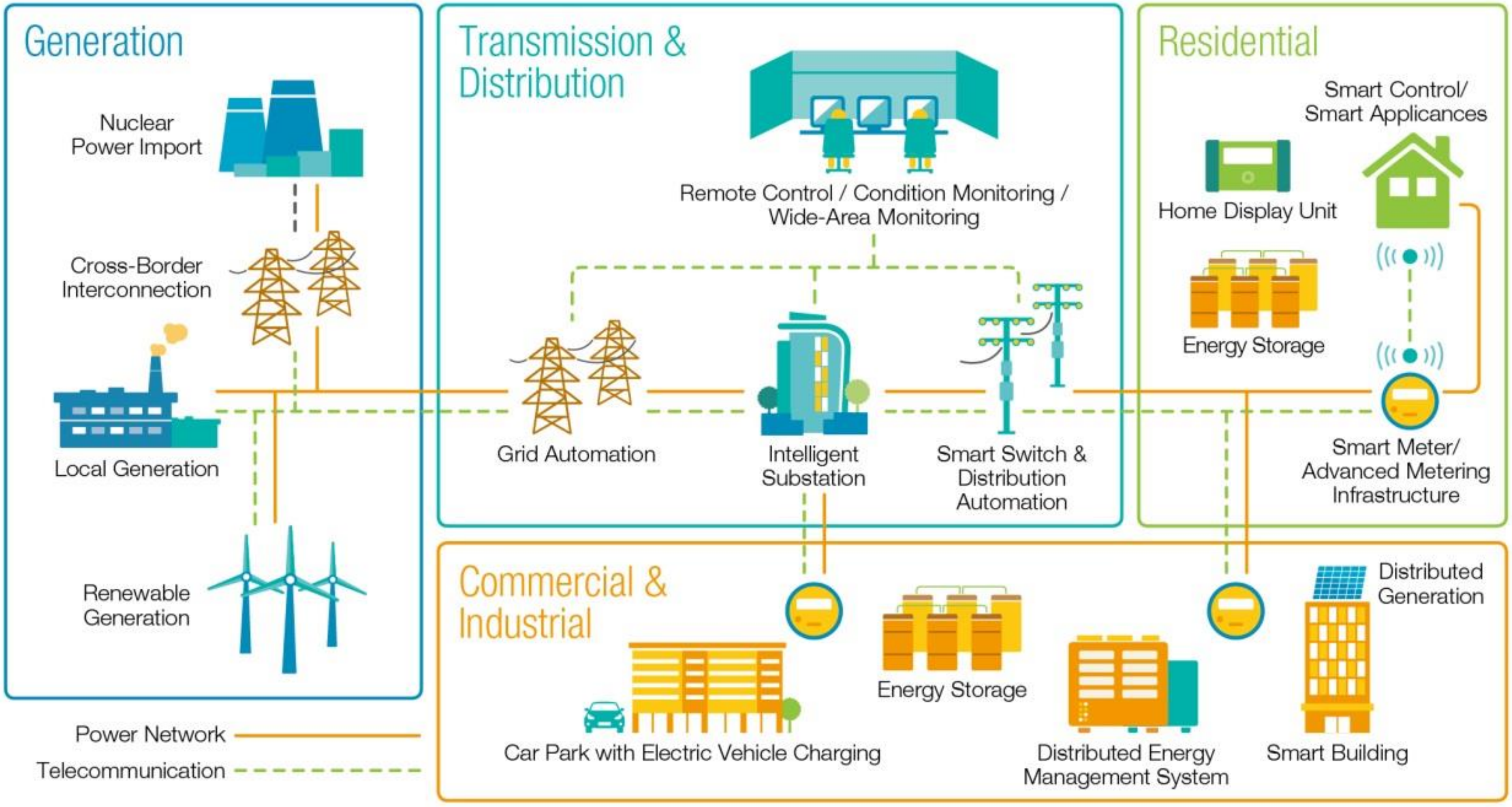
- No ideal voltage sources exist.
- Loads are seldom constant and are typically not entirely resistive.
- Transmission system has resistance, inductance, capacitance and flow limitations.
- Simple system has no redundancy so power system will not work if any component fails.

Have you heard of a Smart Grid?

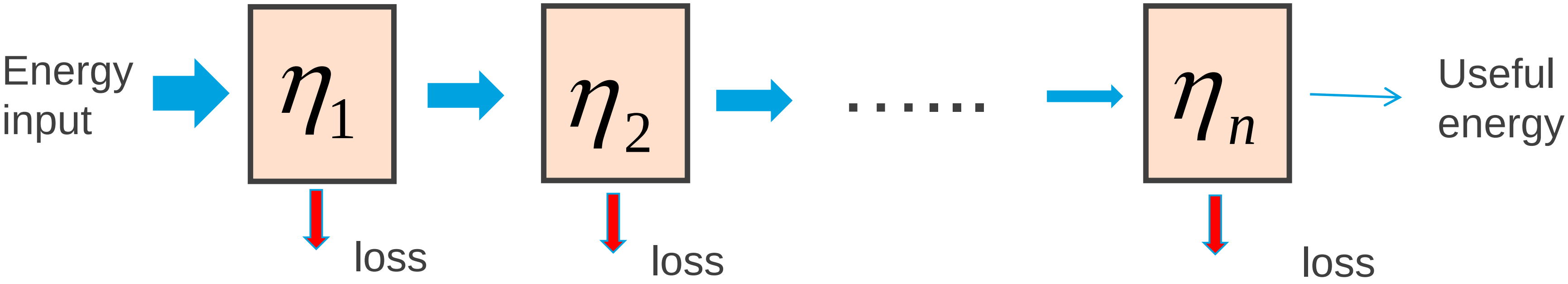
How is it different from the traditional electric grid?



Smart Grid Plan: CLP



Propagation of efficiencies



$$\eta_{overall} = \eta_1 \times \eta_2 \times \cdots \times \eta_n = \prod_n \eta_n$$

Step	Step efficiency	Cumulative efficiency
Extraction of coal	96%	96%
Transportation	98%	94%
Electricity generation	38%	36%
Electricity distribution	91%	33%
Lighting (incandescent)	5%	1.7%

Power Grid

Case 1: Engineers to enable people to see at night

How do people see at night in ancient times?

History?

Modern times?

How does it work?

Case 1: Engineers to enable people to see at night

How do people see at night in ancient times?

fire

candle

History?

Thomas Edison (1880)

Modern times?

