EE4404 : Renewable Energy and Smart Grid

Introduction

By Dr. Sahoo SK, NUS

Learning Outcomes

- Explain the importance of renewable energy;
- Explain the working principle, characteristics and control methods of solar photovoltaic (PV) wind turbine and power generation;
- Calculate the economics of renewable energy projects;
- Understand the impact of renewable energy grid connection on power systems and master the basic principles of analysis and control methods for renewable energy power systems;
- Understand the importance of power electronics and smart grid technologies for renewable energy use.

Syllabus

- **Introduction (3 hours)**
  - Demand for electrical power; Environmental aspects of electrical energy generation;
- **Renewable Energy Sources (15 hours)**
  - Distributed versus traditional power systems; Distributed generation technologies solar thermal and solar PV, biofuels, fuel cell, hydroelectric generation, energy storage
  - Wind turbine types and characteristics, wind turbine generator and control, wind turbine performance and environmental impacts
- **Economics of distributed generation (3 hours)**
  - Utility rate structure, energy economics, energy conservation, combined heat and power, integrated resource planning and demand side management
- **System integration issues and Smart Grid (12 hours)**
  - Overview of energy systems, secure reliable and economic operation, issues with renewable energy sources. Power quality and reliability in operation and planning

Assessment

The module assessment contains the following:

1. Midterm Test (30%)
2. Group Project (30%)
3. Final Examination (40%)

Group research Project

- Each group will have four/five students
  - Form the groups on your own
- Each group will prepare a 15 min presentation (power point and oral presentation) on the topic assigned to the group.
- Each person in the team should contribute towards the presentation.

Importance of Energy

- Energy is defined as the capacity to do any activity in nature.
- Over the millennia, human beings have been improving their ability to harness energy from nature to improve their lifestyles.
- Early human beings burnt fuelwood to give them warmth, protection, and for cooking food.
- In the 19th century, steam engines were developed to convert heat energy into motion which in turn led to the industrial revolution in Europe.
- In the late 1850s, the internal combustion engine was invented which is used in the majority of vehicles today.
- In the late 1800s, Thomas Alva Edison developed an electric light bulb.

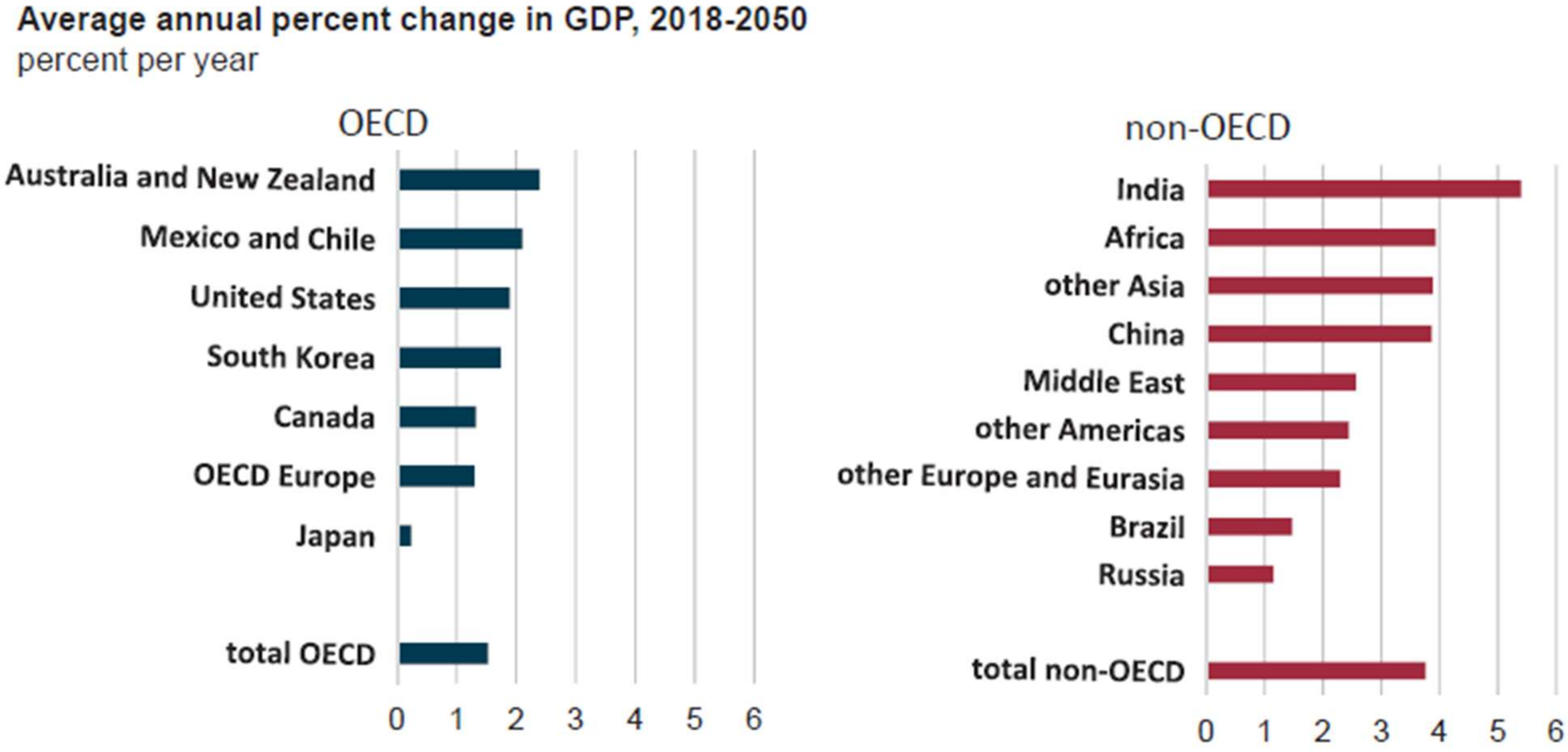
Scales of Energy Use

Use	Watt
Cell phone	2
Laptop computer	10
Human body (2000 calorie diet)	100
Hair dryer	1,500
Automobile	130,000
Wind turbine	2,000,000 (2 MW)
757 Jet engine	5,000,000 (5 MW)
Large power plants	1000,000,000 (1000 MW= 1GW)
Global Energy use	15 TW (15,000 GW)

Per capita GDP grows rapidly

- Gross domestic product (GDP) per person is an indicator of a country's standard of living.
- GDP growth projection between 2018 and 2050, in part of the Organization of Economic Cooperation and Development (OECD) is 1.5% per year whereas for non-OECD countries, it is 3.8% per year on average.
- Since 1990, non-OECD countries have led world economic growth, accompanied by strong growth in energy demand in those countries.
- The following slides show some important statistics on energy use projection, as given in annual report by USA Energy Information Administration

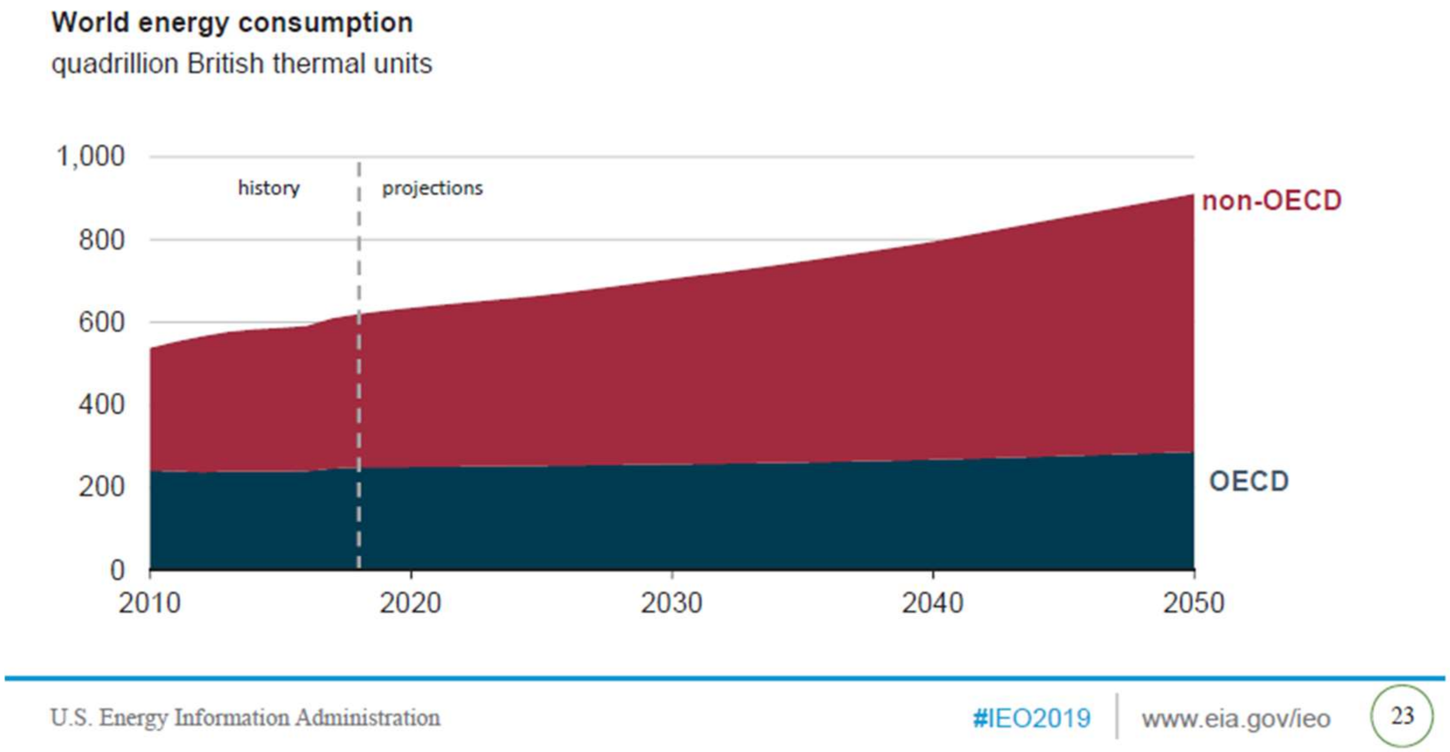
Economic growth varies widely across non-OECD regions in the Reference case—



Highest rates occurring in non-OECD Asia and Africa

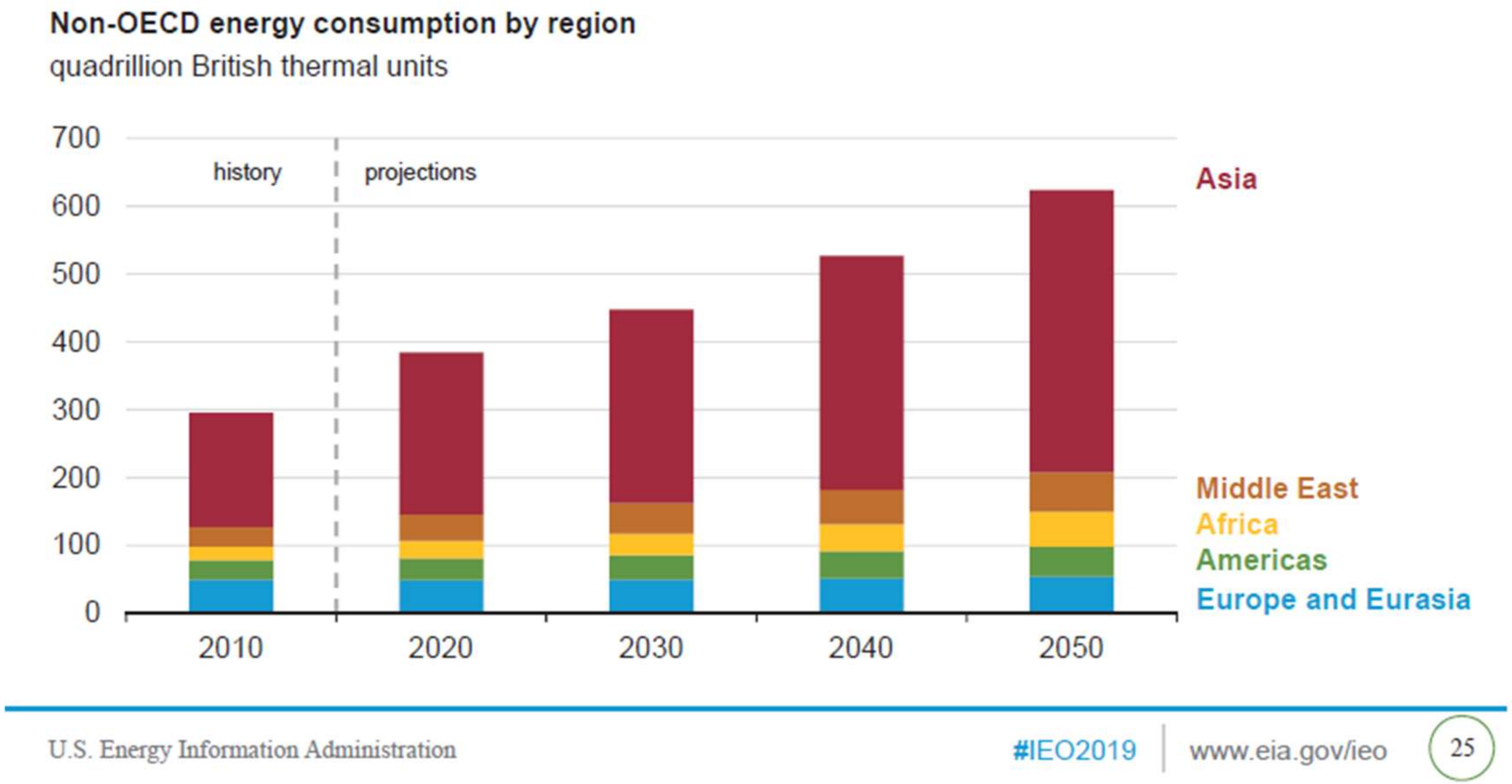
- Both OECD and non-OECD regions are diverse, with wide spreads in economic growth.
- In the non-OECD regions, India, China, other Asia, and Africa grow at an average rate of nearly 4% or higher. These regions were home to about two-thirds of the world's population in 2018.
- Japan (OECD) and Russia (non-OECD) are the slowest-growing economies, partly as a result of declining populations and aging workforces.
- The projected GDP growth in China slows considerably compared with its growth from 2000 to 2010, when GDP increased by an average of about 10% per yearslowed

