EE4511
Renewable Generation and Smart Grids

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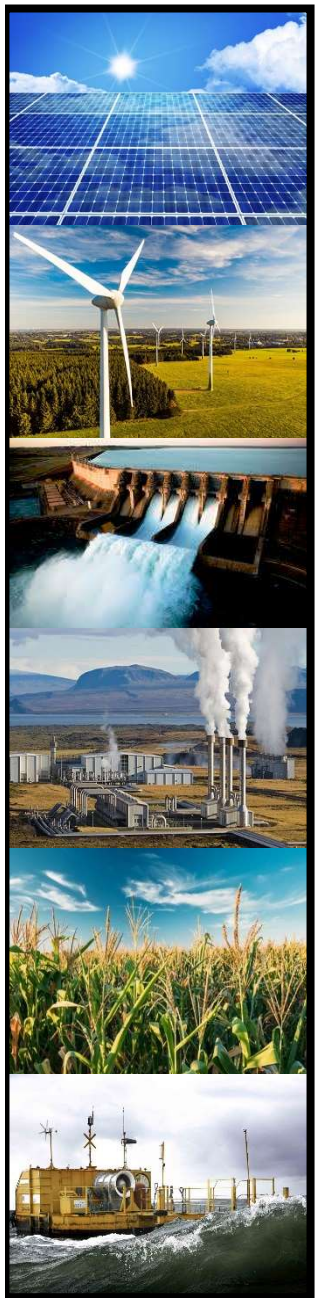
NUS National University of Singapore

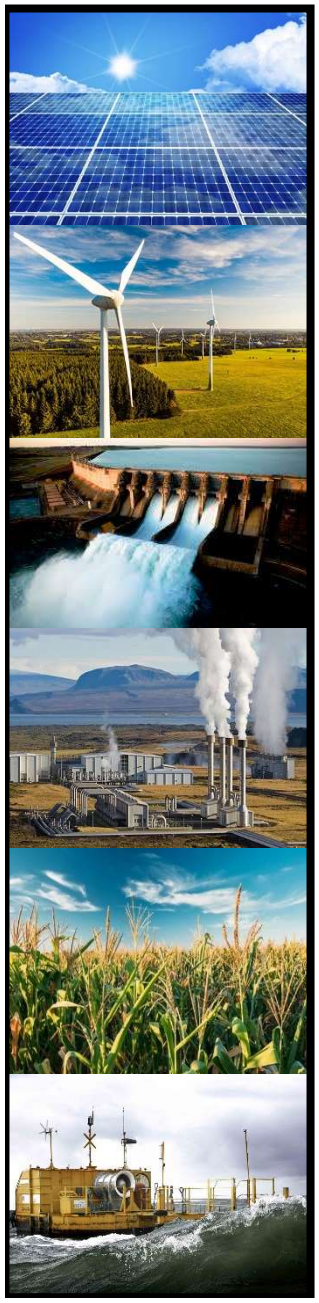
Major Goals of the course:



1.
   - Promote the advancement and use of economically and environmentally sustainable electrical energy systems.

2.
   - Understand the operation of such systems with distributed generation and renewable energy sources

Topics to be covered



1. • **Introduction – Demand for electrical power; Environmental aspects of electrical energy generation**

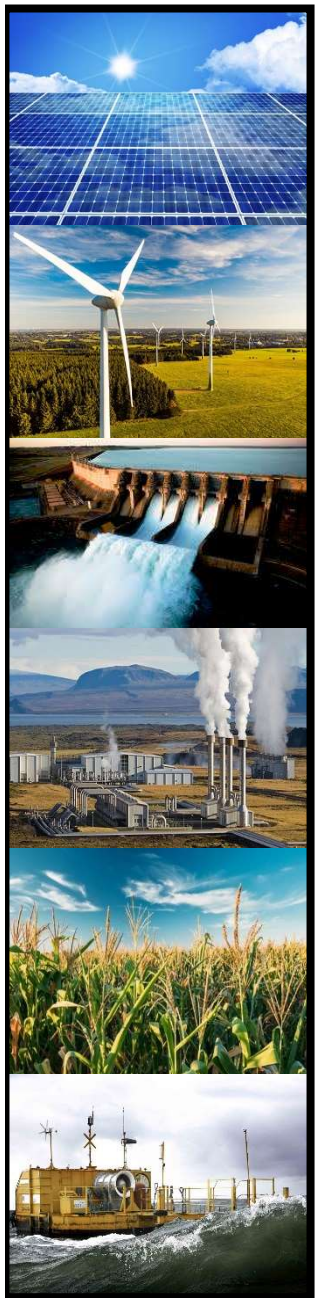
2. • **Renewable Generation technologies:**
   • **Solar thermal and solar PV, Geothermal and hydroelectric generation, Wind Energy, Biofuels, fuel cell**

3. • **Economics of distributed generation- energy economics, integrated resource planning and demand side management**

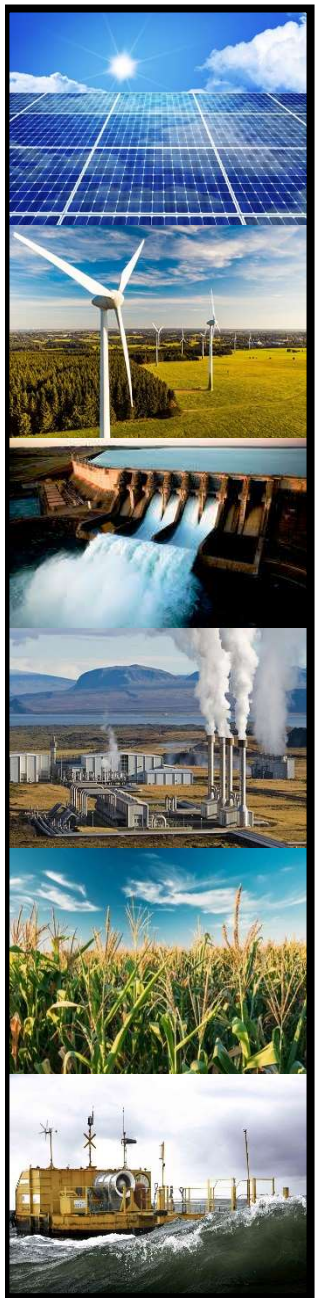
4. • **Smart Grid – Future electricity systems, Microgrids and case studies, Recent developments**