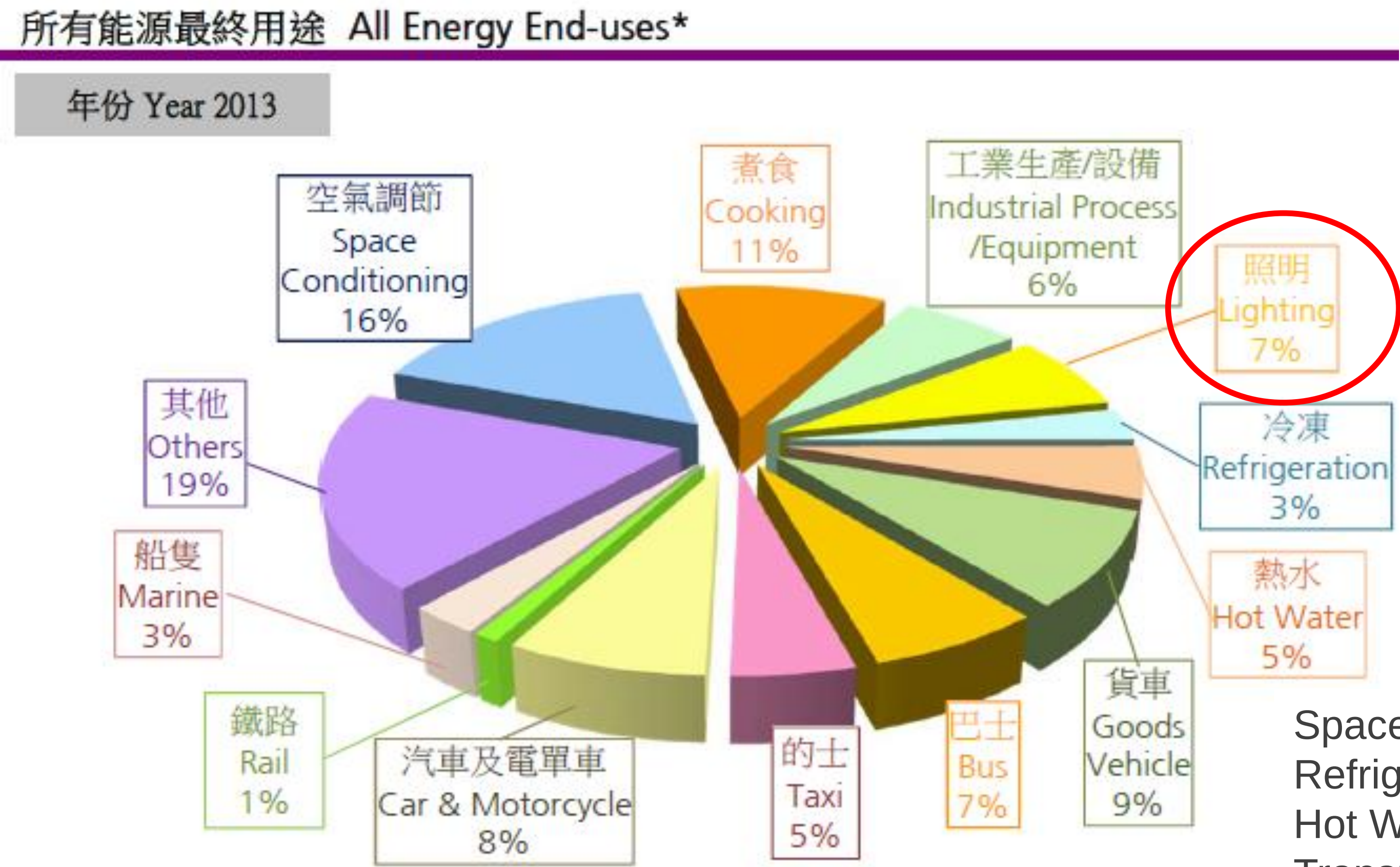
Fluorescent tubes

Light-emitting diodes

How does it work?

Turning electricity to light

Hong Kong energy end-use (2013) – overall divisions



Space conditioning 16%
Refrigeration 3%
Hot Water 5%
Transportation 33%

Lighting 7%

Lightings

Types of lighting

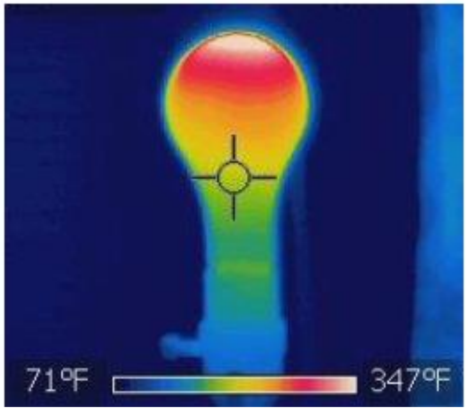
- Incandescent
- Fluorescent
- High Intensity Discharge (HID)
- Light Emitting Diode (LED)

How do they work?

Electricity $\Rightarrow$ light

Incandescent lamps

- Edison (1880)
- Light produced by passing current through **tungsten** filament
- Color: warm white (2700K)
- Lamp life ~ 1,000 hours
- Very inefficient – (4 to 24 lumens/watt) – Efficiency ~ 2-5%; energy loss to heat
- Inexpensive
- Dimmable, immediate on/off
- Phasing out in 2010s due to low efficiency



347 F = 175 °C

Tungsten-Halogen Lamps

- A type of incandescent lamp.
- Encloses the tungsten filament in a quartz capsule filled with **halogen** gas.
- More efficient.
- Lasts longer (up to 6,000 hrs.)

http://www.edisontechcenter.org/halogen.ht

Why does it last longer than normal tungsten bulb?

- Normal tungsten atoms evaporate off and deposit on inside of bulb wall.

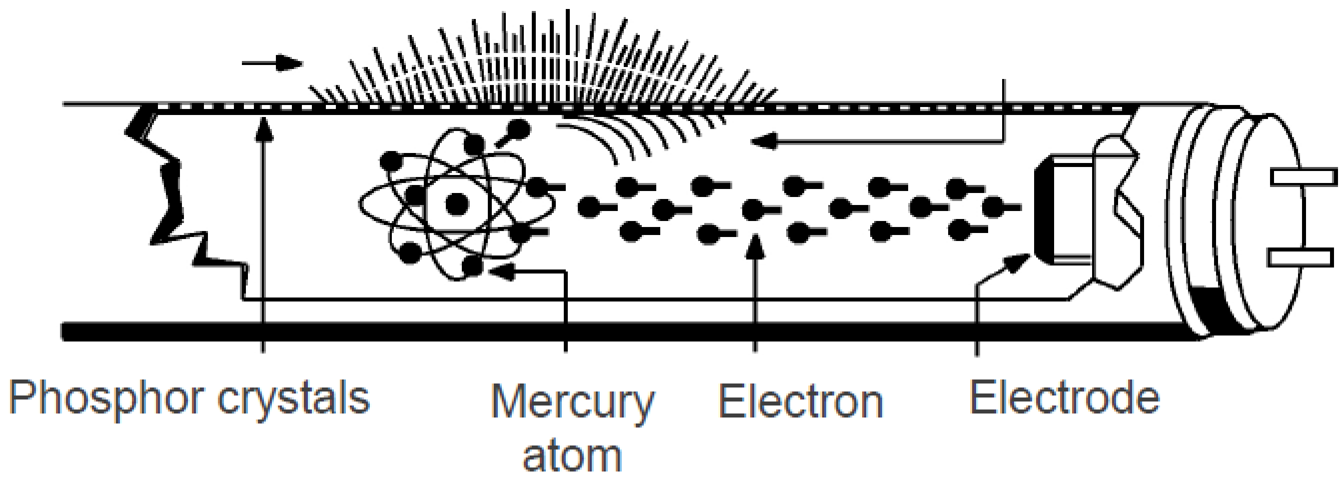
⇒ Filaments get thinner and thinner and eventually breaks

- Tungsten-halogen lamp: Halogen gas combines with the vaporized tungsten and re-deposits on the filament when cooled (halogen cycle)

Fluorescent lamps/Compact fluorescent lamps (CFL)

- Most common commercial lighting technology.
- Many choices (sizes, shapes, wattages, output, etc.)
- Excellent color (temperature) available – comparable to incandescent
- Energy Efficiency ~ 10-20%: up to 100 lumens/watt (3.5 to 4 times incandescent)
- Long Life (generally 10,000 hours – lasts 8-10 times longer than standard incandescent lamps)
- Less expensive dimming now available (0-10V dimming to 5%)

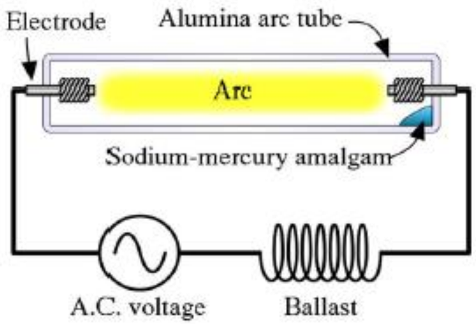
Basic principles of fluorescent lamp



- Apply voltage to **flow electrons between the electrodes** at both ends
- The **electrons interact with mercury vapor atoms** inside the bulb.
- The **mercury atoms become excited**, and when they return to an unexcited state they release UV light
- The **UV light collide with the phosphor** coating the inside of the bulb, and the **phosphor "fluoresces" to produce visible light**.