World energy consumption rises nearly 50% between 2018 and 2050



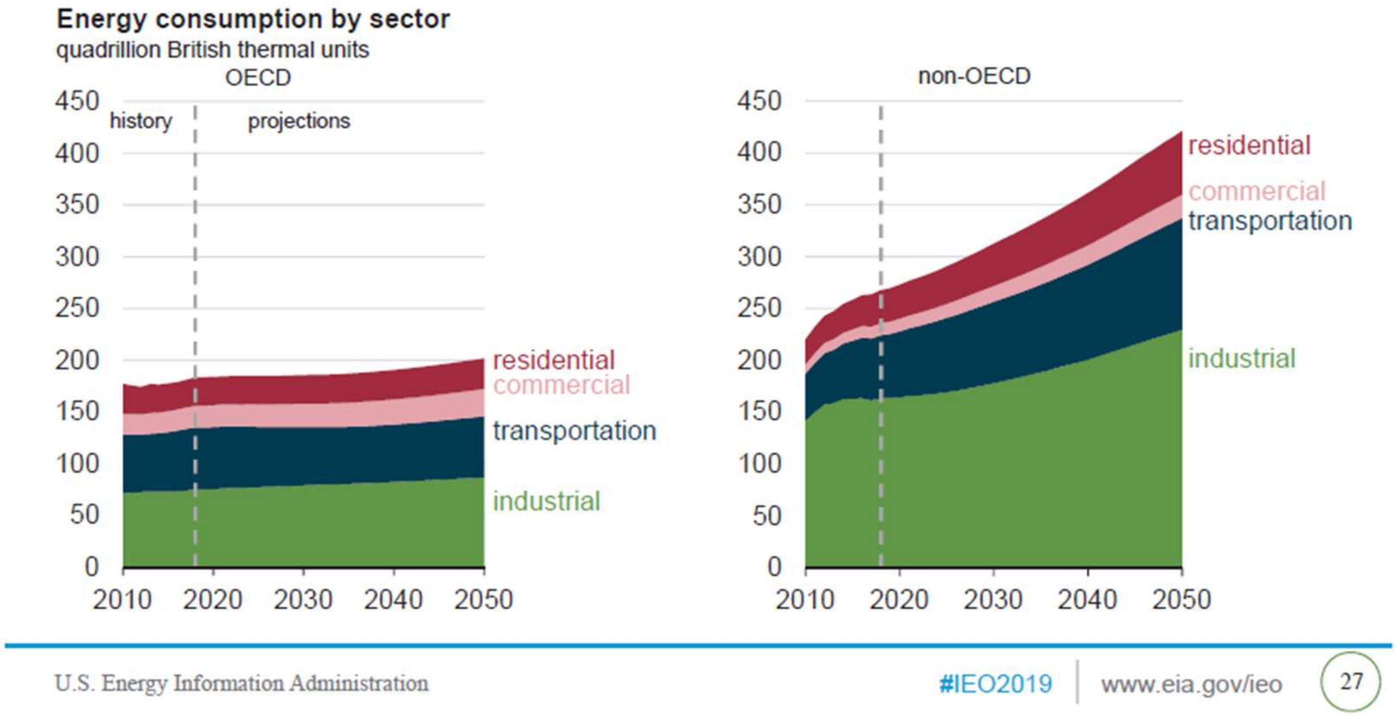
Energy consumption in non-OECD countries increases nearly 70% between 2018 and 2050 in contrast to a 15% increase in OECD countries.

Asia accounts for most of the increase in energy use



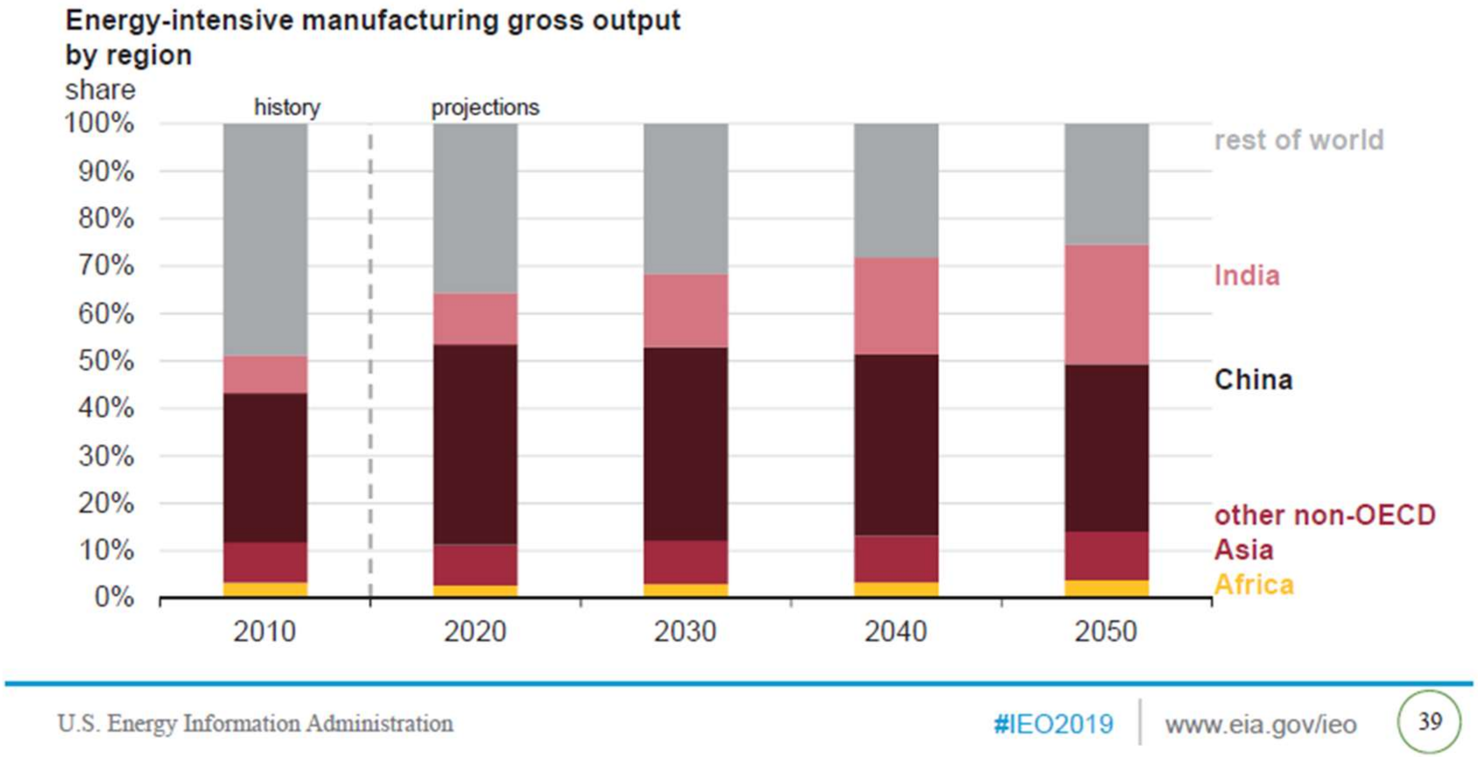
More than half of the projected increase in global energy consumption occurs in non-OECD Asian countries, a group that includes China and India.

The industrial sector is the largest consumer of energy



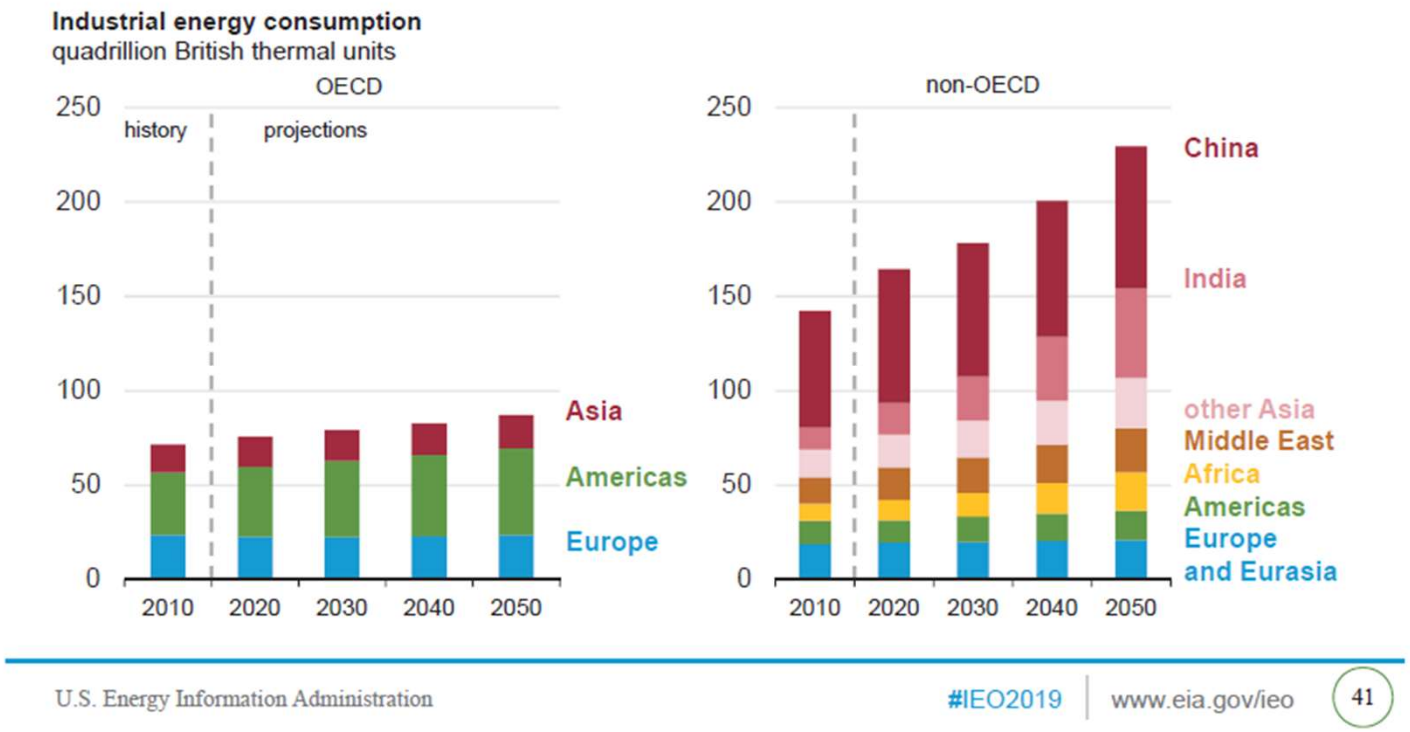
- The industrial sector accounts for more than 50% of end-use energy consumption.
- World industrial sector energy use is projected to increase by more than 30% from 2018 to 2050.