This module covers a broad range of interesting topics

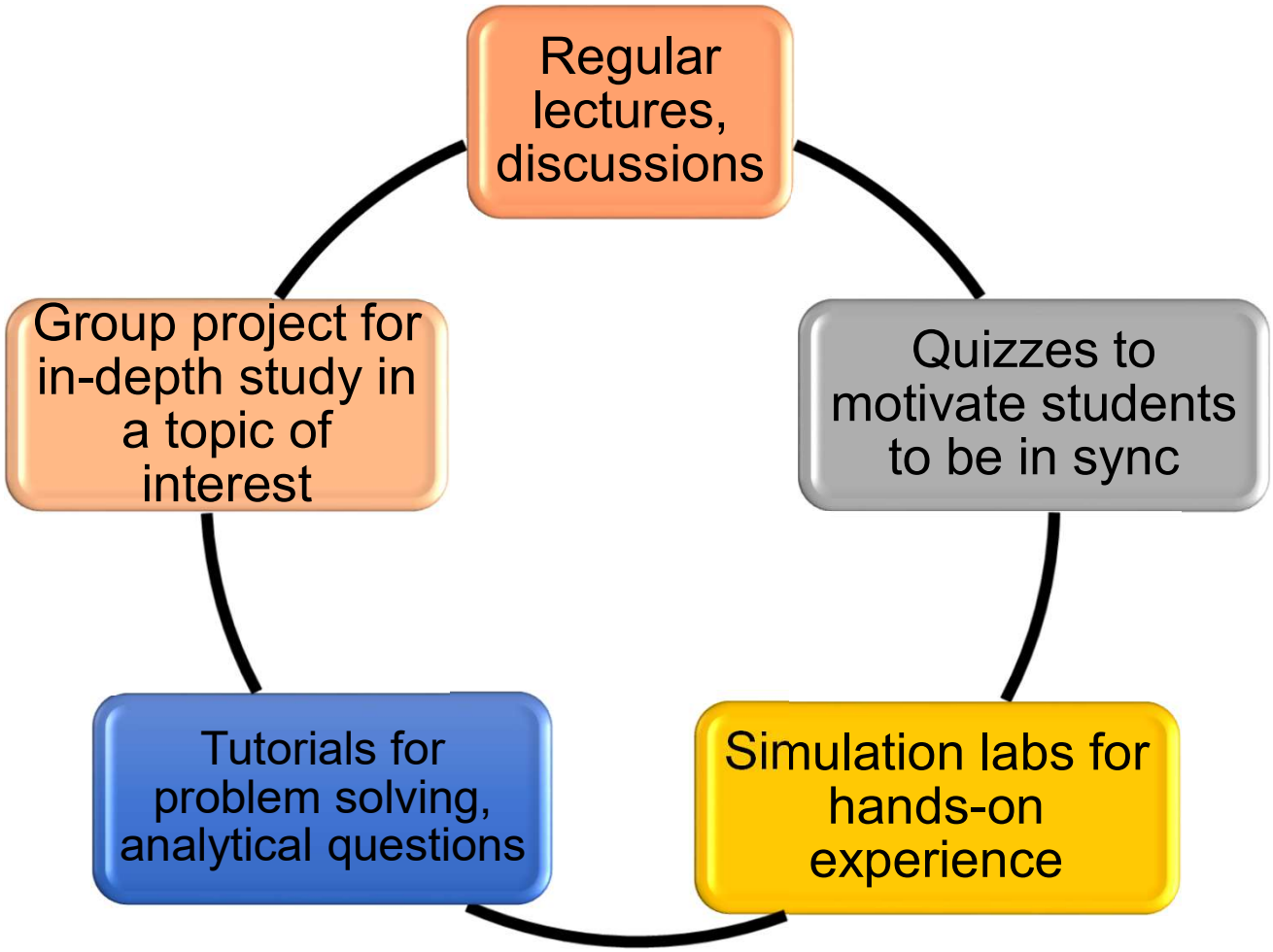
Expected outcomes



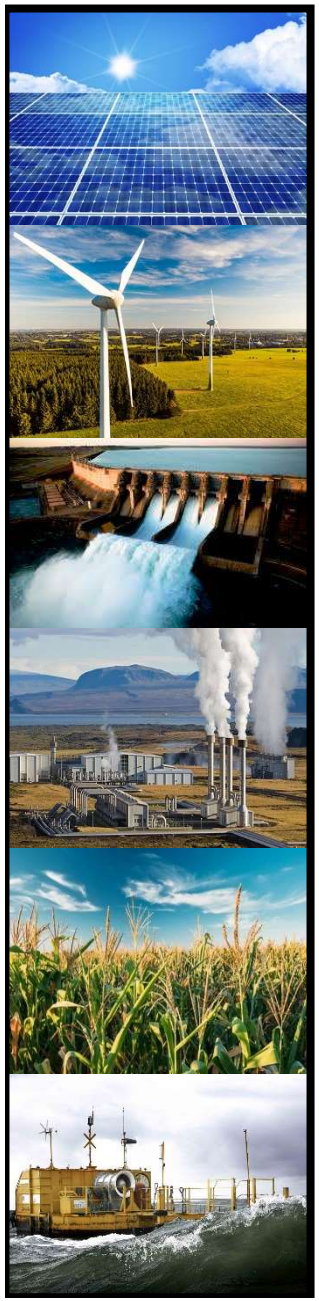
- Understand the range of renewable energy and distributed generation technologies
- Understand the operation of electric energy systems with large number of distributed sources.
- Learn supply and demand side management strategies for efficient utilization of available resources.
- Learn about recent development in smart distribution systems with embedded generation and microgrids



How will the module be conducted?



Schedule of Assessments



Individual tests (50%)

- Total 5 tests – 10% each
- One test on each major topic
- Will be conducted during lecture hour