High intensity discharge (HID) lamps

- produces light by electric arc in tube filled with special gases and metal halide

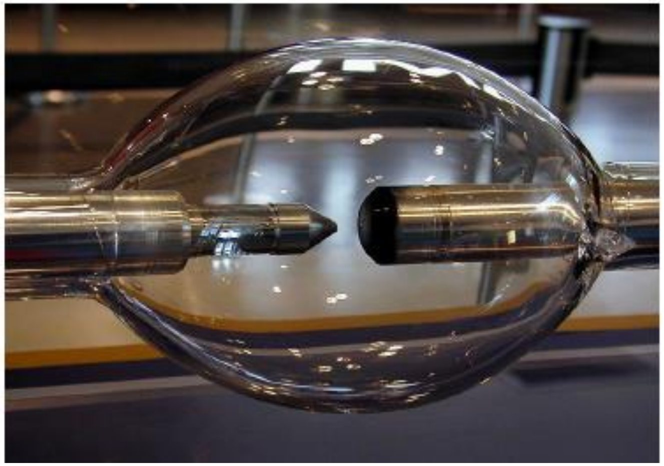


Used in industrial high bay applications, gymnasiums, outdoor lighting, parking decks, street lights

Efficient (up to 150 lumens/watt)

Long Life (up to 25,000 hours)

Drawback – take up to 15 minutes to come up to full light after power outage



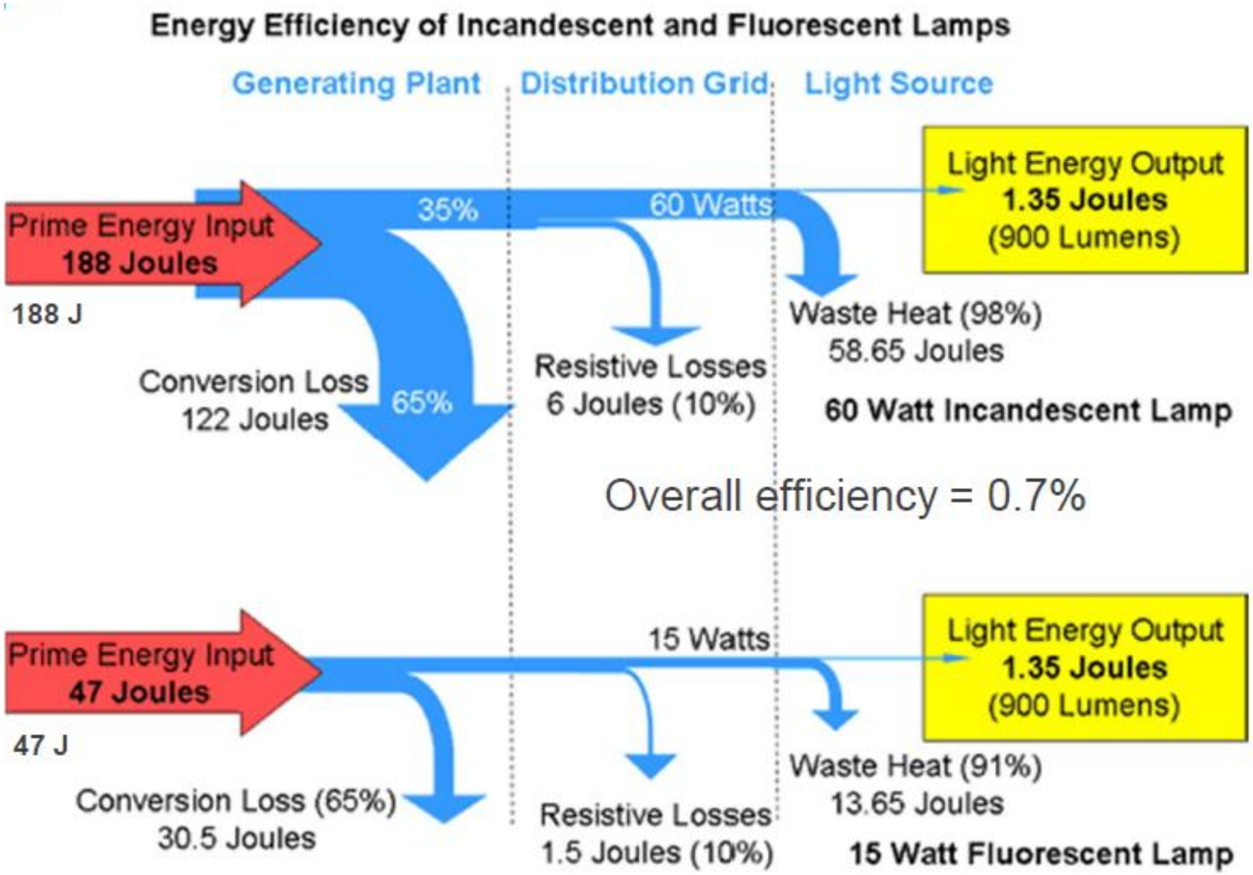
Light emitting diodes (LED)

- Latest lighting technology
- Invented in 1962 (**red**) and then **green**
- In the past, used as indicator lights, automotive lights, and traffic lights; now being introduced for indoor and outdoor lighting

  - Lower energy consumption, higher efficiency
  - Longer lifetime (50,000 to 100,000 hrs)
  - Smaller size
  - Fast switching (on/off response)
  - Greater durability and reliability

The Noble Prize in Physics 2014 – Isamu Akasaki, Hiroshi Amano, Shuji Nakamura *for "invention of efficient* ***blue*** *light-emitting diodes"*

Traditional lighting



Overall efficiency = 0.7%

Overall efficiency = 2.9%

Efficiency ~2-5%

Efficiency ~10-20%

http://www.mpoweruk.com/energy_efficiency.htm

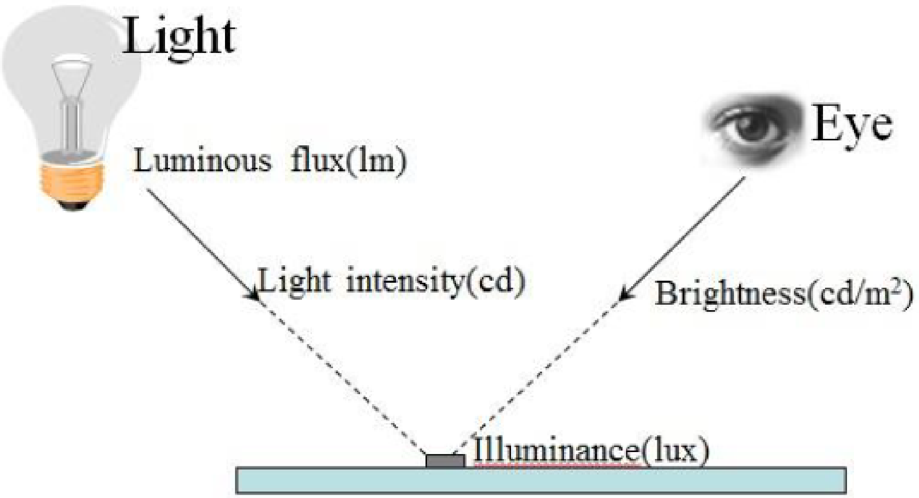
⇒ Higher energy loss from lamp

⇒ Higher energy loss from source

Definitions in lighting

- Luminous efficiency (efficacy)
- Intensity
- Illuminance
- Brightness (luminance)
- Contrast
- Colour temperature

Teach in SEE1003



Power from a light source – luminous flux (φ, unit: lumen (lm))

- **Luminous flux** φ [in unit called lumen (lm)] = power of light (at 555 nm) that is emitted from source
- Electrical power that is supplied to a light source P = I x V

I is electric current in amperes
V is electric potential or voltage in volts

Remember: Luminous efficiency aka luminous efficacy!