Energy-intensive manufacturing shifting towards non- OECD Asia



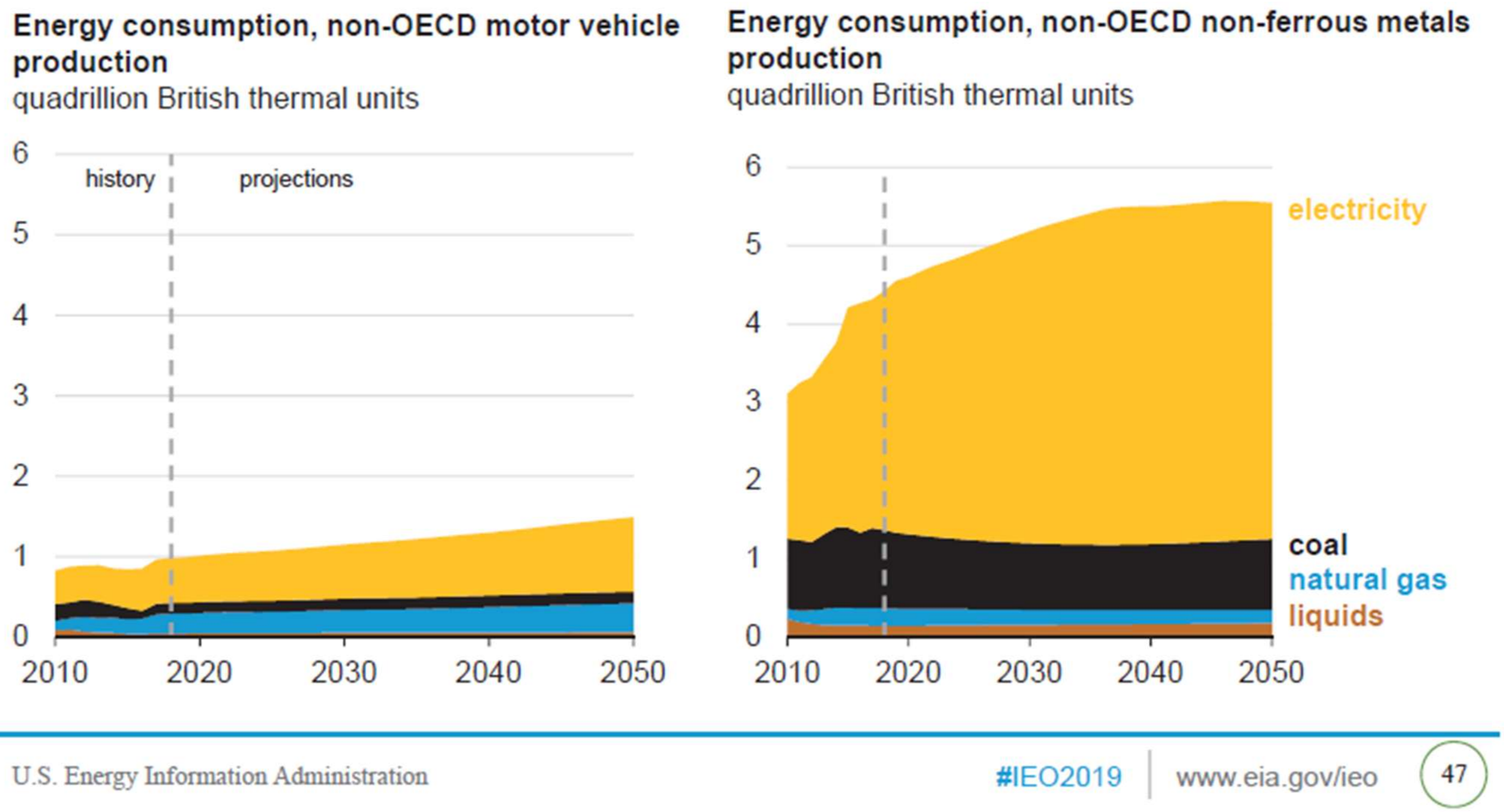
India and China combined account for more than half of global output energy-intensive manufacturing, which includes the production of iron and steel, food, paper, refined oil products, non-metallic minerals, aluminum, and basic chemicals.

Industrial energy consumption

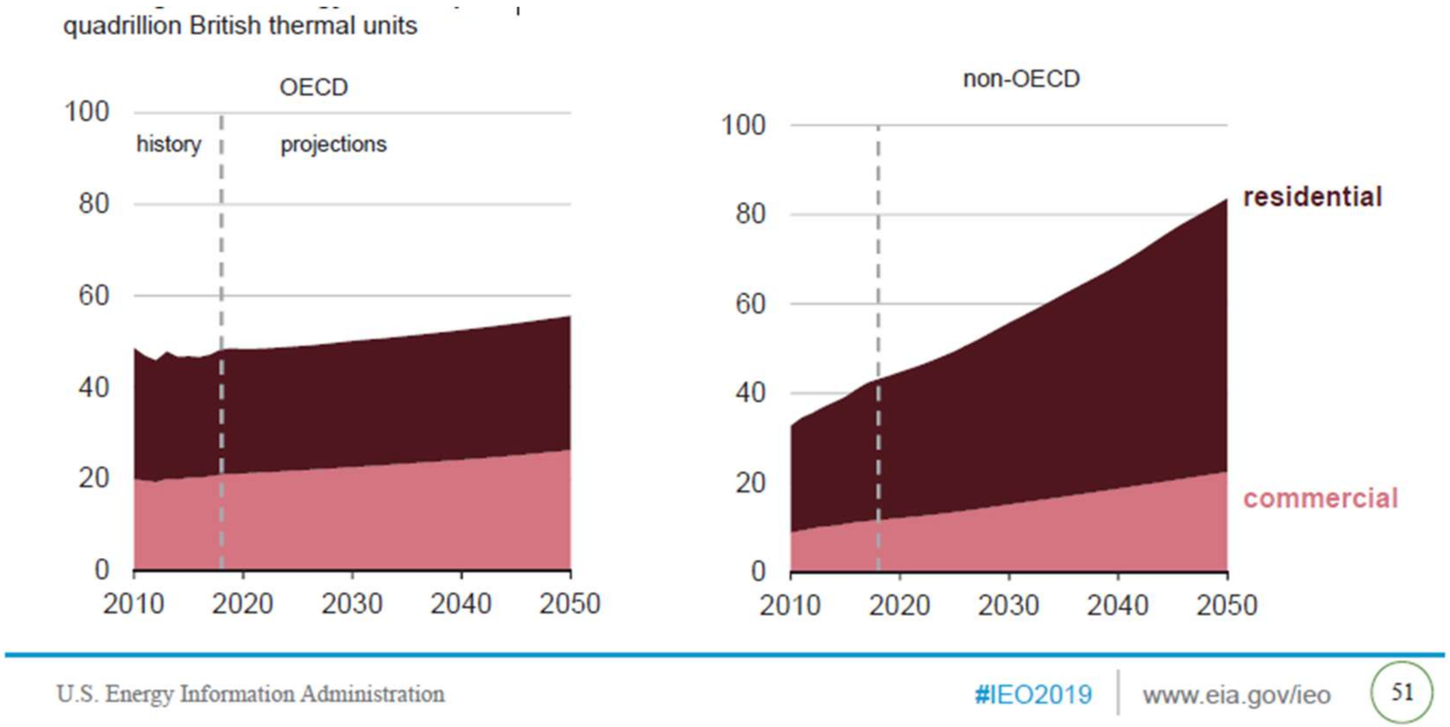


In 2018, China consumed 29% of the world's industrial energy, and although its energy consumption continues to increase modestly throughout the projection period, its share decreases to 24% by 2050.

Non-OECD economies increase industrial electricity use

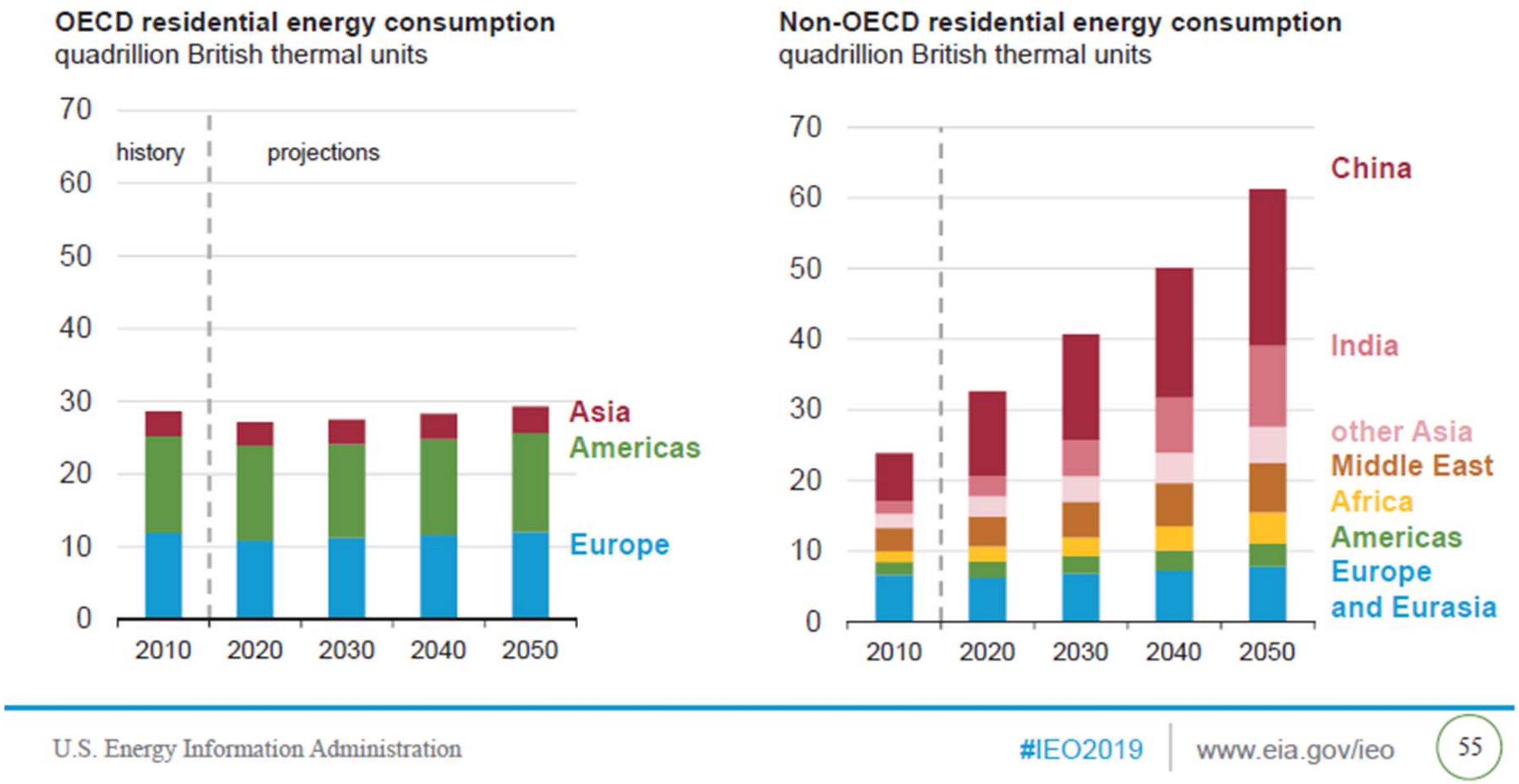


Building sector energy consumption



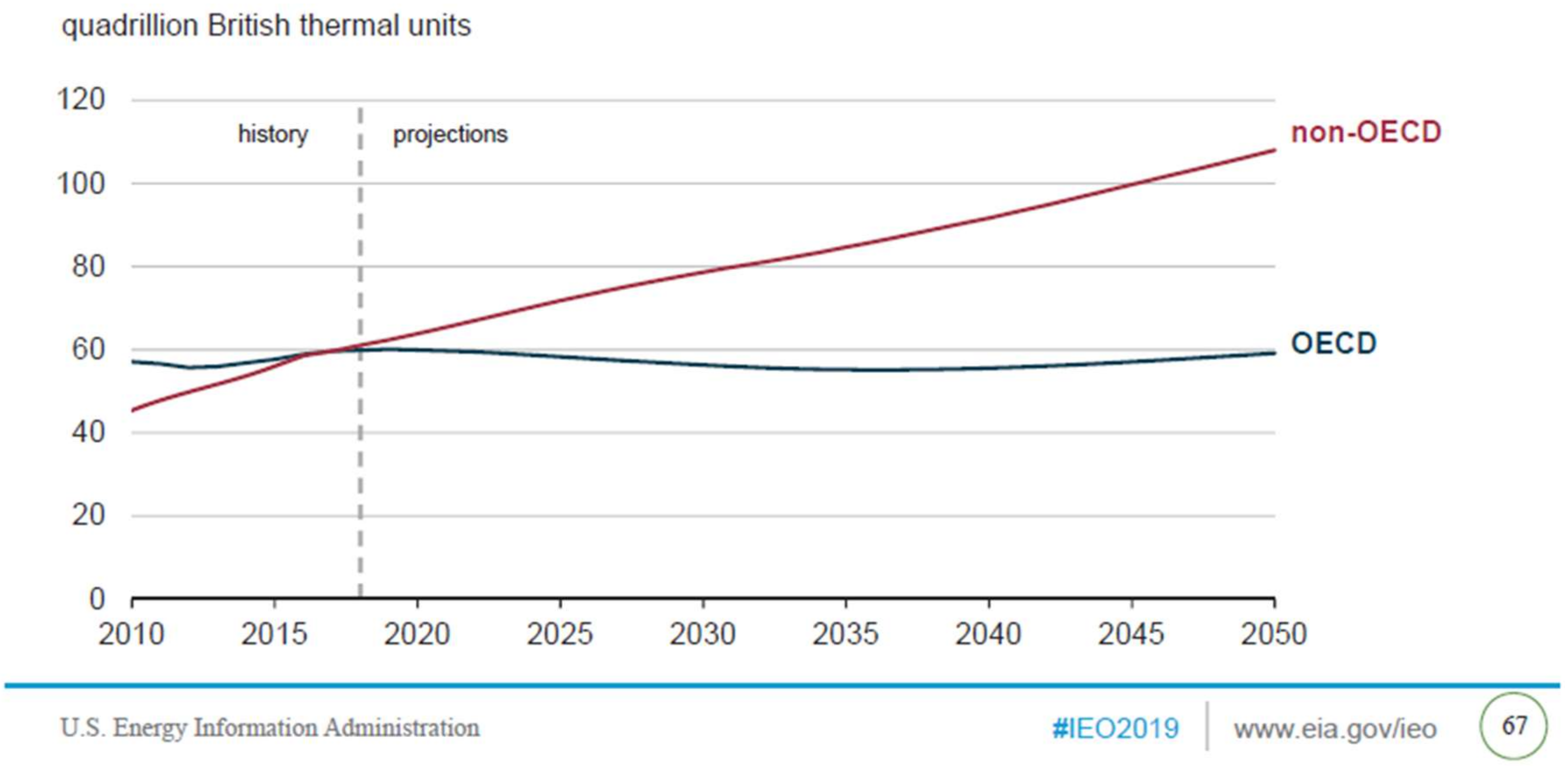
As population and incomes grow, it leads to urbanization and usage of electricity for residential and commercial buildings.