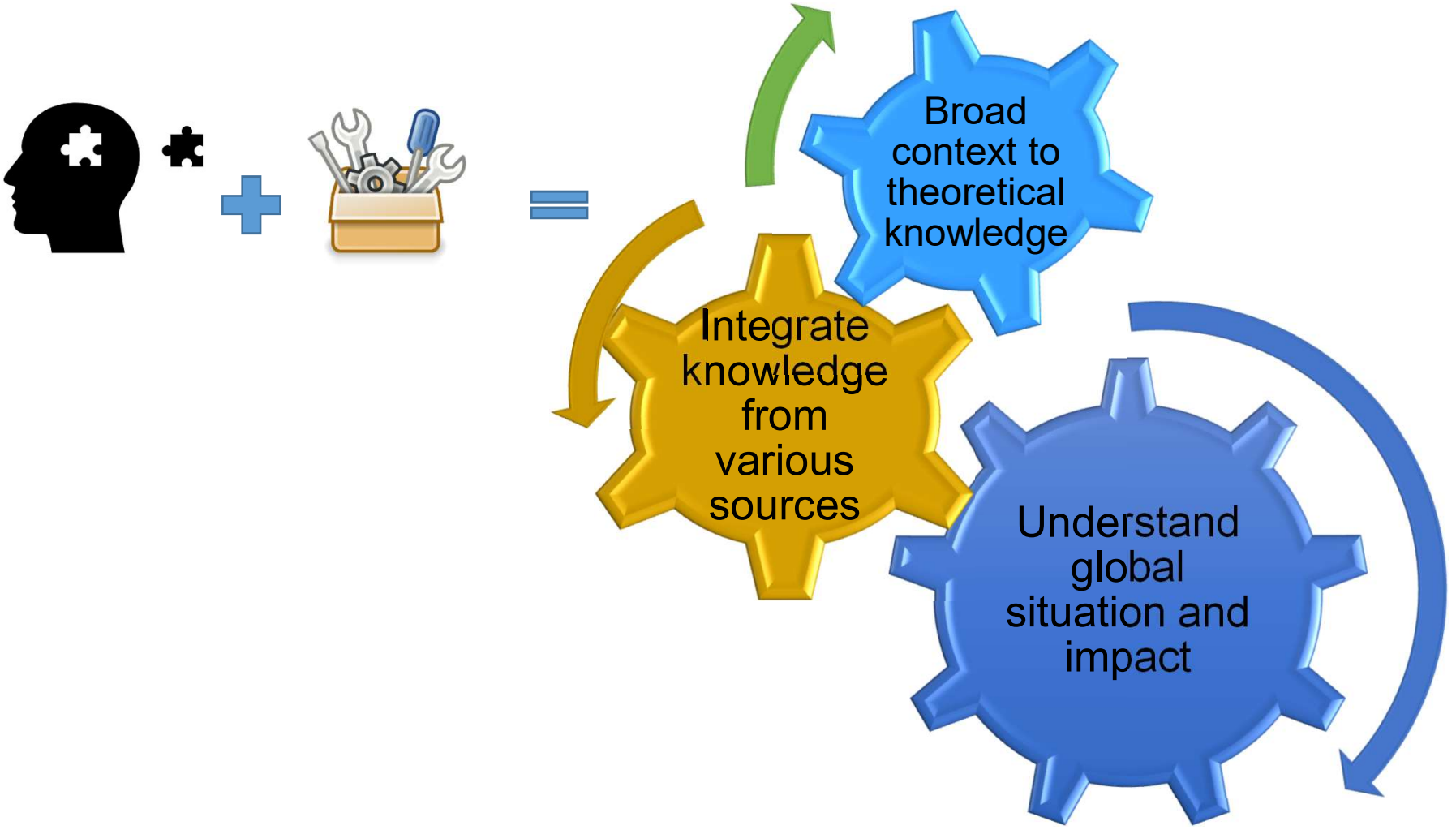
Labs /Assignment (30%)

- How many? - Total 4 simulation-based assignments; 5% each
- Topics: Solar energy, Wind energy, EV/Energy storage, Microgrid energy management
- Duration: About 2 hours each
- One individual assignment – 10%

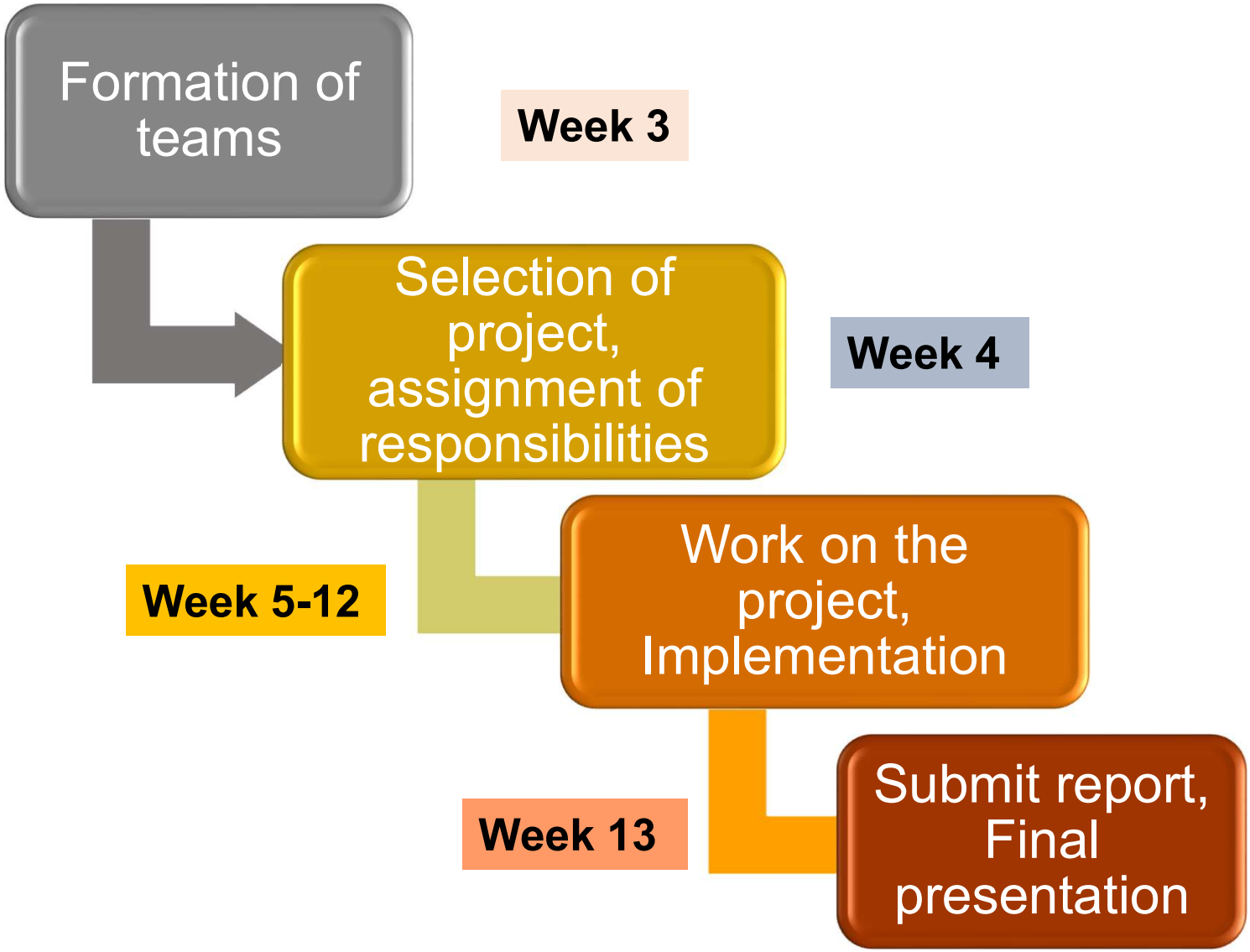
Group project (20%)

- Conducted in groups of 4-5 students
- Simulation/analysis/evaluation type
- Final report and presentation in week 13