- Luminous efficiency [in unit of lm/W] = a measure of how energy efficient is the light produced

$$\boxed{\text{Luminous efficiency} = \Phi_{\text{lum}} / (I\,V)}$$

Light source		Luminous efficiency
Edison's first light bulb (with C filament)	(a)	1.4 lm/W
Tungsten filament light bulbs	(a)	15–20 lm/W
Quartz halogen light bulbs	(a)	20–25 lm/W
Fluorescent light tubes and compact bulbs	(b)	50–80 lm/W
Mercury vapor light bulbs	(c)	50–60 lm/W
Metal halide light bulbs	(c)	80–125 lm/W
High-pressure sodium vapor light bulbs	(c)	100–140 lm/W

Increase in Efficiency
→
Requires less energy to get more light

Which one is brighter? Which one is more efficient?

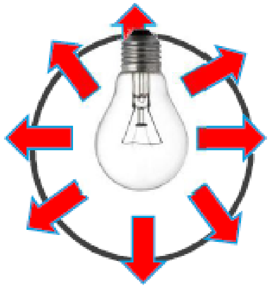
4 light bulbs	A  incandescent bulb (tungsten)	B  Tungsten-halogen	 C compact fluorescent bulb	 D LED bulb
Rating	40W	(28W but eq. to 40W "light") Use 30% less	(13W but eq. to 70W "light") Use 81% less	(9W but eq. to 70W "light") Use 87% less
Actual power	38.3W	30.7W	13.1W	8.3W
Luminous efficacy	11.6 lumen/W	16.6 lumen/W	57 lumen/W	89.5 lumen/W
Luminous flux	444 lumen Assume η = 5%	509 lumen	747 lumen	743 lumen

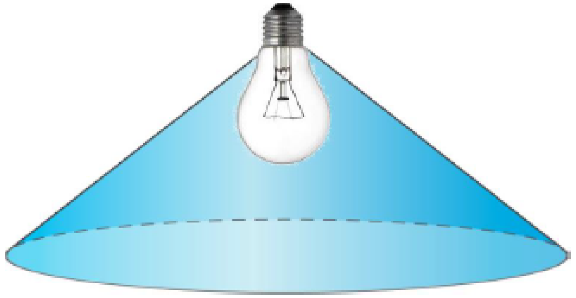
Intensity from a light source

Suppose the light source has power Φ (in lm)

Intensity of the light depends on how "spread out" the power is

e.g. a bare light bulb vs. a shaded light bulb

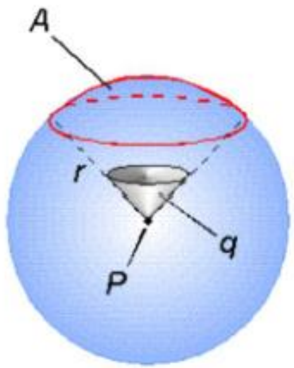




Intensity is higher here
Light is more "concentrated"

"Spread" is defined by "portion" of a sphere surrounding the bulb
- Solid angle (Ω)

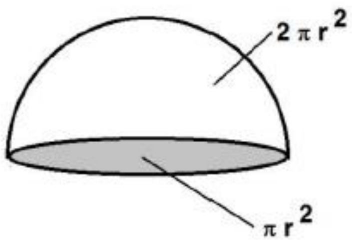
Solid angle (Ω, unit: steradian (sr))



1. If light is spread out uniformly in all directions (3D), solid angle is defined as

$$\Omega = 4\pi$$

i.e. spread over a "surface area" of a sphere with unit length ($A = 4\pi r^2 = \Omega r^2$)

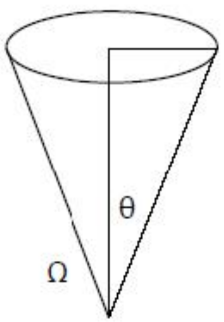


2. If light is spread out in a hemisphere

$$\Omega = 2\pi$$

3. If light is spread out in a cone with angle θ

$$\Omega = 2\pi(1 - \cos\theta)$$



$\Omega = 2\pi\,(1\text{-}\cos\theta)$

<u>Light intensity (I) is defined as "power" over "spread"</u>

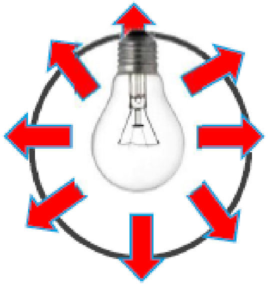
$$\boxed{I = \frac{\Phi}{\Omega}}$$

if intensity is uniform across the solid angle

Intensity from a light source (I, unit: candela (cd))

Light intensity (I) is defined as "power" over "spread" $$I = \frac{\Phi}{\Omega}$$ if intensity is uniform across the solid angle

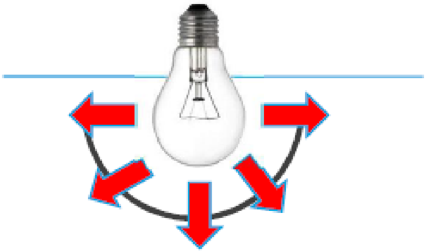
Unit of light intensity = candela (cd)
1 cd = 1 lm/sr
1 cd = intensity from a standardized candle



e.g. if we have a 9W LED spread out in all directions
What is the intensity? How many "candles" is it equivalent to?

Take luminous efficacy Φ = 90 lm/W
all direction: $\Omega = 4\pi$
$I = 90(9)/4\pi = 64.4$ cd

Equivalent to 64.4 candles

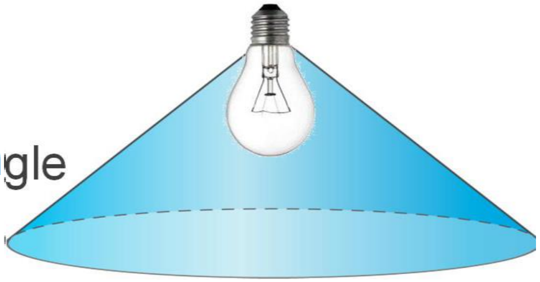


If light is only confined to a hemisphere, $\Omega = 2\pi$

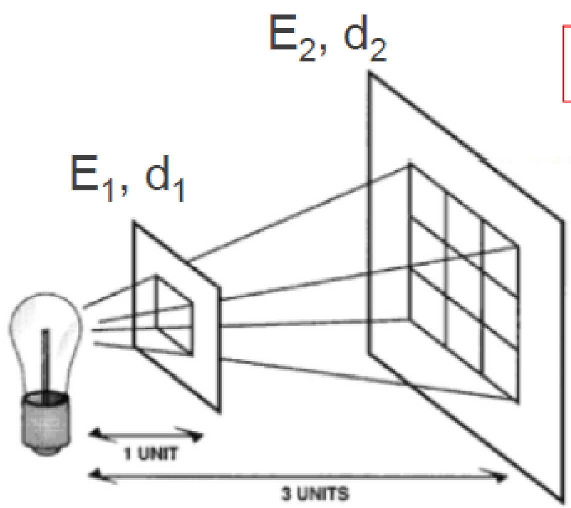
$I = 90(9)/2\pi = 128.8$ cd

Illuminance (E, unit: lux)