Residential energy consumption



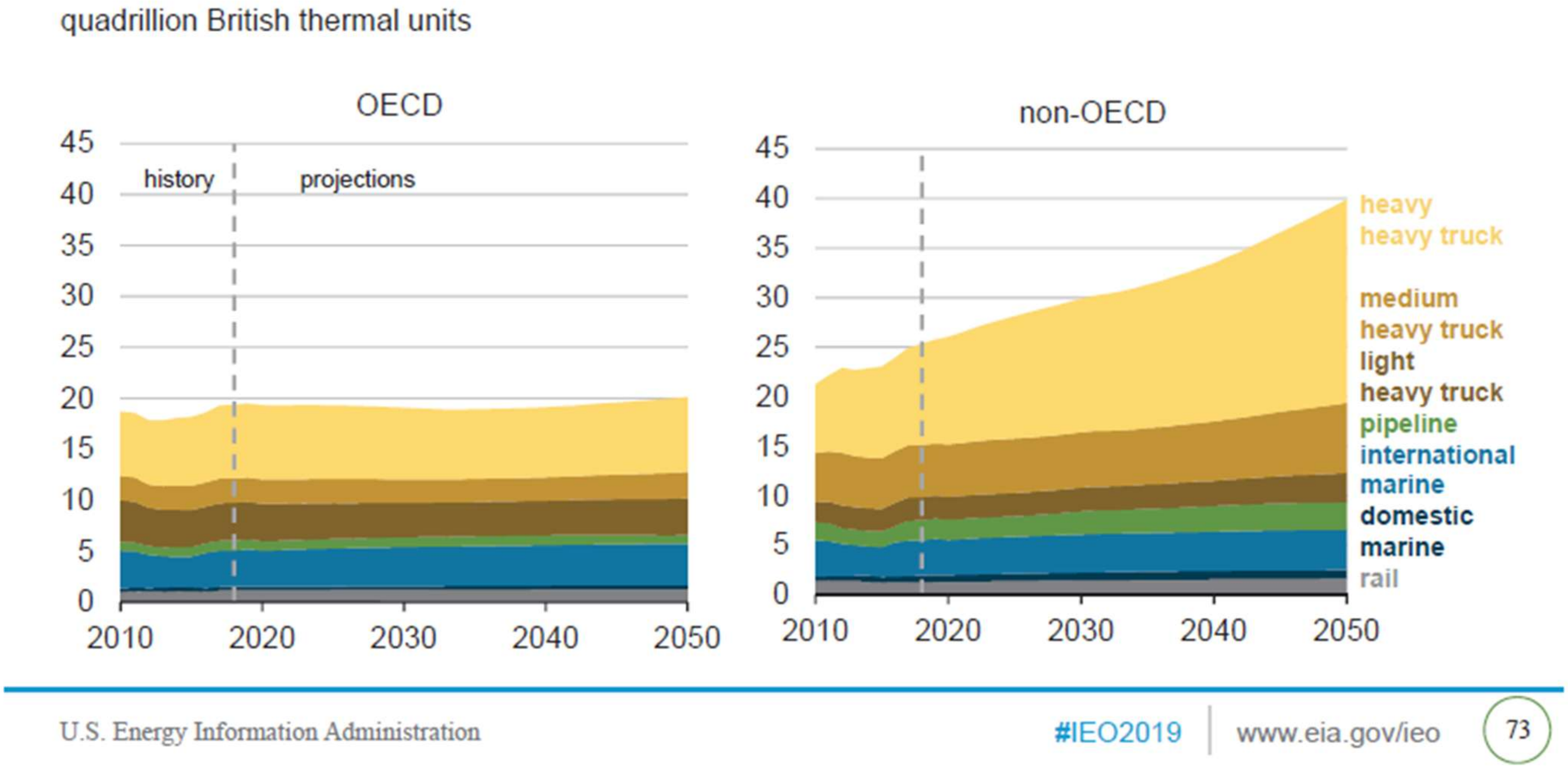
As standards of living increase and as demand for lighting and energy-using appliances and equipment increases.

Transportation energy consumption



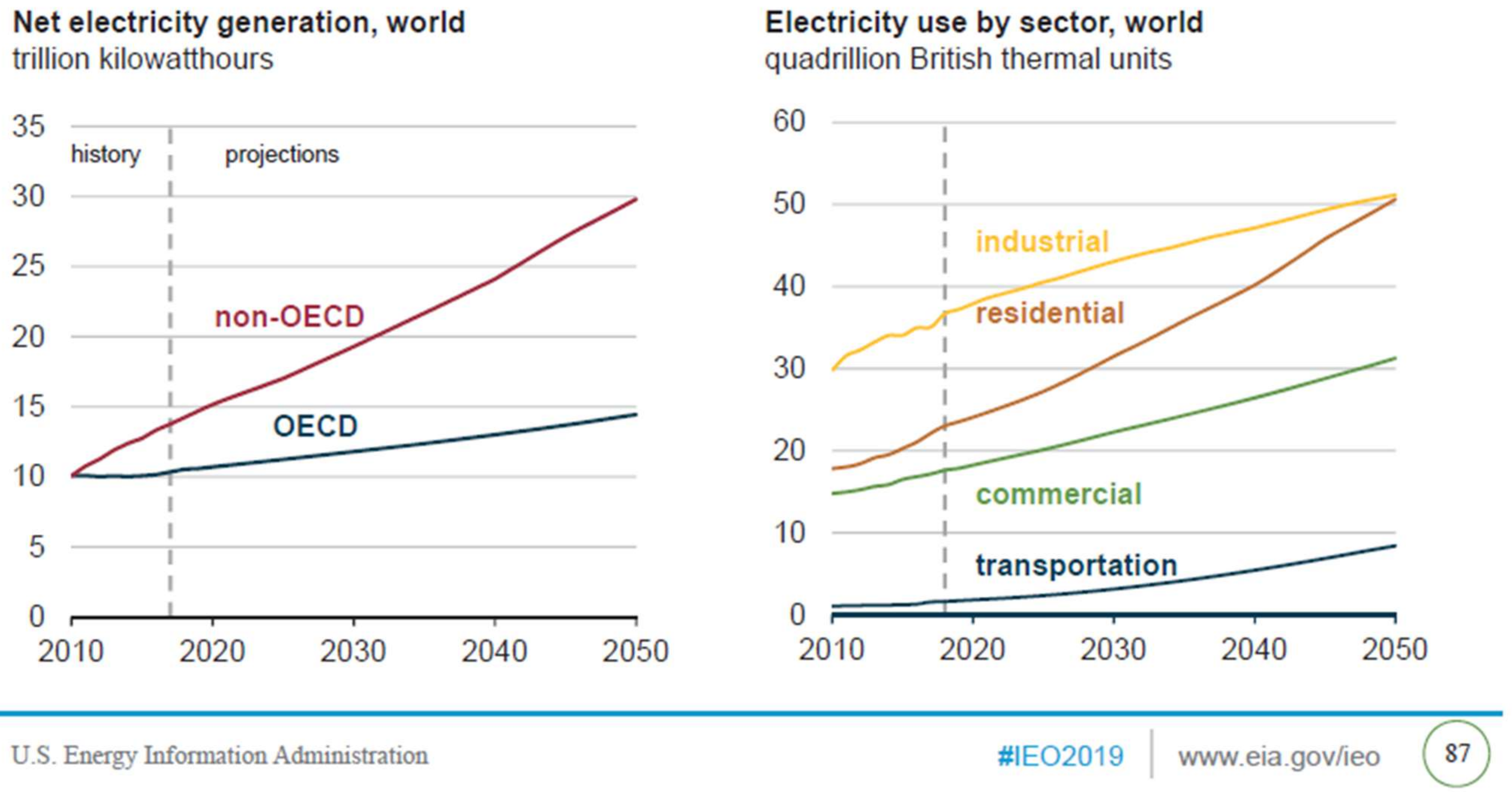
Transportation energy consumption in non-OECD countries has exceeded that in OECD countries since 2017.

Freight transportation energy



Increases in industrial output lead to growing energy use in all modes of freight transport

Projected growth rate in net electricity generation



A Brief History Of Electric Power Systems

World's first power system – DC system

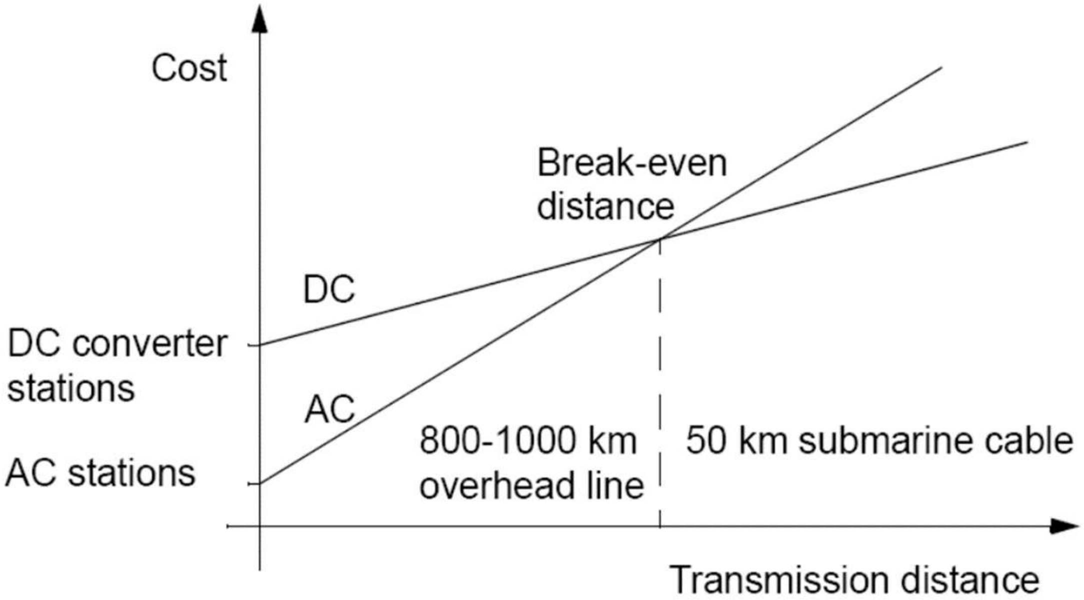
- Edison Electric Illuminating Company of New York inaugurated the Pearl Street Station in 1881.
- The station had a capacity of four 250-hp boilers supplying steam to six engine-dynamo sets.
- Edison's system used a 110-V dc underground distribution network with copper conductors insulated with a jute wrapping.
- In 1882, the first water wheel-driven generator was installed in Appleton, Wisconsin.
- The low voltage of the circuits limited the service area of a central station, and consequently, central stations proliferated throughout metropolitan areas.

AC System

- The invention of the transformer, made AC systems possible.
- The first practical ac distribution system in the U.S. was installed by W. Stanley at Great Barrington, Massachusetts, in 1866 for Westinghouse.
- Early AC distribution utilized 1000-V overhead lines.
- The Nikola Tesla invention of the induction motor in 1888 helped replace DC motors and hastened the advance in use of ac systems.
- The first American single-phase AC system was installed in Oregon in 1889.
- Southern California Edison Company established the first three-phase 2.3 kV system in 1893.

AC vs DC system

- Due to advantage of supplying power efficiently over large area, AC system was adopted for bulk power.
- These days, with power electronic converters, DC also can be stepped-up and HVDC systems are becoming popular for power transfer over very long distance.