Goal is to simultaneously acquire conceptual and practical knowledge



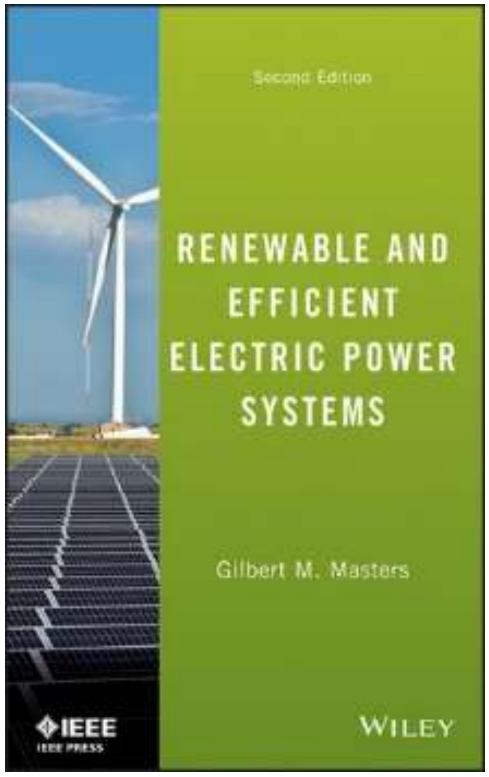
Group Project



Tentative schedule of labs/projects

Labs		Tentative date	Week
Lab 1 materials uploaded	Standalone and Grid Connected Solar PV Systems	31.01.2022	W4
Lab 2 materials uploaded	Fixed and Variable Speed Wind Energy Conversion Systems (WECS)	14.02.2022	W6
Individual Design Project materials uploaded	Microgrid Design and Optimization using HOMER	07.03.2022	W8
Lab 3 materials uploaded	Demand Side Management (DSM)	21.03.2022	W10
Lab 4 materials uploaded	Energy Management System (EMS) for Battery Energy Storage Systems (BESS) in Microgrids	04.04.2022	W12
Term Projects		**Tentative date**	**Week**
Lab & term project briefing		20.01.2022	W2
Term project topics announced		20.01.2022	W2
Submit term project groups & preferred 3 project topics to GA by		**31.01.2022**	**W4**
(for those without a group) Submit group allocation requests & preferred 3 project topics to GA by		**04.02.2022**	**W4**
Term project groups & topics released		07.02.2022	W5
Individual meetings with groups		7 to 18.03.2022	W8-9
Term project presentations		**11.04.2022**	**W13**

Text Book



Renewable and Efficient Electric Power Systems
By Gilbert M. Masters

Most of the tutorial problems and other material will come from this book

- Due to the nature of this module, the material will be sourced from a large number of published papers, reports and books
- The main textbook is available in NUS Digital library

Readings

- **REN21 Renewable Global Status Reports**
- Energy Information Administration (EIA), US Department of Energy reports
- Sustainable Energy, Tester, Drake, Driscoll, Golay and Peters, 2nd Ed. MIT Press, 2012
- Renewable Energy Resources, Twidell and Weir, 2nd Ed., Taylor and Francis, London.
- Energy for Sustainability: Technology, Planning, Policy. Randolph and Masters.
- Sustainable Energy – Without the Hot Air. McKay. (free PDF from website: http://www.withouthotair.com/download.html
- The Future of Geothermal Energy, Tester, et al. See https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf
- The Future of Coal: MIT Coal Study, Deutch, et al. See: http://web.mit.edu/coal/The_Future_of_Coal.pdf
- The Intergovernmental Panel on Climate Change(IPCC): Climate Change : – Summary for Policymakers, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

Teacher / Student Contract

On my part:

I will do my very best to teach this subject in as interesting a manner as possible
I will provide opportunities to discuss course components
I will clearly inform students about:

- Course objectives (*"What are we trying to learn in here?"*)
- Assignment descriptions (*"What do I have to do?"*)
- Specific due dates (*"When do I have to have it done?"*)

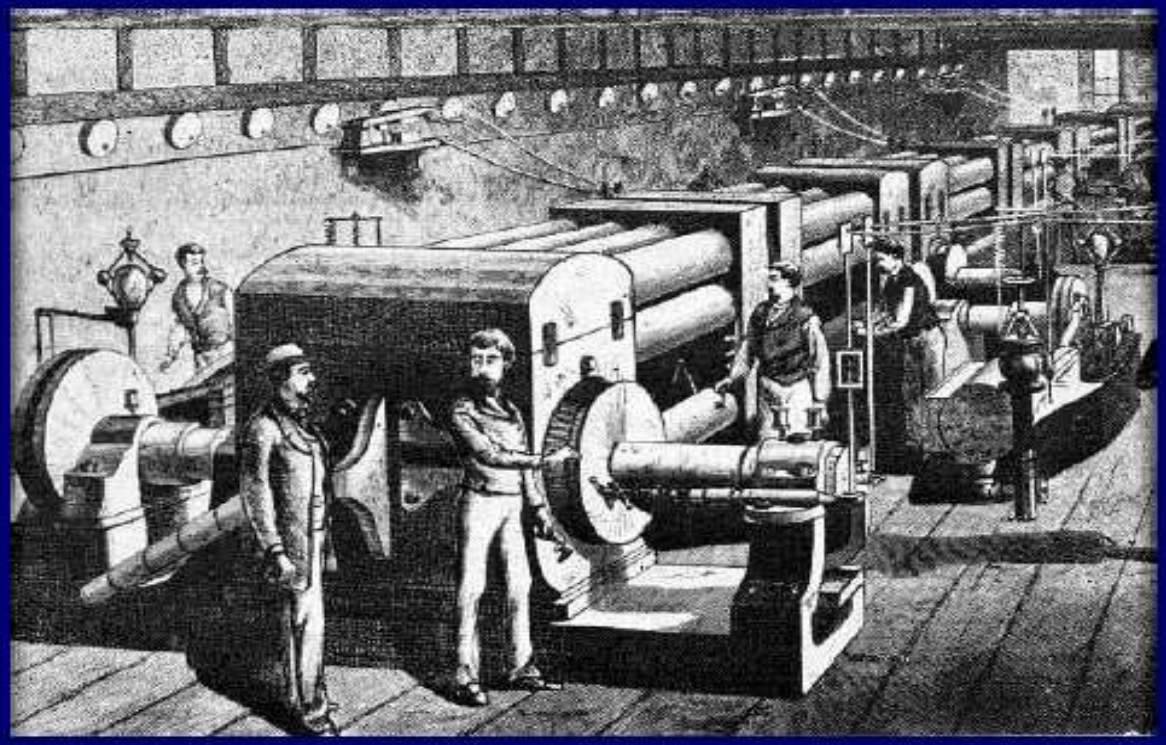
I expect that students will:

- Arrive in class on time and stay engaged for the entire class period
- Those needing clarification or assistance will ask for it
- Immediately inform me when extenuating circumstances affect his/her attendance in projects/tests
- Share concerns about the class in time for mid-course adjustments to be made