Intensity (I) – light power spread over a certain solid angle
– independent of distance from source



Logically, the "amount" of light should depend on how far we are



Illuminance (E) – light "power" per unit area (in lux)

For a fixed angle,
if distance is multiplied by 3,
projected area increase by 9 times,
Illuminance decrease by 9 times

$$\boxed{E = \frac{\Phi}{A} = \frac{I}{d^2}}$$

$A = \Omega\, d^2$

d = distance to source
Inversed-square law

1 lux = 1 lm/m^2 = 1 cd sr/m^2

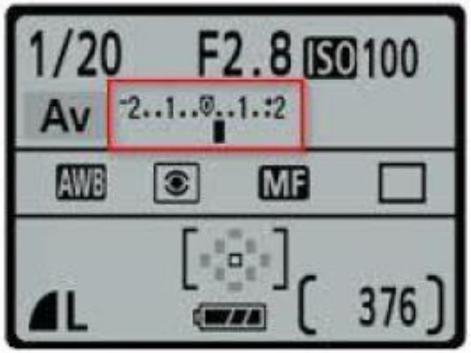
or $$\frac{E_1}{E_2} = \frac{{d_2}^2}{{d_1}^2}$$

If you know illuminance at another spot

How to measure illuminance?

Lux meter
- Photo cell to convert light to electric current

Other place you find light meter



To control brightness and contrast
- Adjust the aperture size

Illuminance scale




Illuminance	Surfaces illuminated by:
0.0001 lux	Moonless, overcast night sky (starlight)
0.002 lux	Moonless clear night sky with airglow
0.27–1.0 lux	Full moon on a clear night
3.4 lux	Dark limit of civil twilight under a clear sky
10 lux	Street lighting
80 lux	Office building hallway/toilet lighting
100 lux	Very dark overcast day
320–500 lux	Office lighting
400 lux	Sunrise or sunset on a clear day.
1000 lux	Overcast day;typical TV studio lighting
10000–25000 lux	Full daylight (not direct sun)
32000–100000 lux	Direct sunlight

http://en.wikipedia.org/wiki/Lux

Illuminance (example)

A desk lamp with a height of 40 cm gives an illuminance of 400 lux on a book.
What can you do if you want to increase the illuminance on the book to 500 lux?

Option 1: Change to a brighter light bulb

How much more power will you use?

For the same type of light bulb (same luminous flux), illuminance $\propto$ power.
Therefore, required power = 1.25 times

Option 2: Change distance of the lamp

E_1 = 400 lux d_1 = 40 cm

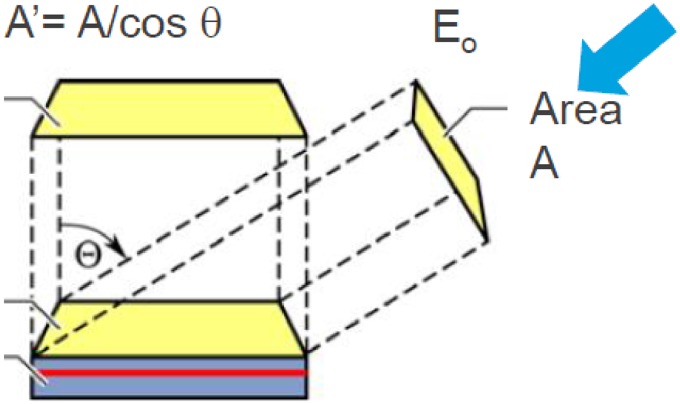
E_2 = 500 lux d_2 = ? cm

$$\frac{E_1}{E_2} = \frac{d_2^{\,2}}{d_1^{\,2}}$$

d_2 = 35.8 cm

Move light down by 4.2 cm

Illuminance – effect of orientation



θ – angle between the **normal** planes

E_o – incoming light with area A

If light is shine on a surface with an angle θ from the normal, projected area A' = A/cos θ
(i.e. spreading light over a larger area)

$$E = \Phi/A'$$

Illuminance (E) at an angle θ from the normal is

$$E = E_o \cos\theta$$

Lambert's cosine law

$\theta \rightarrow 0°$, $E \rightarrow E_o$

$\theta \rightarrow 90°$, $E \rightarrow 0$

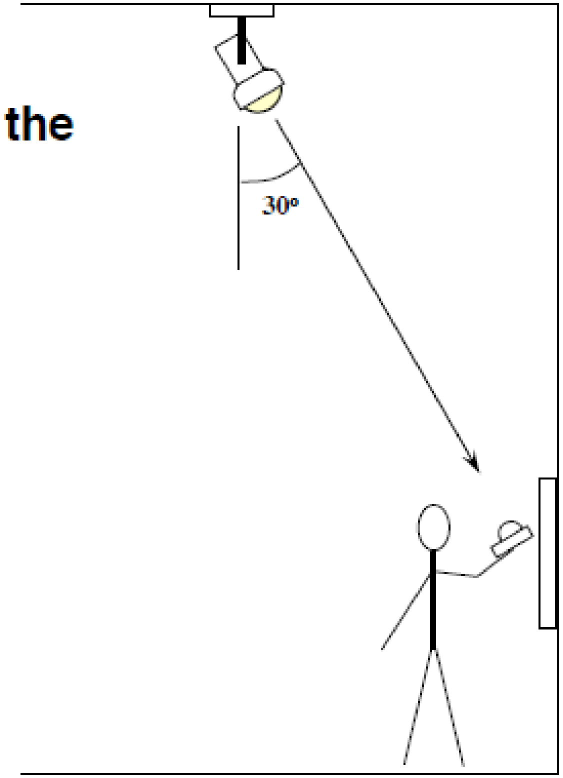
Illuminance – effect of orientation (example)

Example A ceiling-mounted spot lamp illuminates a wall-mounted painting as illustrated in the figure below. The direct illuminance measured at the painting is 1000 lux. What is the illuminance on the surface of the painting?

Solution:

The incidence angle with the normal of the surface of the painting is 60°.
The illuminance on the painting is