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Cosolidation

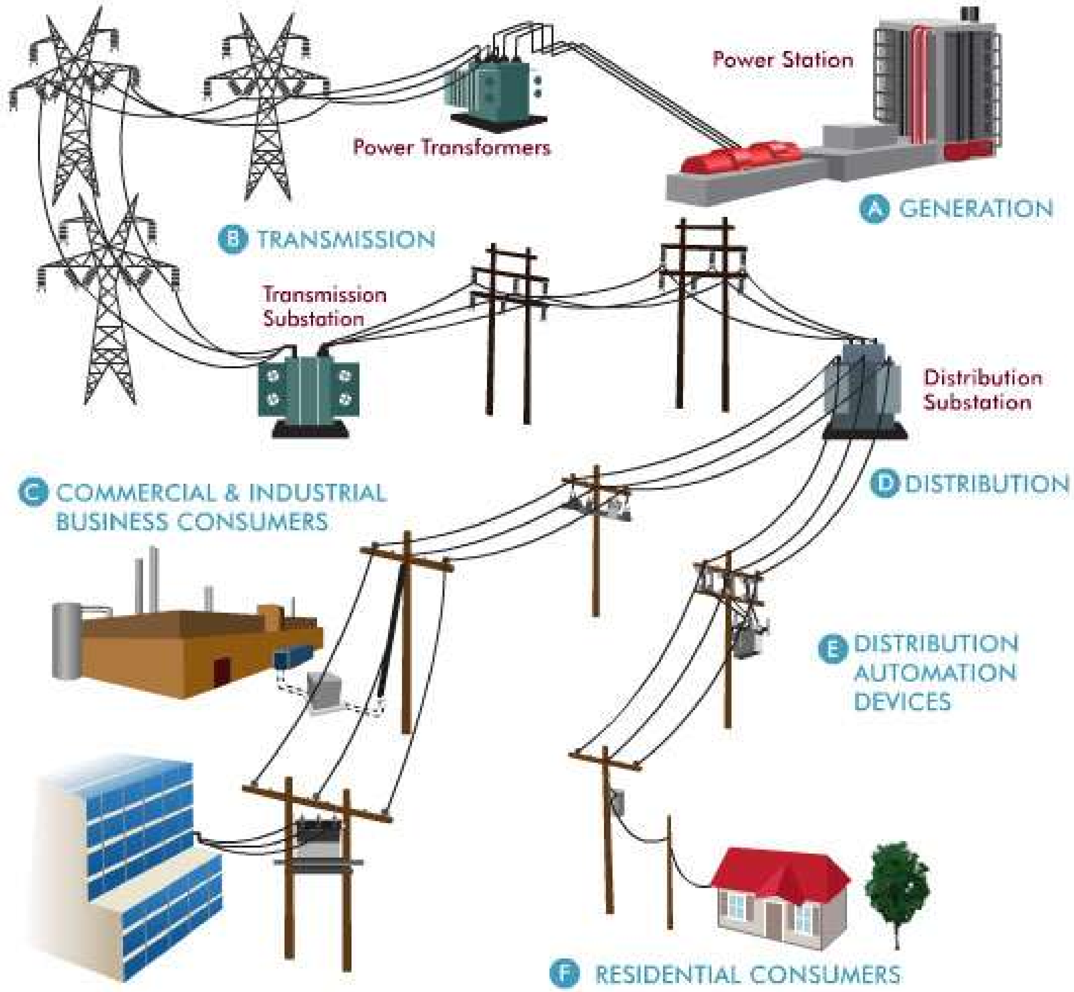
- Consolidation of electric companies enables the realization of
  - economies of scale in generating facilities,
  - the introduction of equipment standardization, and
  - the utilization of the load diversity between areas.

- Three Gorges Dam in China holds the title of the world's largest power station in terms of installed capacity. The Three Gorges Dam has a total installed capacity of approximately 22.5 gigawatts (GW). It is a hydroelectric power station located on the Yangtze River in Hubei Province, China.

Origin of the grid

- The growth in size of power plants and in the higher voltage equipment was accompanied by interconnections of the generating facilities.
- These interconnections
    - decreased the probability of service interruptions,
    - made the utilization of the most economical units possible, and
    - decreased the total reserve capacity required to meet equipment-forced outages.
- This was accompanied by use of sophisticated analysis tools such as the network analyzer.
- Central control of the interconnected systems was introduced for reasons of economy and safety.

Generation, Transmission and Distribution



- Most of bulk generation, transmission and distribution of electricity is three-phase.
- Only small residential loads are single phase.

Power transfer over very long distance

- Extra higher voltage (EHV) has become dominant in electric power transmission over great distances.
- Today, transmission voltages of 230 kV, 287 kV, 345 kV, 500 kV, 735 kV, and 765 kV are commonplace, with the first 1100-kV line already energized in the early 1990s.
- The trend is motivated by economy of scale due to
  - the higher transmission capacities possible,
  - more efficient use of right-of-way,
  - lower transmission losses, and
  - reduced environmental impact.

HVDC line

- In 1954, the Swedish State Power Board energized the 60-mile, 100-kV dc submarine cable with capacity of 20 MW, which is world's first high-voltage direct current (HVDC) link.
- Currently, numerous installations HVDC lines are in operation around the world.
    - Changji-Guquan UHVDC (China): 1100 kV, capacity of 12 GW and spans over 3320 km.
    - Xiangjiaba–Shanghai HVDC Line (China): 800kV, capacity of 6400 MW and stretches over 2015 km.
    - Raigarh-Pugalur HVDC System(India): 800 kV, 6 GW, 1830 km
    - Baltic Cable (Germany/Sweden): 450kV, capacity of 600 MW, 250 km.
    - NorNed (Norway/Netherlands): 450kV, capacity of 700 MW, 580 km.

Electricity Generation

- The backbone of any electric power system is a number of generating stations operating in synchronism.
- At each station there may be several synchronous generators operating in parallel.
- Synchronous machines represent the largest single-unit electric machine in production.
- Generators with power ratings of several hundred to over a thousand megavoltamperes (MVA) are fairly common in many utility systems.
- A synchronous machine provides a reliable and efficient means for energy conversion.

How Electricity is Generated?

- Electricity is generated from other forms of energy to electricity through the energy conversion process.
- The most common conversion process to generate electricity is to convert mechanical energy using a generator.
- This process is called “Electromagnetic induction”.
- The mechanical energy comes from turning the turbine (prime mover).

Prime Mover-Turbine → Generator → Electricity

Conversion efficiencies

Conversion	Type	Efficiencies
Natural Gas Furnace	Chemical → Heat	90-96%
Internal combustion engine	Chemical → Mechanical	15-25%
Power Plant Boilers	Chemical → Heat	90-98%
Steam Turbines	Heat → Mechanical	40-45%
Electricity Generator	Mechanical → Electricity	98-99%
Gas Turbines	Chemical → Mechanical	35-40%
Hydro	Grav. Potential → Mechanical	60-90%
Geothermal	Thermal→ Mech→ Electricity	6-13%
Wind	Kinetic → Mech→ Electricity	30-60%
Photovoltaic Cells	Radiation → Electricity	10-15%
Ocean Thermal	Thermal→ Mech→ Electricity	1-3%

Source: Sustainable Energy

Sustainable Energy – Fall 2010 – Conversion 17

Humanity's Main Energy Source: Chemical reactions

Fuel combustion

- $CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$ – natural gas
- $C_8H_{12} + 11\ O_2 = 8\ CO_2 + 6\ H_2O$ – gasoline
- $C_6H_{12}O_6 + 6\ O_2 = 6\ CO_2 + 6\ H_2O$ – cellulosic biomass

Hydrogen production

- $CH_4 + H_2O = CO + 3H_2$ – steam reforming of methane
- $CO + H_2O = CO_2 + H_2$ – water gas shift reaction

Hydrogen Fuel cell

- $H_2 + ½\ O_2 = H_2O$ + electricity + heat

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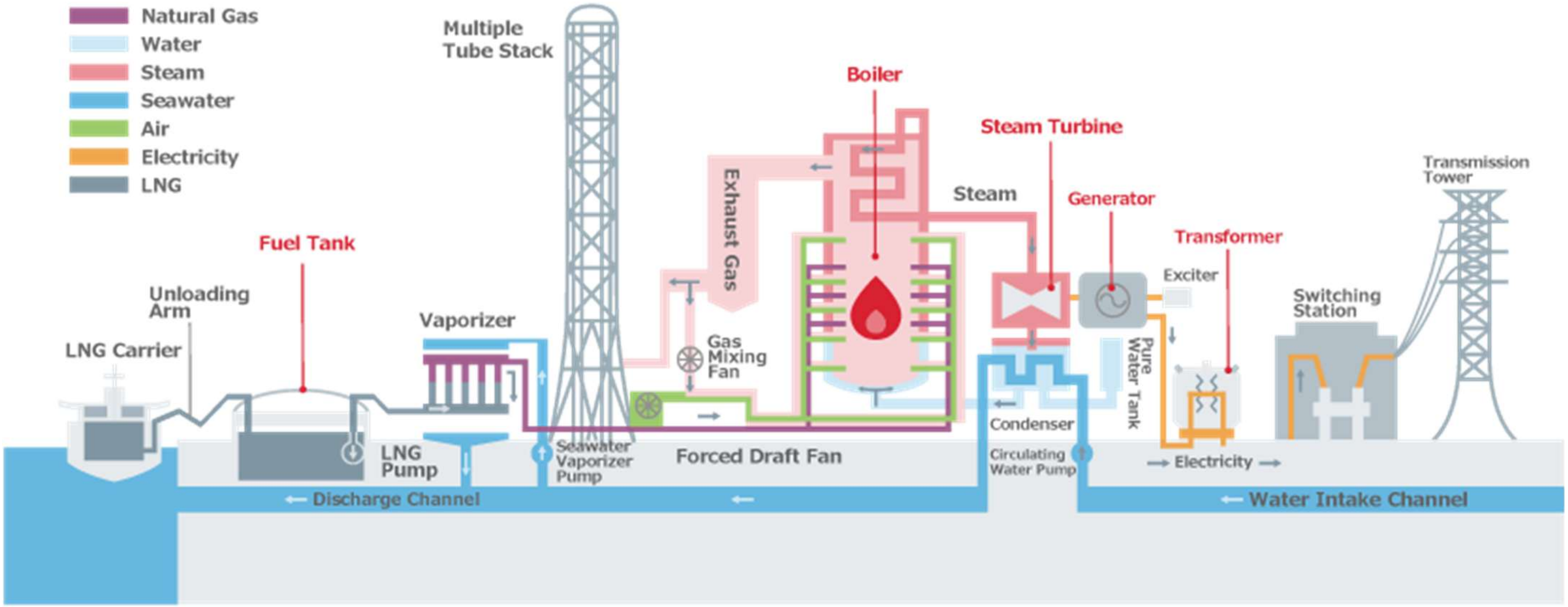
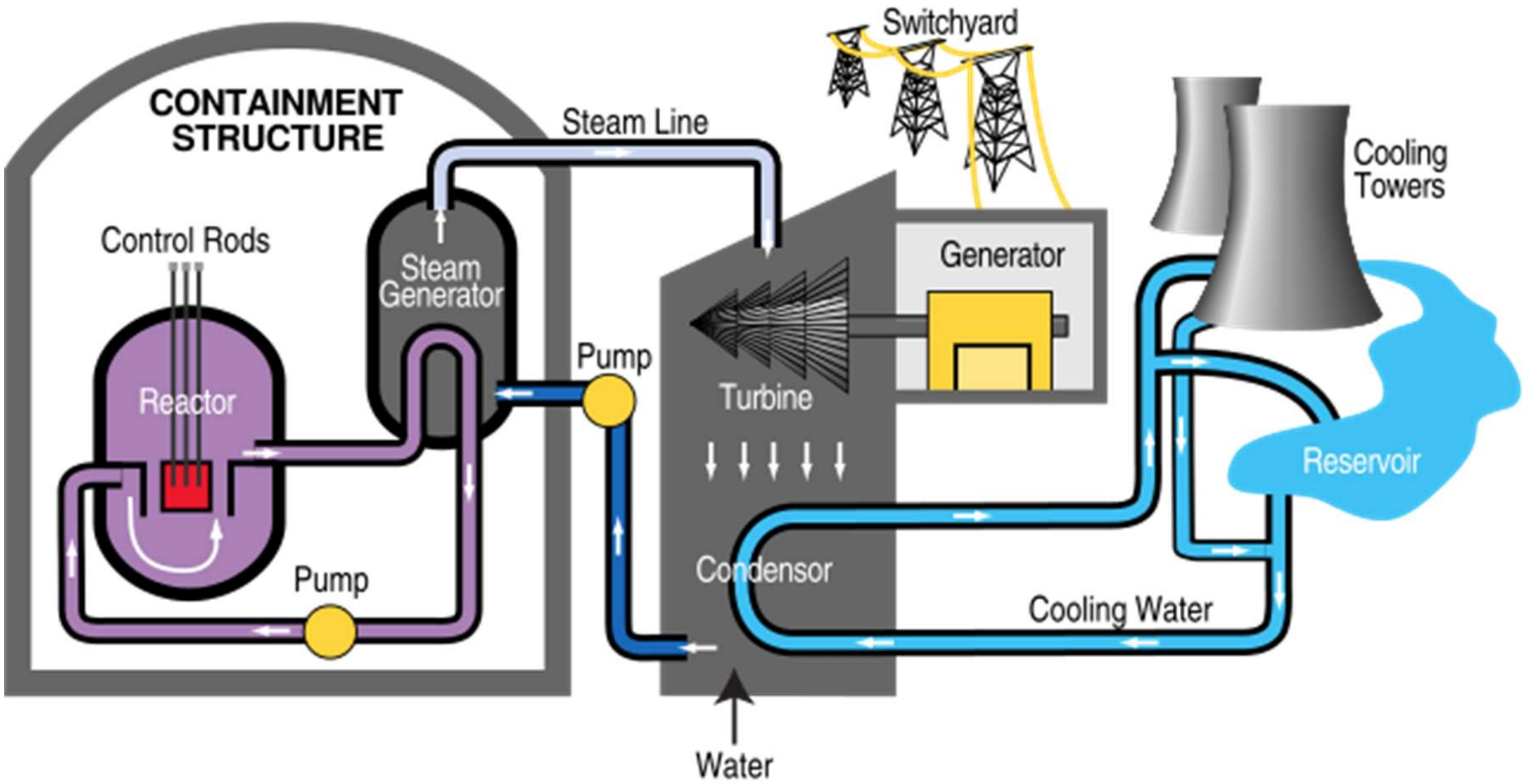
An Example of LNG fired Thermal Power Plant