Brief history of Electric Power

World's first electric power station

Edison's Pearl Street Station
Dynamo Room, 1882



Brief History of Electric Power

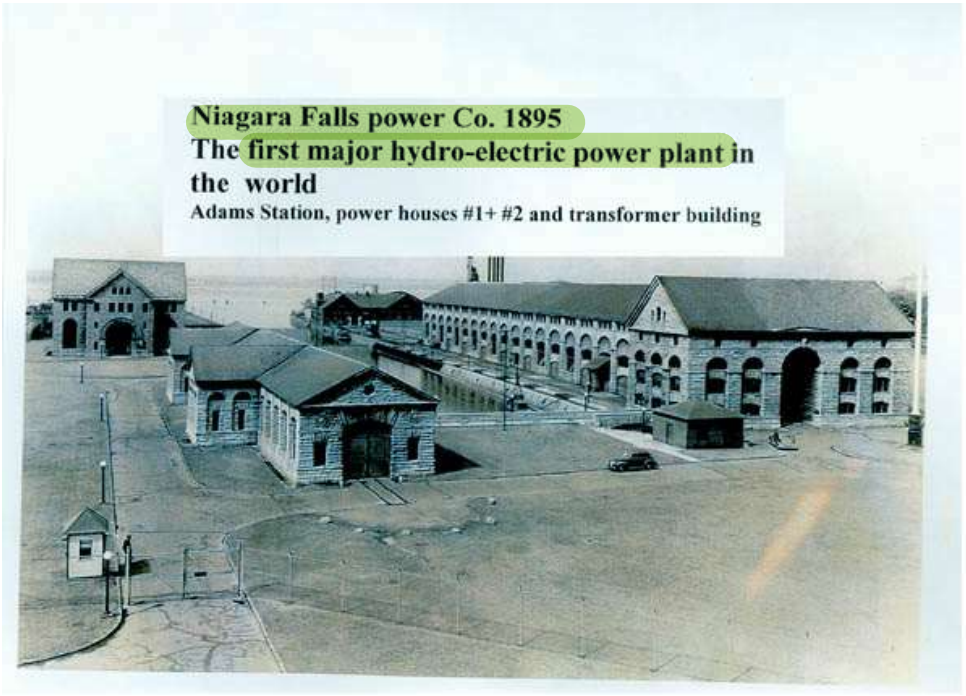
- Early 1880's – Edison's Pearl Street DC system starts operation, supplying 59 customers within 1 mile radius

- 1884 – Sprague produces first DC motor
- 1885 – Invention of transformer

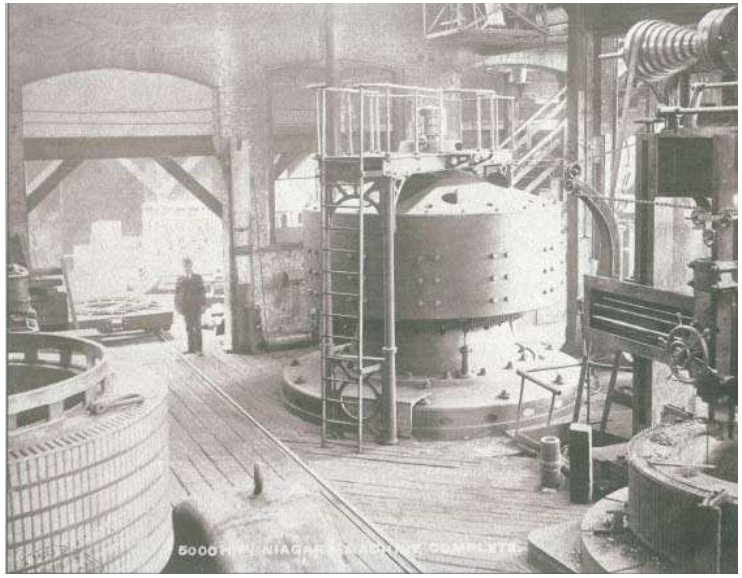
- Mid 1880's – Tesla/Westinghouse introduce AC system
- Late 1880's – Tesla invents AC induction motor

- 1893 – First 3-phase transmission system begins operation at 2.3 kV, 12 km in Southern California