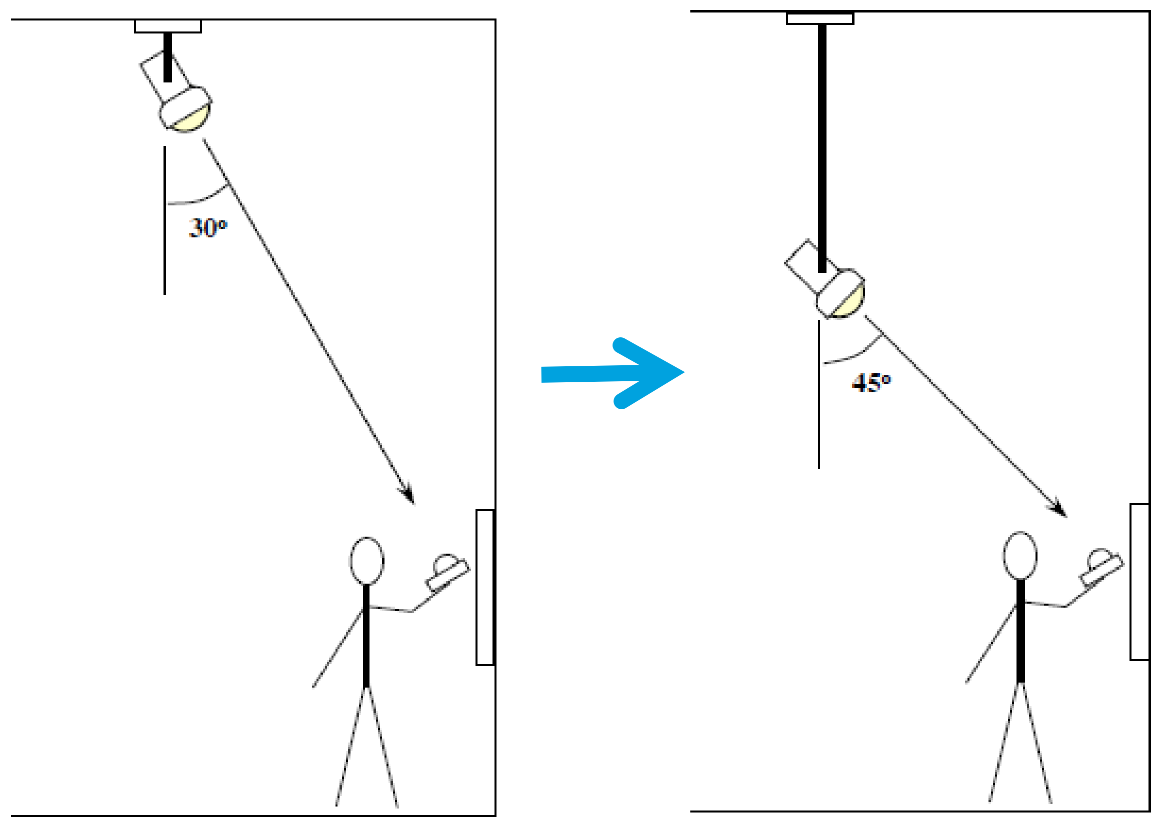
$$E = E_o \cos(\theta) = 1000 \cos(60^o) = 500 \text{ lx}$$



Illuminance – effect of orientation (example 2)

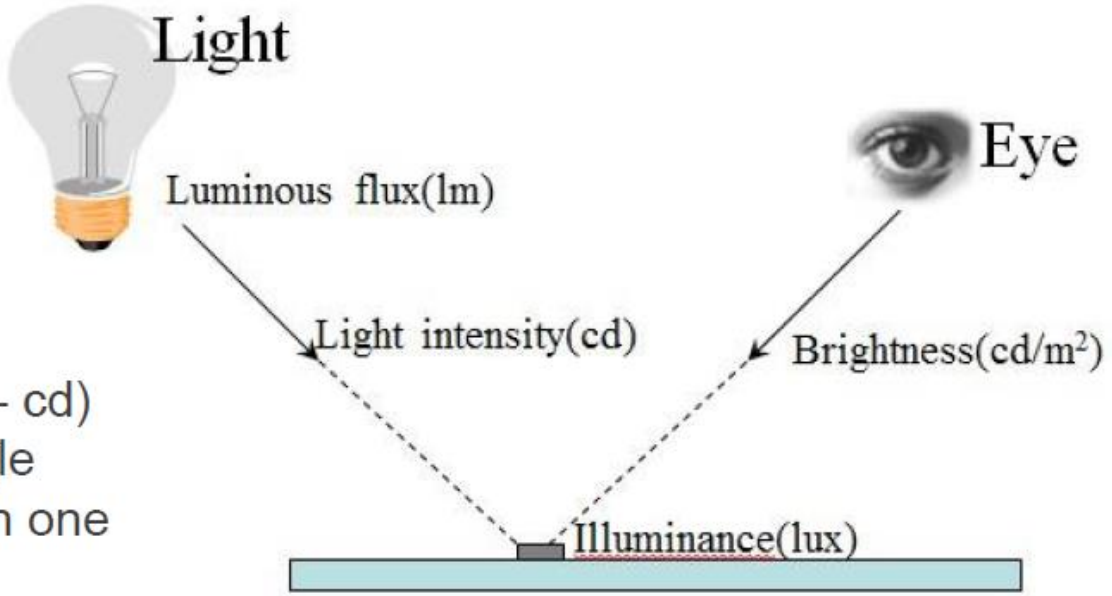
Example For the previous example, if the same ceiling-mounted spot lamp is moved to a lower position and turned towards the painting as illustrated in the following figure, what is the illuminance on the surface of the painting?

Distance changed
Angle changed



Summary – luminous flux, intensity and illuminance

Luminous flux (Φ - lm) – total light power at 555 nm emitted from source (include all directions)



Luminous intensity (I - cd) – lumen per solid angle
Light intensity going in one direction

- Independent on distance from source
- Depends on direction

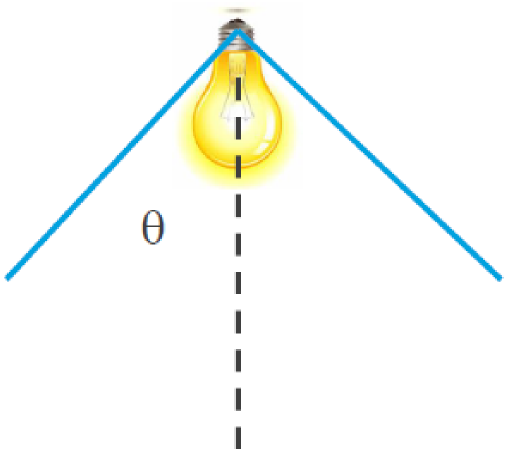
$$I = \frac{\Phi}{\Omega}$$

$$E = \frac{I}{d^2}$$

Illuminance (E – lux = lm/m^2)

- Amount of light falling on a unit area on a surface (detector)
- Depends on distance from source and orientation of surface

Example on luminous flux

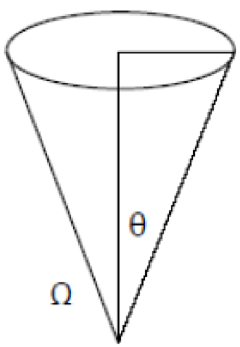


Given that a 40W light with an isotropic light intensity within a cone pertained by $\theta = 45^\circ$

If the illuminance at a distance 1 m from the source is 500 lux, what is the luminous efficiency of the light?

E = 500 lux at d = 1m

$$I = Ed^2 = 500 \text{ cd}$$



$\Omega = 2\pi\ (1\text{-}\cos\theta)$

Solid angle pertain by an angle q is given by

$$\Omega = 2\pi(1-\cos\theta) = 2\pi(1-\cos 45^\circ) = 1.84sr$$

Luminous flux

$$\Phi = I\Omega = 500 \times 1.84 = 920 \text{ lm}$$

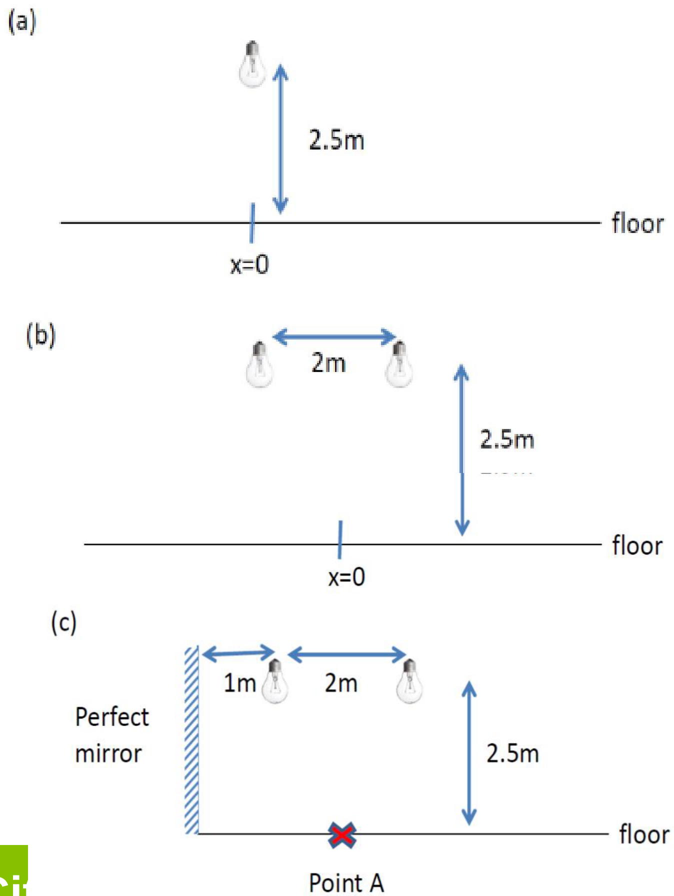
Luminous efficiency = 920 lm/40W = 23 lm/W