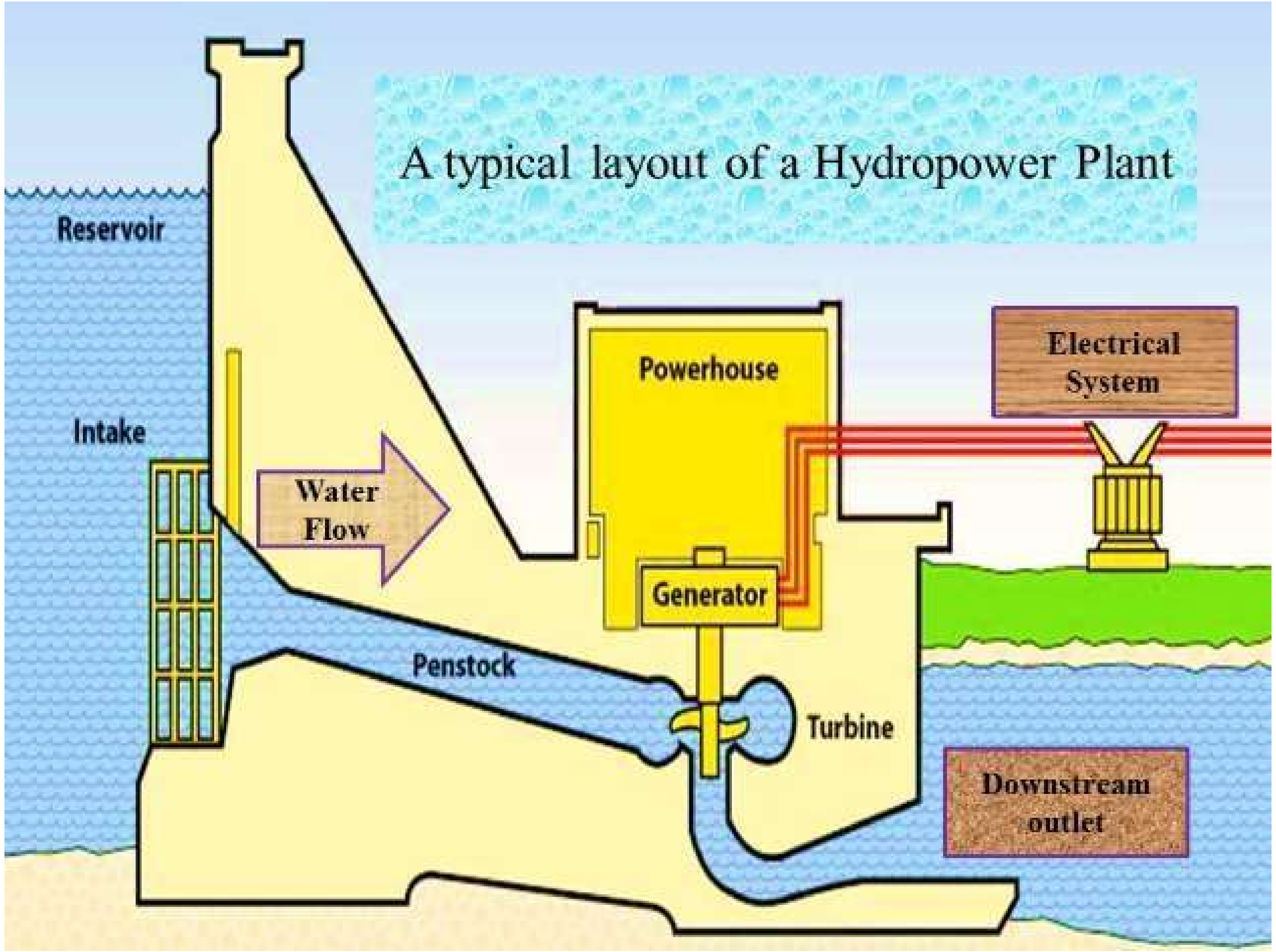
Source: https://www.jera.co.jp/english/business/thermal-power/type

Nuclear Power Plant

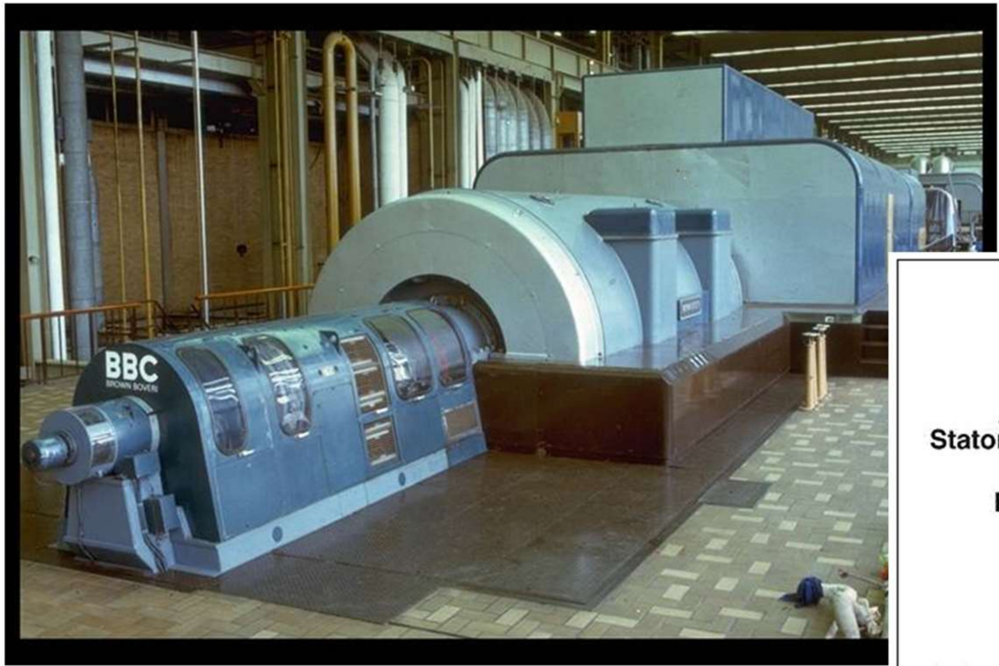


Source: https://en.wikipedia.org/wiki/File:PWR_nuclear_power_plant_diagram.svg

Example of a hydroelectric plant

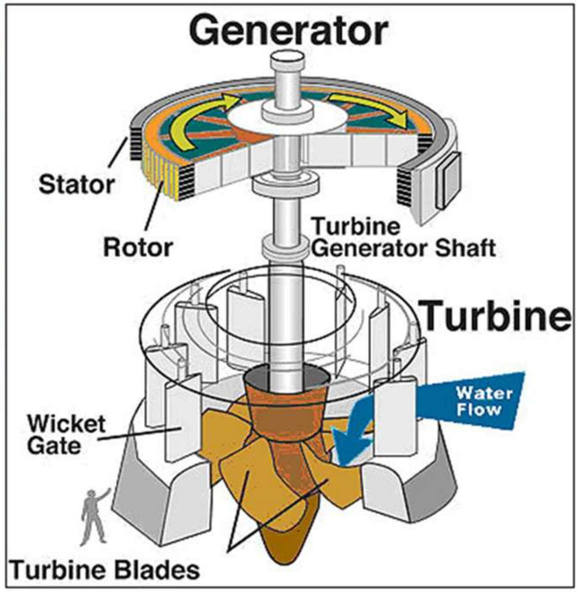


A Generator



Source: Electrical Power System Essentials

Source: http://archive.powerauthority.on.ca/Page.asp?PageID=924&SiteNodeID=233



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Transmission System

- Electric energy is produced at electric power generating stations and transported over high-voltage transmission lines to utilization points.
- The trend toward using higher voltages is motivated by the increased line capacity while reducing line losses per unit of power transmitted.
- The reduction in losses is significant and is an important aspect of energy conservation.
- Better use of land is a benefit of the larger transmission capacity of the lines.

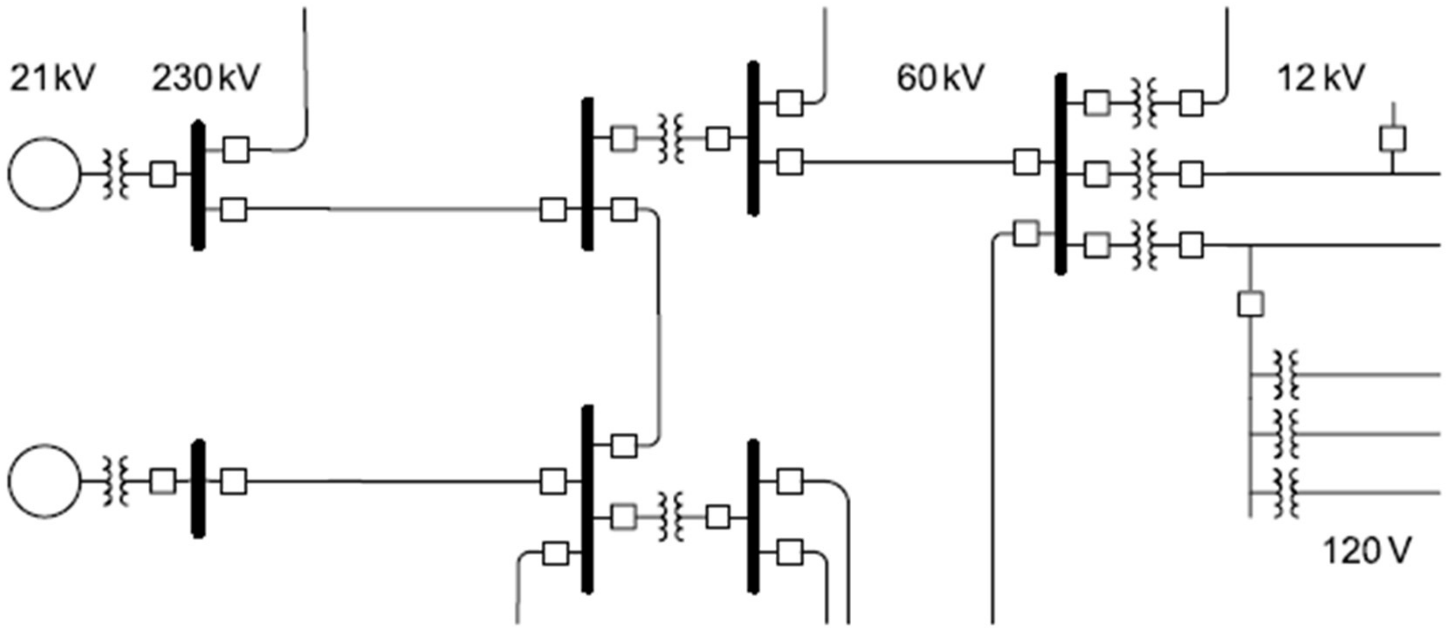
Distribution System

- Power delivery systems are divided into two general tiers: a transmission system that spans long distances at high voltages on the order of hundreds of kilovolts (kV), usually between 60 and 500 kV, and a more local distribution system at intermediate voltages in the low tens of kV.
- The latter is more specifically referred to as primary distribution, in contrast to the secondary distribution system, which consists of the wires that directly connect most domestic and small commercial customers, at voltages in the 100-200 V range.

Transmission and Distribution System

- Larger commercial and industrial customers often receive their service at higher voltages, connected directly to the primary distribution system.
- The transmission system is also further subdivided into sub-transmission, operated in the neighborhood of 100 kV, and longer-distance transmission at several hundred kV.
- Collectively, the entire power delivery system is referred to as the transmission and distribution (T&D) system.