World's First Hydro-electric Power Plant built by Nikola Tesla and Westinghouse



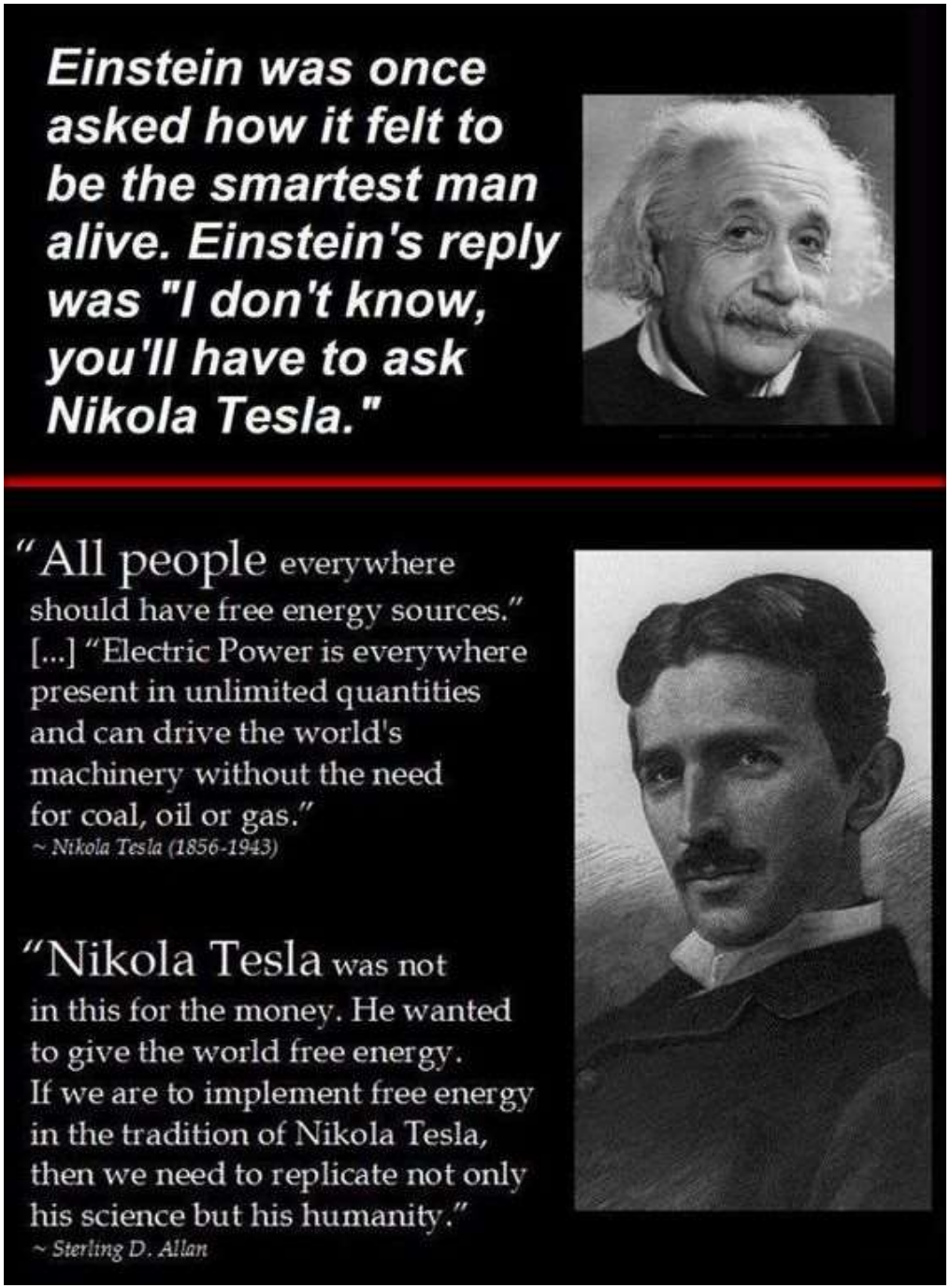
Niagara Falls Power Plant



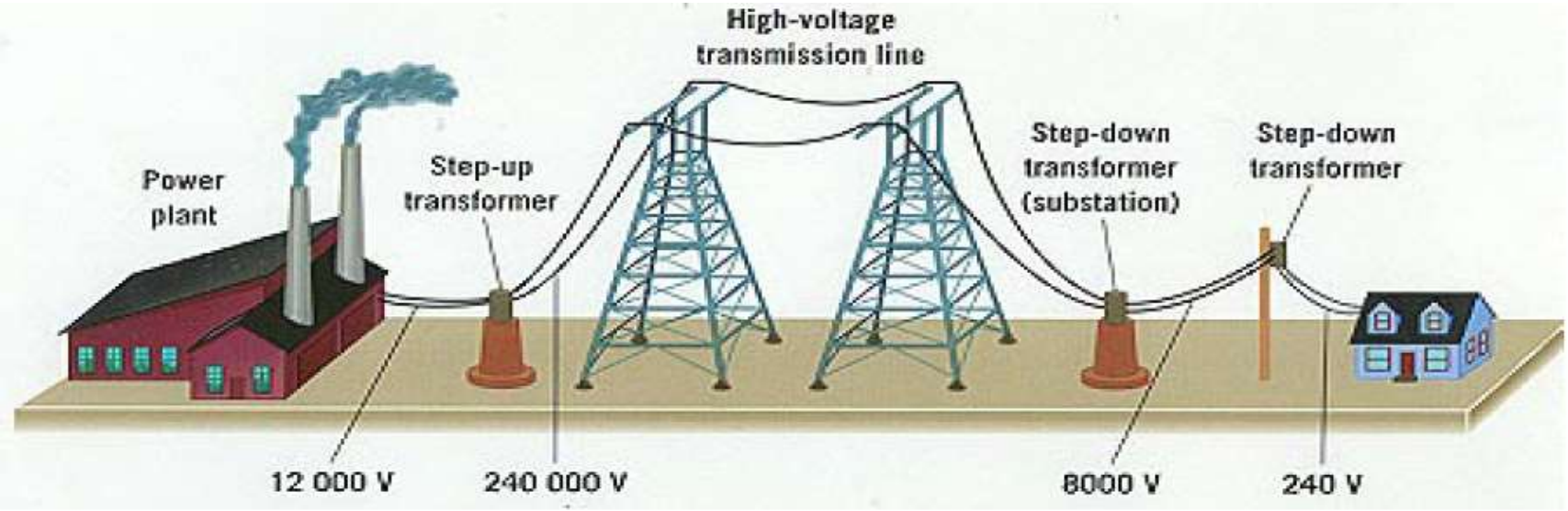
Interior of Power House No. 1 of the Niagara Falls Power Company (1895-1899)

This was the final victory of Tesla's Alternating Current over Edison's Direct Current!

Nikola Tesla was a brilliant genius who invented the modern-day power system.



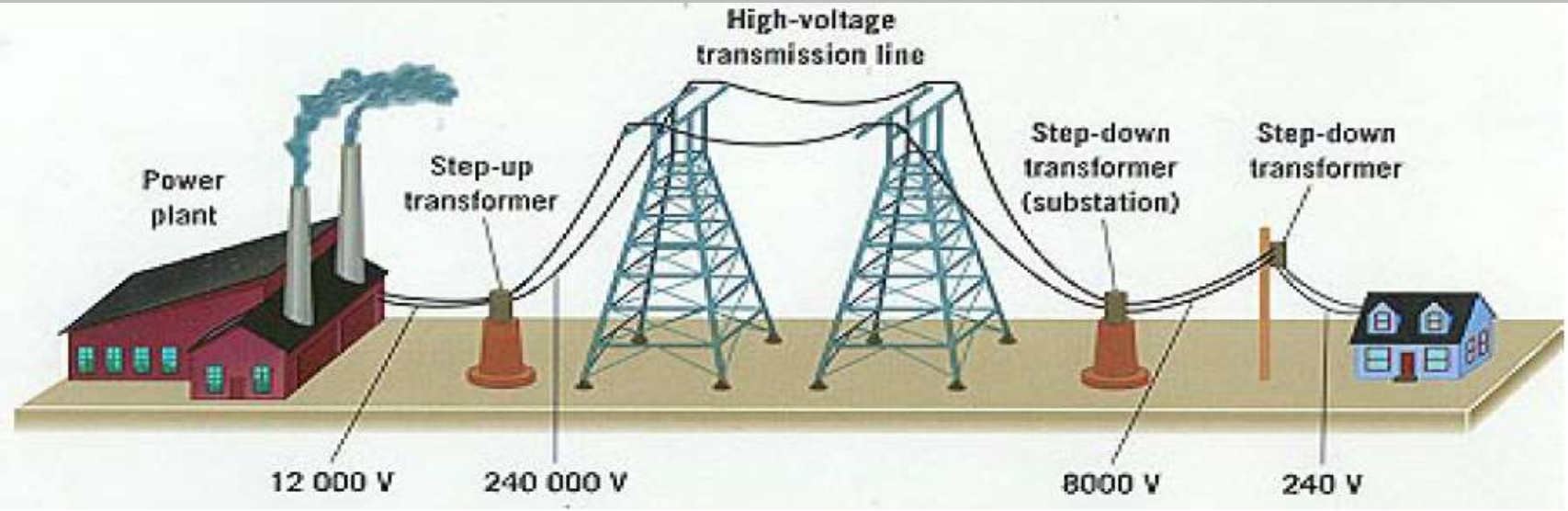
The world according to Edison and Tesla



- Edison designed the entire electrical system down to the wall outlet and in 1881 established the first power company
- In the 1930s isolated power systems melded into interconnected systems
- In the 1950s and 1960s, isolated systems were converted to large regional pools
  - Bulk delivery over long distances
  - Originated at large generating plants

With economics of scale, prices declined and demands increased

Electrical Energy systems: Transforming society



- **The vast networks of electrification are the greatest engineering achievement of the 20th century**

  - US National Academy of Engineering

How was electricity produced?