Extra Questions

a. Given a light with a uniform luminous distribution. The measured illuminance is 500 lux at a distance 50cm away. What is the illuminance on the floor right underneath the light if you install the light on a 2.5m ceiling? Derive the illuminance distribution function E(x) along the floor in the x-axis (assuming no walls)?

b. If you install 2 of these lights spaced 2m apart. What is the illuminance on the floor between the lights (point A) assuming no walls?

c. If you install a perfect mirror on one side of the wall 1 m away from one of the light. What is the illuminance on the floor between the lights (point A)?



Illuminance – effect of orientation (example 2)

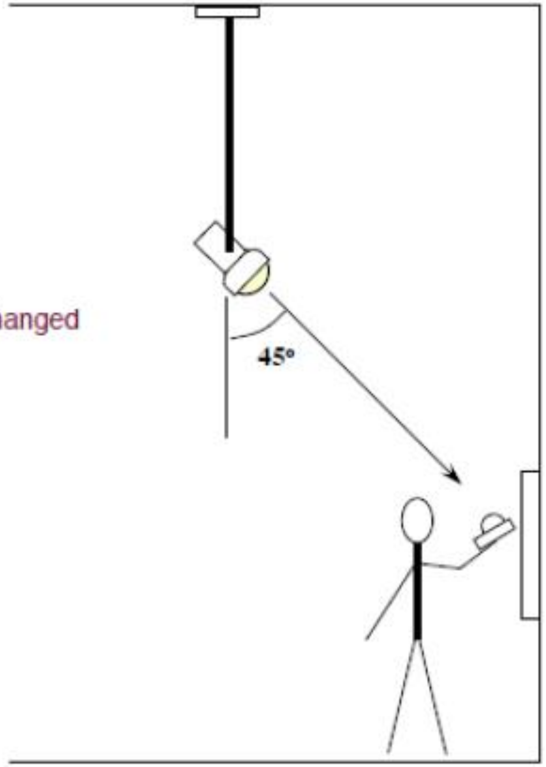
Example For the previous example, if the same ceiling-mounted spot lamp is moved to a lower position and turned towards the painting as illustrated in the following figure, what is the illuminance on the surface of the painting?

Solution:

After moving the lamb, the distance between the light bulb and the painting is reduced. The ratio of the original distance to the new distance is

$$\frac{D_1}{D_2} = \frac{1/\sin(30^\circ)}{1/\sin(45^\circ)} = 1.414$$

horizontal distance unchanged



The new direct illuminance is

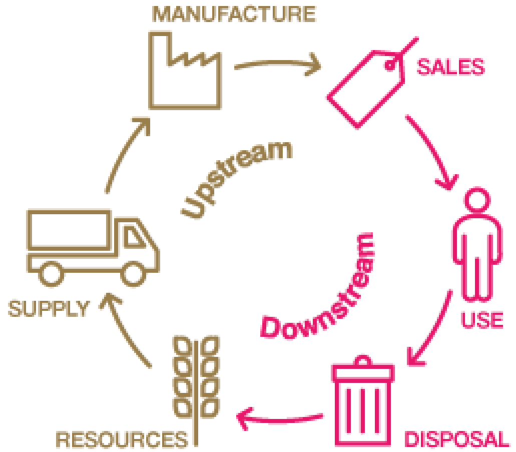
$$E_{o2} = E_{o1}\frac{D_1^{\ 2}}{D_2^{\ 2}} = 1000\text{lx} \times 1.414^2 = 2000\text{lx}$$

The illuminance on the painting is

$$E_2 = E_{o2}\cos(\theta) = 2000\cos(45^o) = 1414\ \text{lx}$$

Lighting: Environmental Implications

- Toxic material required for manufacturing
- Energy efficiency of older variants
- Environmental impacts during the end-of-life
  - Disposal of these fixtures



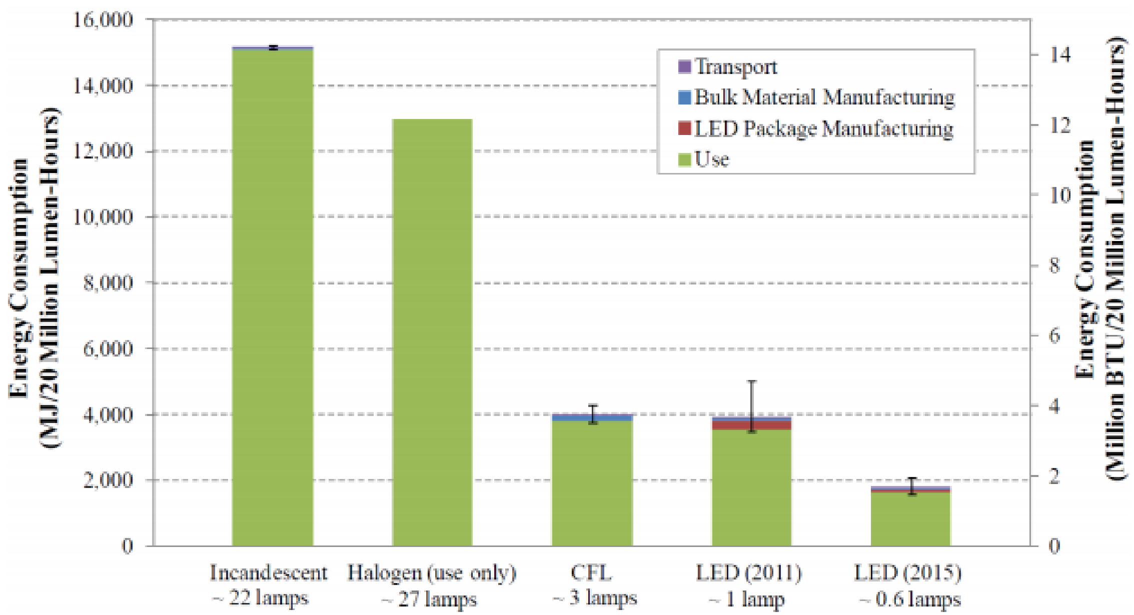


Figure 2-1. Life-Cycle Energy of Incandescent Lamps, CFLs, and LED Lamps (DOE, 2012a)