One-line diagram showing basic power system structure



Topology

- An important characteristic of transmission and distribution systems is their topology, or how their lines are connected.
- In a radial configuration lines branch out sequentially and power flows strictly in one direction
- In a network, any two points are usually connected by more than one path, meaning that some lines form loops within the system

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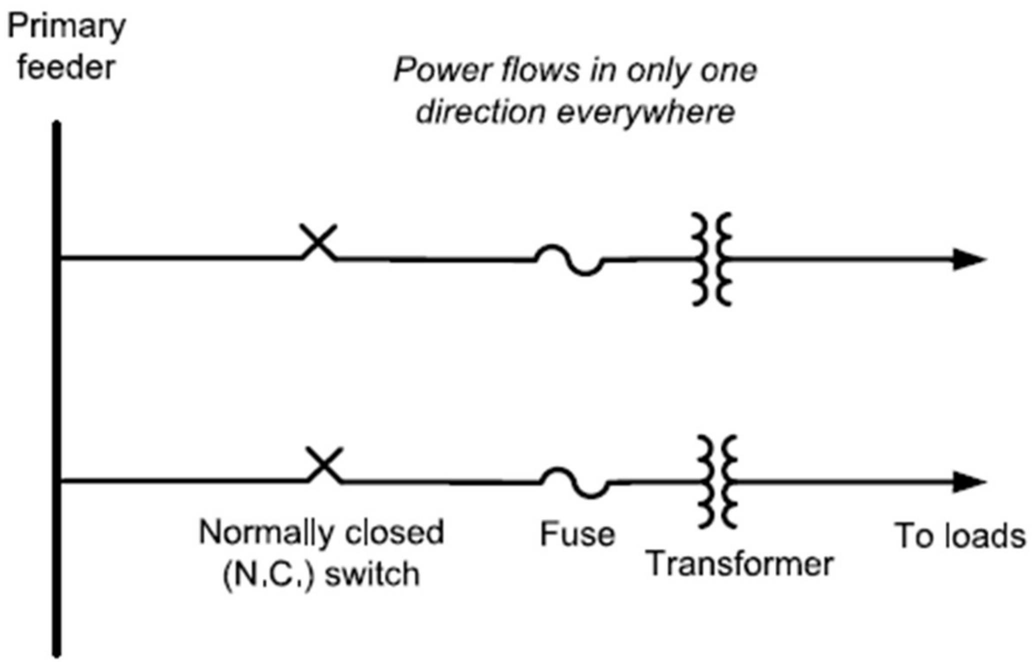
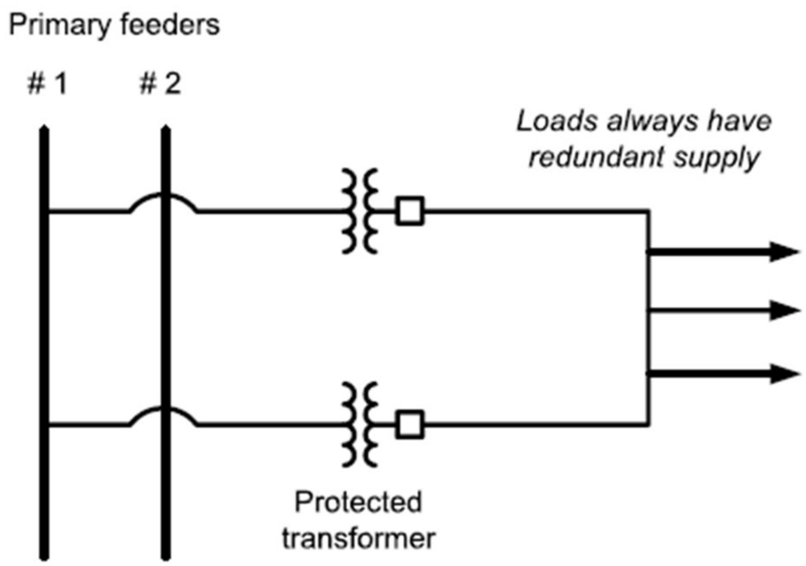
Radial distribution system



- In a radial system, circuit breakers can readily be located so as to isolate a fault—for example, a downed line—immediately upstream of the problem, interrupting service to all downstream components.

Network



- A networked system is generally more reliable because of the built-in redundancy: if one line fails, there is another path for the power to flow.

- Networks are often used in downtown metropolitan areas where reliability is considered extremely important, and where the load density justifies the capital expense.

Loads

- In the context of electric circuits, the term load refers to any device in which power is being dissipated (i.e., consumed).
- From the circuit perspective, a load is defined by its impedance, which comprises a resistance and a reactance.
- The impedance of an individual device may be fixed, as in the case of a simple light bulb, or it may vary, for example, if an appliance has several operating settings

Types of Loads

- Resistive loads are those consisting basically of a heated conductor, whether a heating element in a toaster oven or a glowing filament in a light bulb.
- Inductive loads are the most common and include all types of motors, fluorescent lights, and transformers like those used in power supplies for lowervoltage appliances—basically, anything with a coil in it.
- Capacitive loads are as standard components of electronic circuits, but not on the macroscale among utility customers. While capacitance occurs in small amounts deep within many appliances, it does not dominate the overall electrical appearance of these appliances to the power system.

Types of loads

- Most motors are designed for alternating current (a.c.) at a specific frequency and voltage, although there are also direct current (d.c.) motors.
- Fluorescent lamps require a.c. because the radiation discharge depends on the continuing reversal of the electric field across the tube.
- Pure resistors are the most forgiving loads, being tolerant of low voltage and completely indifferent to the direction of current flow; any resistor will operate interchangeably on a.c. or d.c.
- Electronic devices operate on d.c. internally, but are manufactured to interface with the standard a.c. grid power.

Motors

- Electric motors represent an important fraction of residential, commercial, and industrial loads; 60% of the electric energy used.
- Motor loads comprise fans, pumps of all kinds including refrigerators and air conditioners, power tools from hand drill to lawnmowers, and even electric streetcars—basically, anything electric that moves.
- Typical energy conversion efficiencies range from an average of 65% for small (fractional horsepower) to over 95% for very large (over 500 hp) motors.
- The operating efficiency depends both on the motor design and the operating condition, with most motors running most efficiently near their rated capacity (the load for which they were presumably designed).

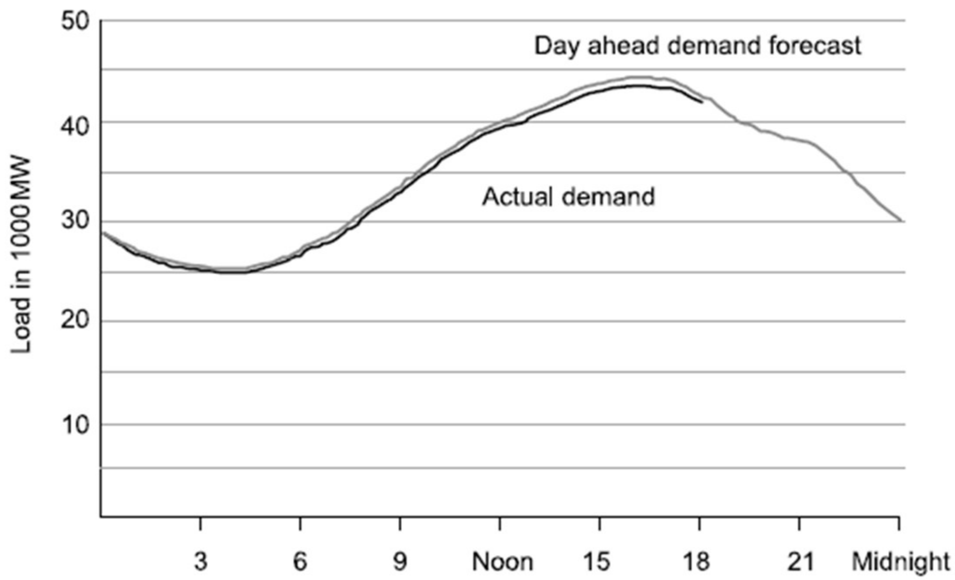
Load From The System Perspective

- From the point of view of the power grid, individual customers and their appliance are small, numerous, and hardly discernible as distinct loads.

- This section thus deals with aggregate load, that is, the combined effect of many customers both in terms of the magnitude and timing of electric demand

Load Profiles

- Instantaneous demand, as it varies over the course of a day, is represented in a load profile.
- The maximum demand, which tends to be of greatest interest to the service provider, is termed the peak load, peak demand, or simply the peak.



Load factor

- Quantitatively, the ratio between peak and average demand is defined as the load factor.
- From the standpoint of economics as well as logistics, a relatively flat load duration curve with a high load factor is clearly desirable for utilities.
- This is because the cost of providing service consists in large part of investments related to peak capacity, whereas revenues are generally related to total energy consumed (i.e., average demand).
- A pronounced peak indicates a considerable effort that the service provider must undertake to meet demand on just a few occasions, although the assets required to accomplish this will tend not to be utilized much during the remainder of the year.

Faults And Protection Of Electric Energy Systems

Faults in electric system

- A short-circuit fault takes place when two or more conductors come in contact with each other when normally they operate with a potential difference between them.
- The contact may be a physical metallic one, or it may occur through an arc. In the metal-to-metal contact case, the voltage between the two parts is reduced to zero.
- On the other hand, the voltage through an arc will be of a very small value.

Causes of faults

- Generator and transformer failure is caused by insulation breakdown between turns in the same slot or between the winding and the steel structure of the machine.
- The breakdown is due to insulation deterioration combined with switching and/or lightning overvoltages.
- Overhead lines are constructed of bare conductors. Wind, sleet, trees, cranes, kites, airplanes, birds, or damage to supporting structure are causes of accidental faults on overhead lines.

Consequence of fault

- A fault will cause currents of high value to flow through the network to the faulted point.
- The amount of current may be much greater than the designed thermal ability of the conductors in the power lines or machines feeding the fault.
- As a result, temperature rise may cause damage by annealing of conductors and insulation charring.
- Short-circuit and protection studies are an essential tool for the electric energy systems engineer.

Requirements for protective systems

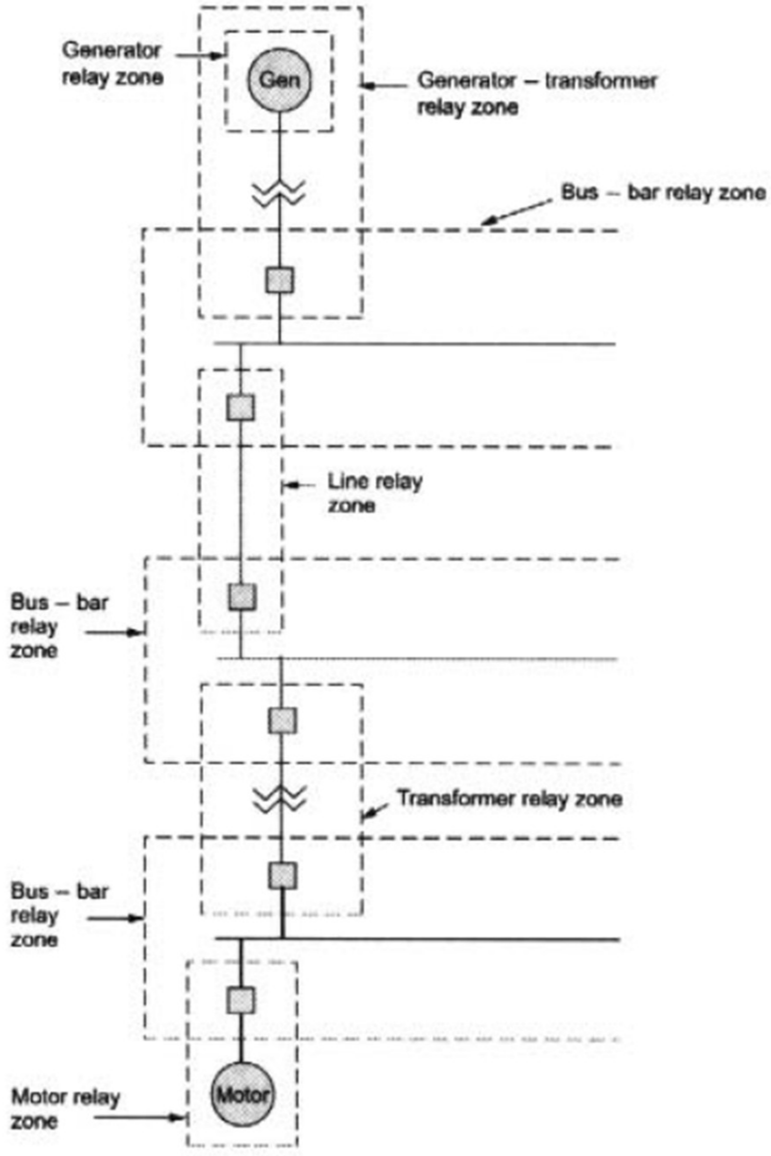
1. Reliability: Provide both dependability (guaranteed correct operation in response to faults) and security (avoiding unnecessary operation). Reliability requires that relay systems perform correctly under adverse system and environmental conditions.
2. Speed Relays should respond to abnormal conditions in the least possible time. This usually means that the operation time should not exceed three cycles on a 60-Hz base.
3. Selectivity: A relay system should provide maximum possible service continuity with minimum system disconnection.
4. Simplicity and economy: The requirements of simplicity and economy are common in any engineering design, and relay systems are no exception.

Protective System

- A protective system detects fault conditions by continuously monitoring variables such as current, voltage, power, frequency, and impedance.
- Measuring currents and voltages is performed by instrument transformers of the potential type (P.T.) or current type (C.T.). Instrument transformers feed the measured variables to the relay system, which in turn, upon detecting a fault, commands a circuit-interrupting device known as the circuit breaker (C.B.) to disconnect the faulted section of the system.

Protective Relays

- A relay is a device that opens and closes electrical contacts to cause the operation of other devices under electric control.
- The relay detects intolerable or undesirable conditions within an assigned area.
- The relay acts to operate the appropriate circuit breakers to disconnect the area affected to prevent damage to personnel and property.



Operation of any electric power system

The following criteria govern the operation of any electric power system:

- Safety
- Quality
- Reliability
- Economy

Operation of any electric power system

- The first criterion is the most important consideration and aims to ensure the safety of personnel, environment, and property in every aspect of system operations.
- Quality is defined in terms of variables, such as frequency and voltage, that must conform to certain standards to accommodate the requirements for proper operation of all loads connected to the system.
- Reliability of supply does not have to mean a constant supply of power, but it means that any break in the supply of power is one that is agreed to and tolerated by both supplier and consumer of electric power.
- Making the generation cost and losses at a minimum motivates the economy criterion while mitigating the adverse impact of power system operation on the environment.

Tasks performed in Power System

- Maintain the balance between load and generation.
- Maintain the reactive power balance to control the voltage profile.
- Maintain an optimum generation schedule to control the cost and environmental impact of the power generation.
- Ensure the security of the network against credible contingencies. This requires protecting the network against reasonable failure of equipment or outages.