Environmental Comparison

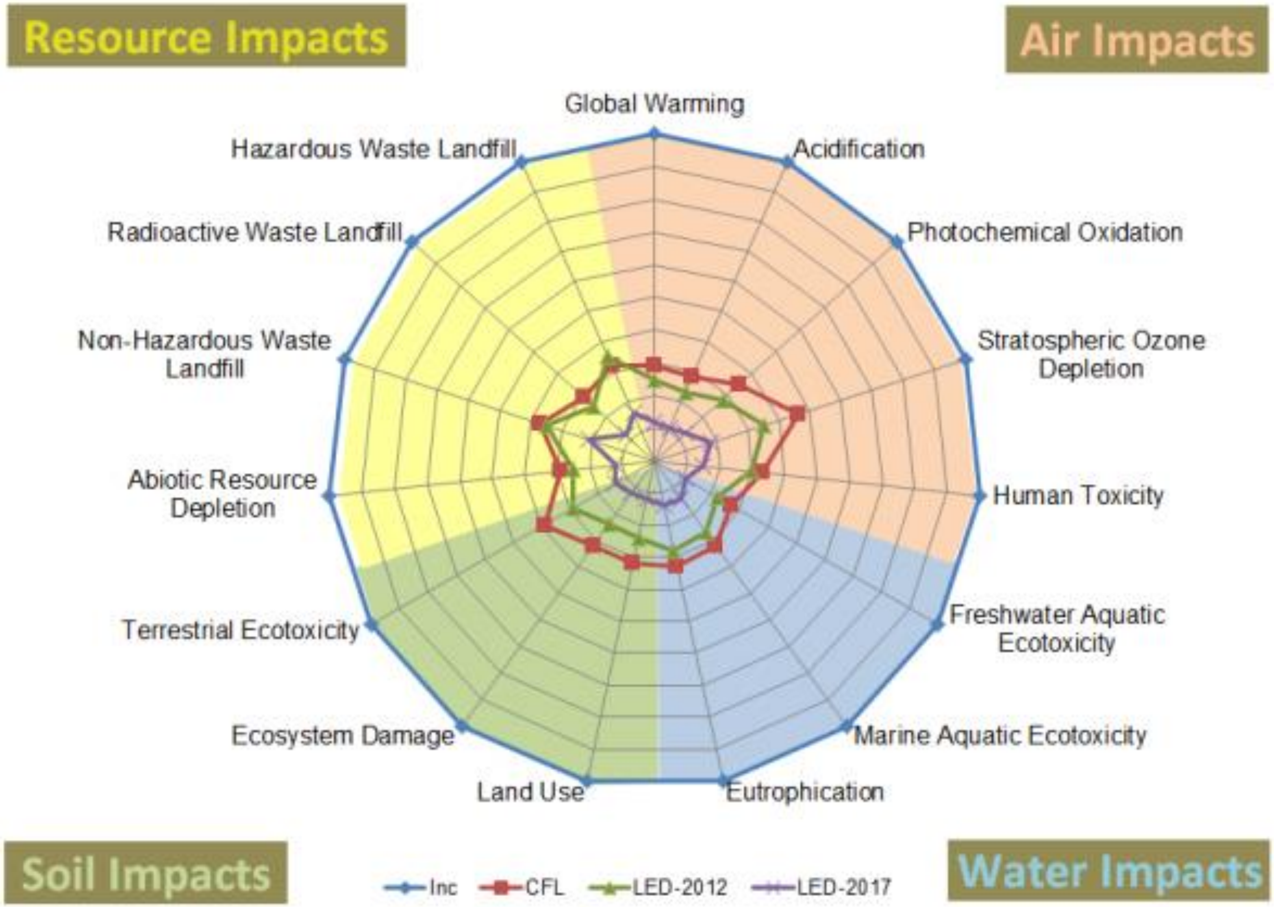
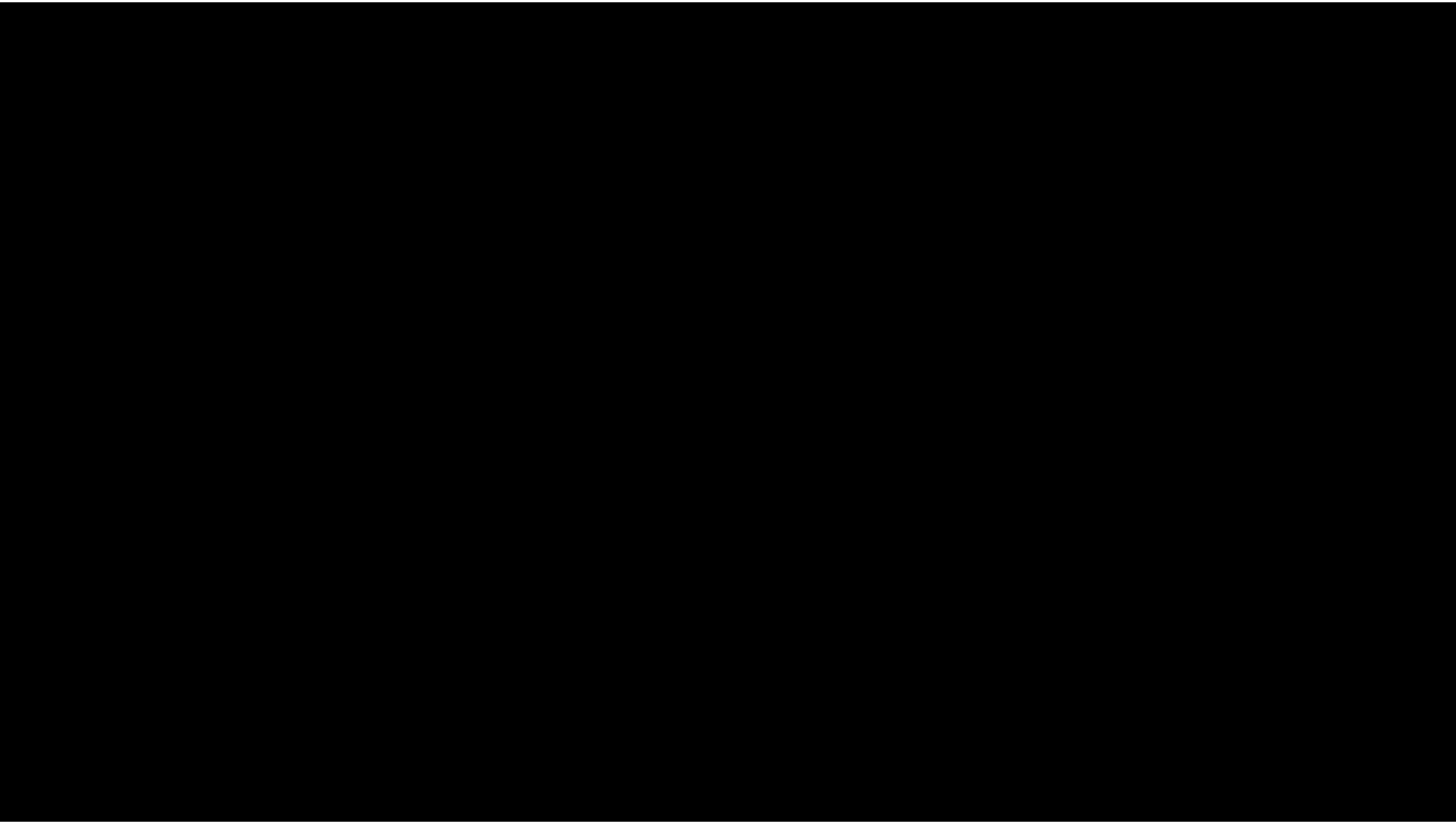


Figure 7-6. Life-Cycle Assessment Impacts of the CFL and LED Lamps Analyzed (Detail)

Light pollution in Hong Kong



Summary

- Energy and Electricity
  - Energy Efficiency
  - Power Grids

- Application: Lighting
  - Types of fixtures
  - Luminous Flux
  - Luminous Intensity
  - Illuminance

- Homework posted on Canvas and is due on 14th Feb.