Challenges in power system

- Power network is ever changing because loads and networks configuration change, the response of many power network apparatus is not instantaneous. For example, the startup of a thermal generating unit takes a few hours. This is mitigated by keeping spinning reserve.
- Systems to be operated much closer to security limits (thermal, voltage and stability). When a power system is operated closer to the limit, a relatively small disturbance may cause a system upset.
- Decisions will have to be made on the basis of predicted future states of the system.

What are the problems with present energy use?

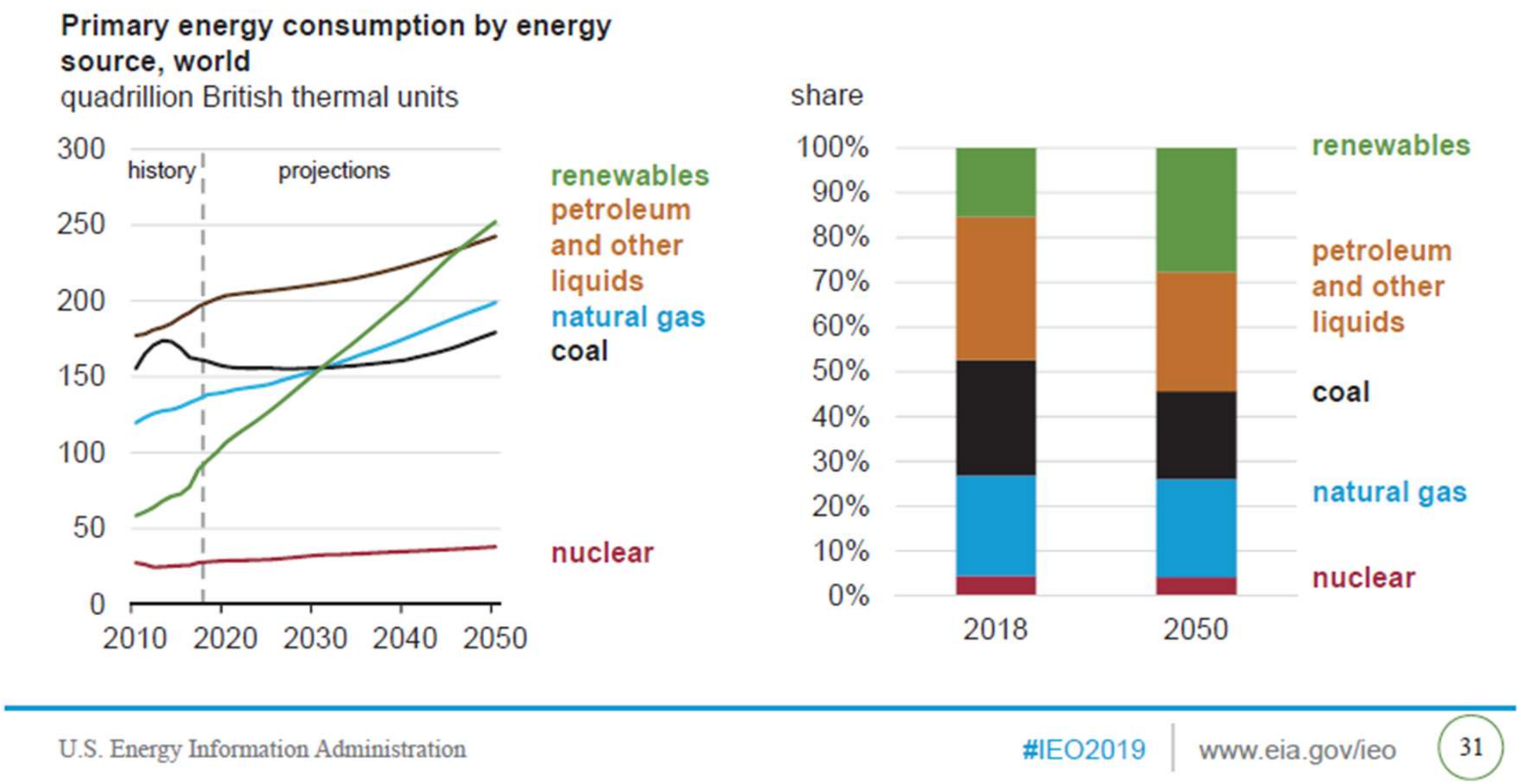
- Global Energy consumption is growing because:
  - Population is growing
  - Energy use per capita is growing –especially in developing countries
- Energy access is unequally distributed
- Growing megacities need concentrated energy sources
- Transportation systems depend largely on petroleum fuels
- Major fossil energy sources have problems
  - Security of supply/price stability (esp. petroleum)
  - Depletion
  - Climate impacts from greenhouse gas emissions
- Global economy is significantly dependent on present fossil energy prices and availability –changes to include “externality” costs may slow economic growth (or at least cause major short-term disruptions in the economy)

Climate Change Concerns

- Global energy demand is growing and over 80% of primary energy is supplied by fossil fuels today
- Combustion of fossil fuel generates greenhouse gases – predominately CO_2–that can lead to global warming and associated impacts (melting of glaciers and polar ice, sea level rise, changes in local rainfall and climates, increases in storm severity, impacts on biosphere and agriculture, changes in ocean circulation, etc.)
- Methane, CH_4, is also a GHG and reaches the atmosphere through agricultural activities and leakage
- There is no "silver bullet" replacement for fossil fuels

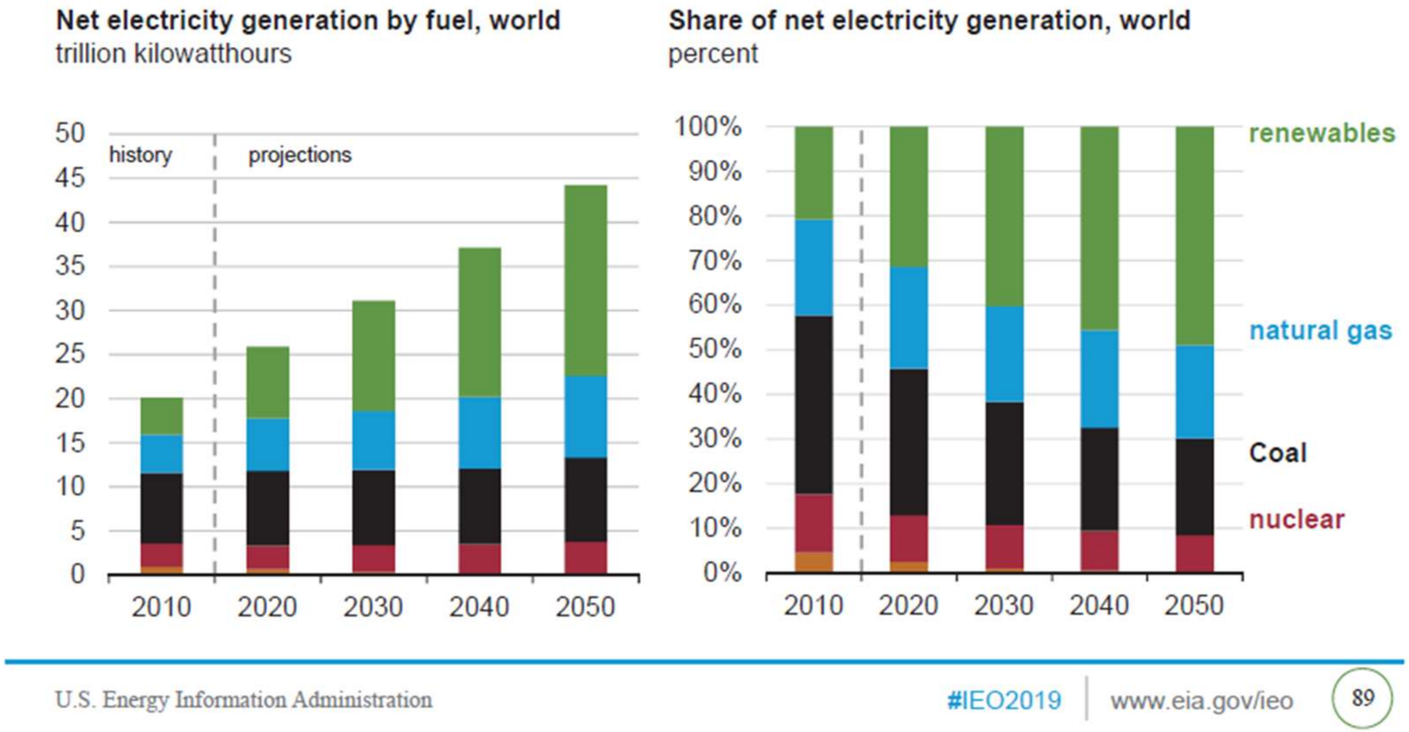
Renewable Energy and Smart Grid

Renewable energy becomes the leading source of primary energy consumption by 2050



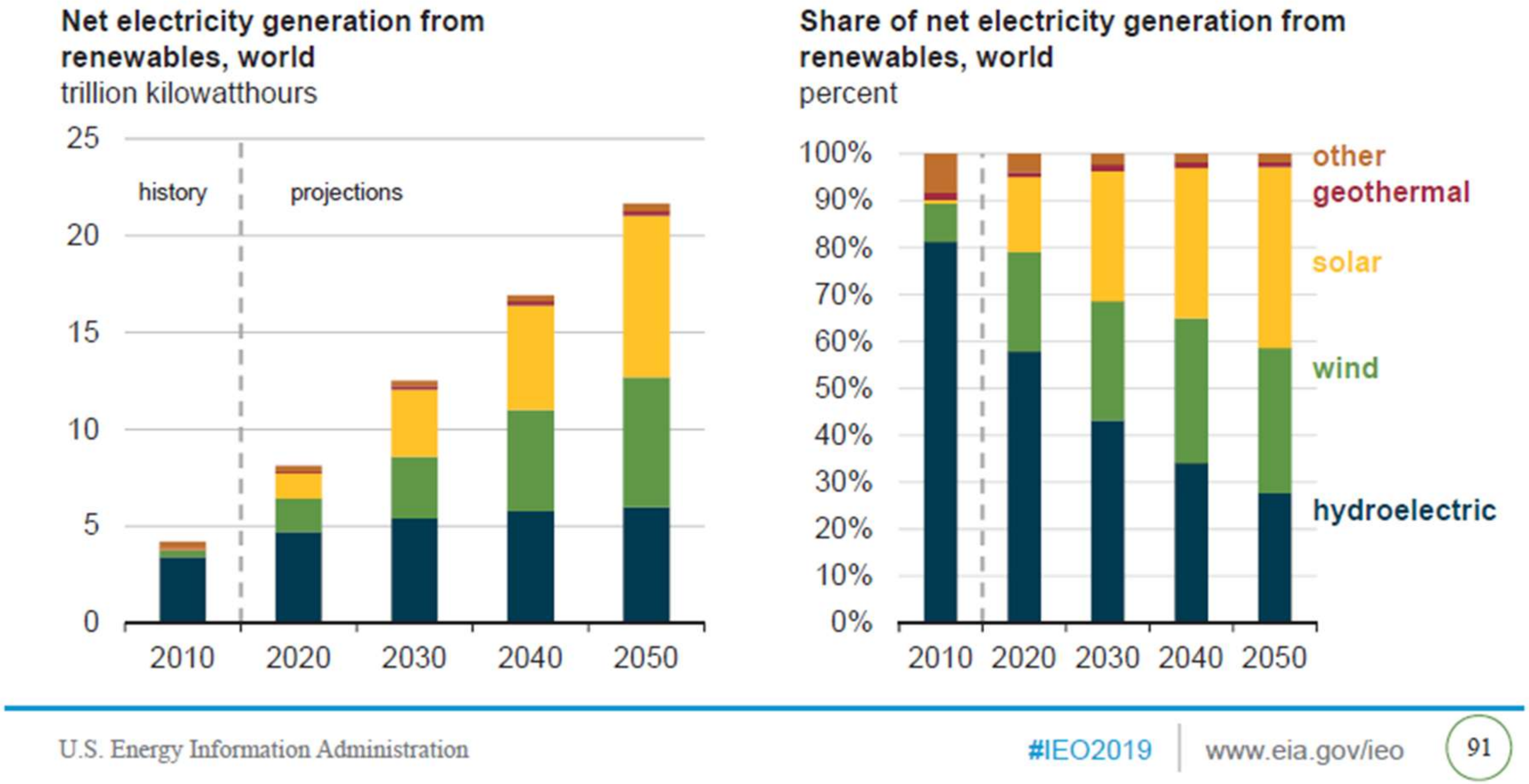
Driven by electricity demand growth and economic and policy drivers, worldwide renewable energy consumption increases by 3% per year between 2018 and 2050.

Growth in electricity generation is fuelled by renewables and natural gas



By 2025, in the Reference case, renewables surpass coal as the primary source for electricity generation, and by 2050, renewables account for almost half of total world electricity generation.

Wind and solar dominate growth in renewables generation



By 2050, wind and solar account for over 70% of total renewables generation.

Smart Grid - definition

To have a fully automated power delivery network that monitors and controls every customer and node, ensuring two-way flow of information and electricity between the power plant and the appliance, and all points in between.

NUS National University of Singapore

Smart Grid - expectation

- Increased integration of large-scale renewable energy systems
- More efficient transmission of electricity
- Quicker restoration of electricity after power disturbances
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers.
- Reduced peak demand, which will also help lower electricity rates
- Significantly reduce the environmental impact of the whole electricity supply system
- Improved security