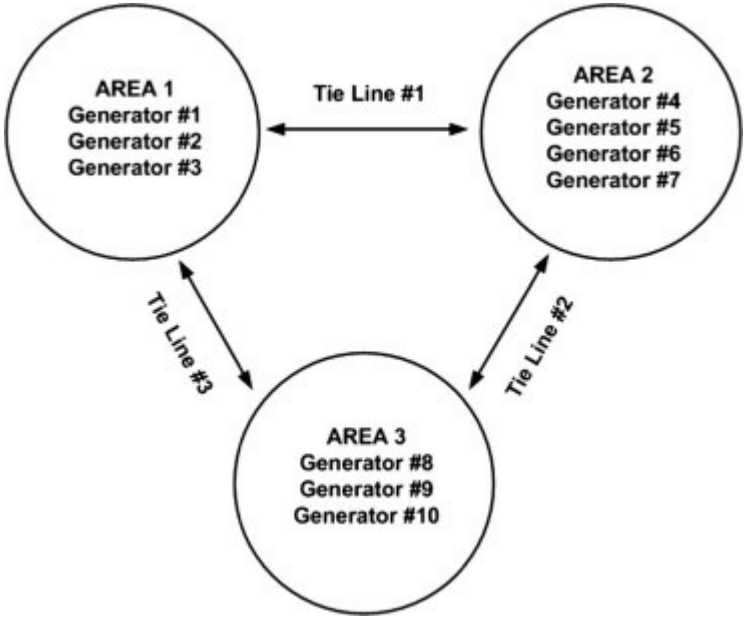
Conventional Power Plants

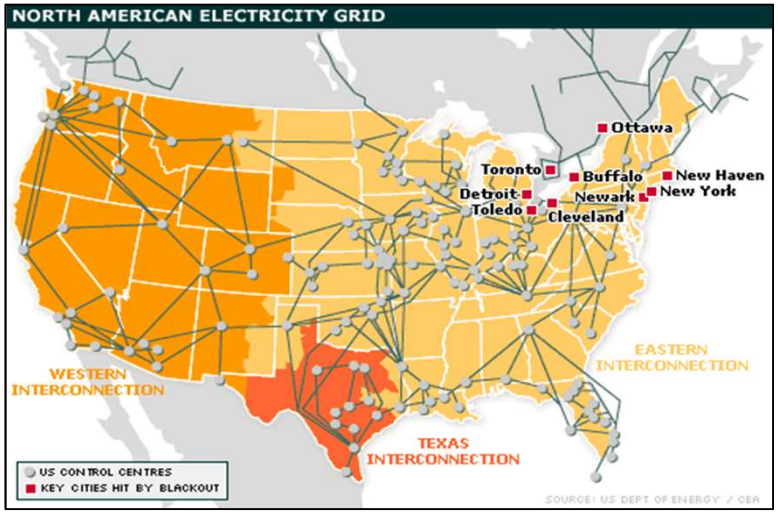
Electricity was produced in bulk using coal, oil, nuclear or hydro power

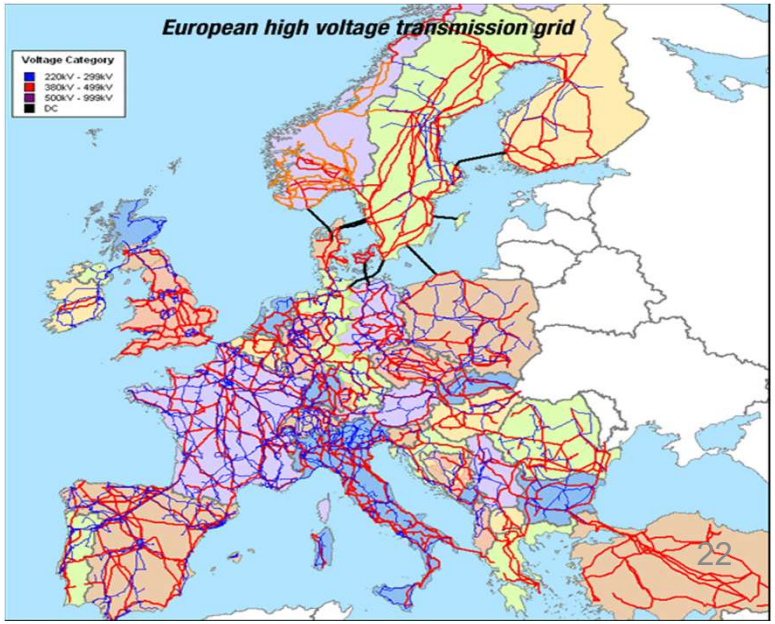
Interconnected Power Systems

- Modern power systems have interconnections to neighboring systems.

Companies exploited bigger, more efficient technologies which eventually reduced the price of electricity







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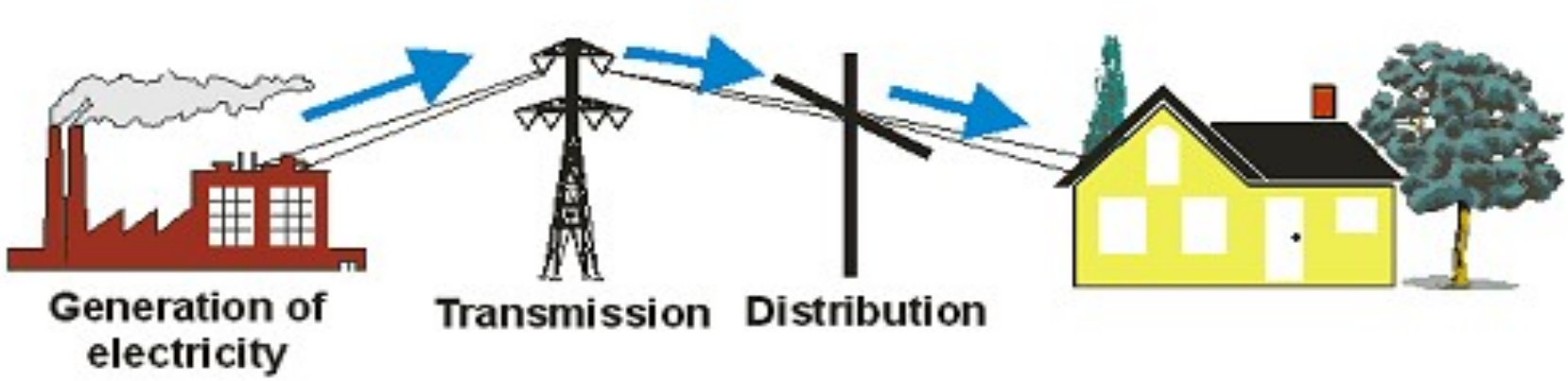


Electrical energy was:

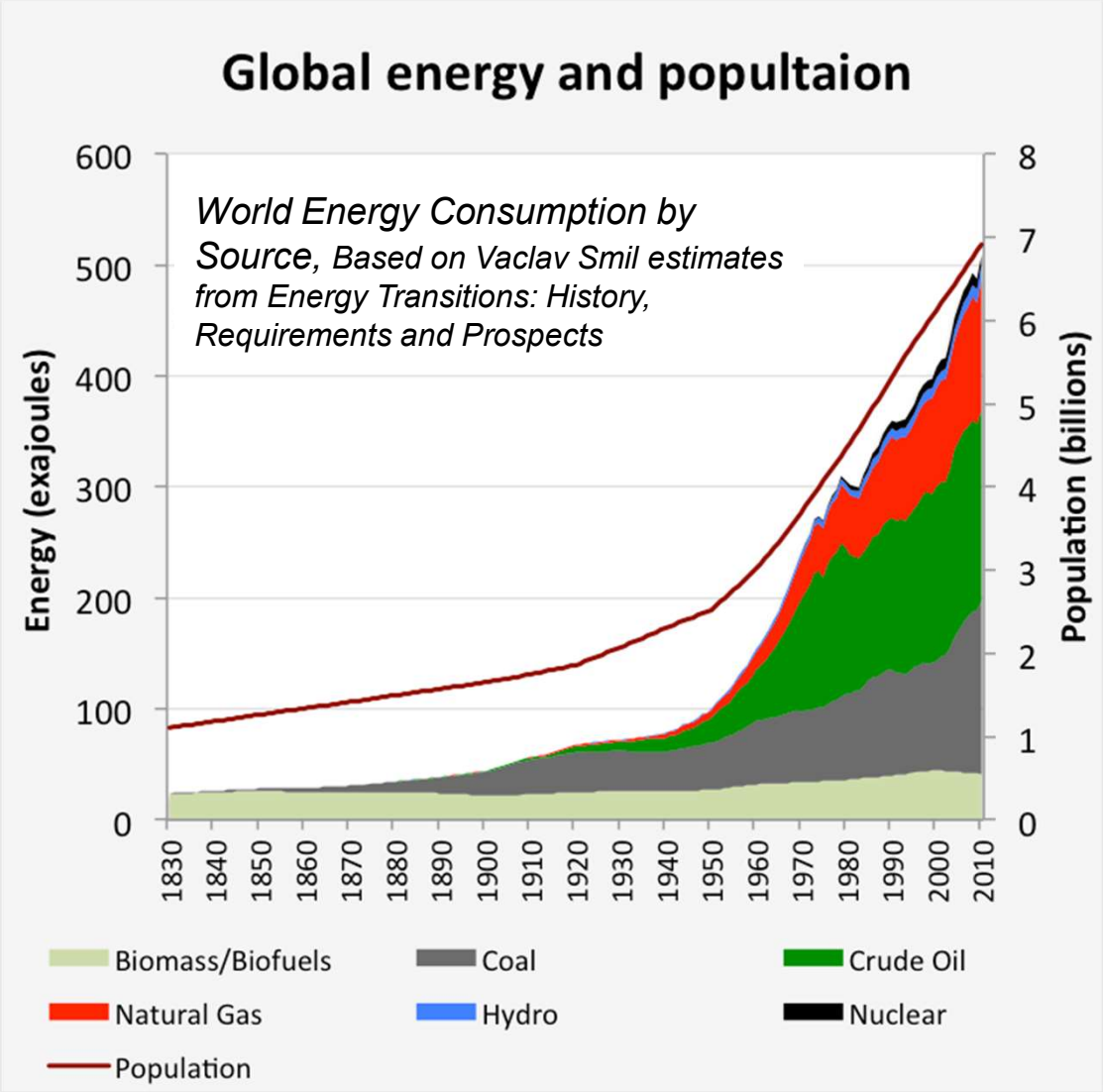
- Centrally dispatched
- Efficiently distributed
- Affordably priced
- Effortless to end user

Consumption continued to grow!

↳ but supply is limited!

How has global energy consumption grown over the years?

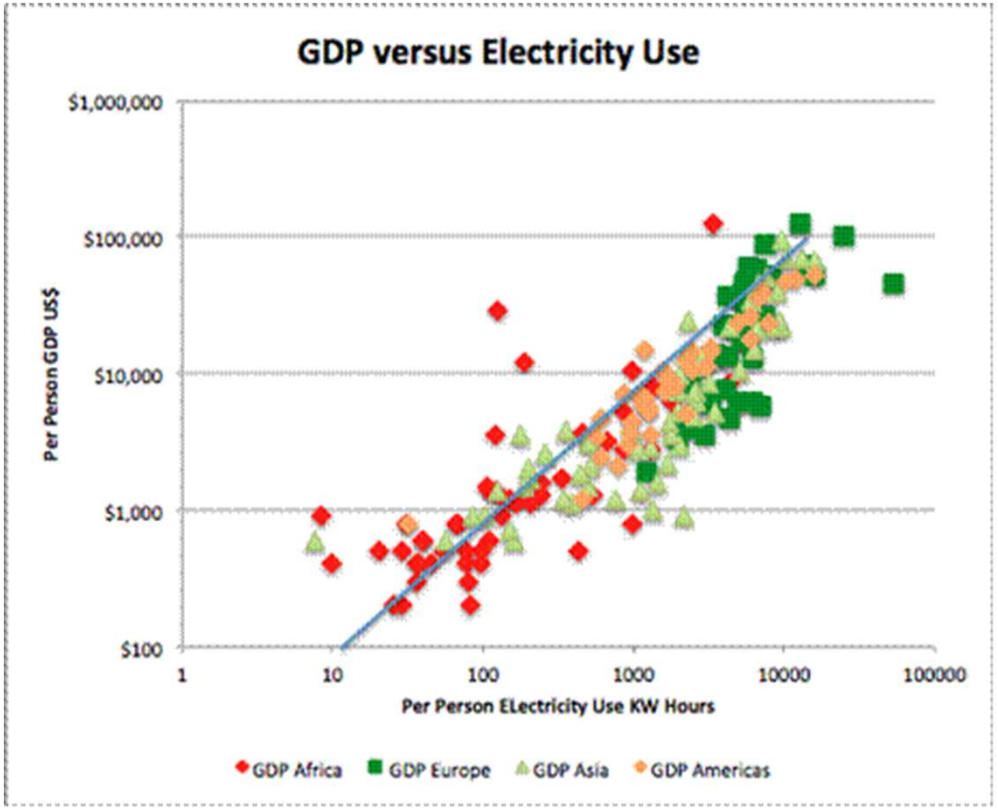
Historical World Energy consumption and Trends



World energy consumption is the total energy used by all of human civilization, across every single industrial and technological sector, across every country.

↑ population,
↑ electricity consumption

Electricity Consumption per Capita vs GDP

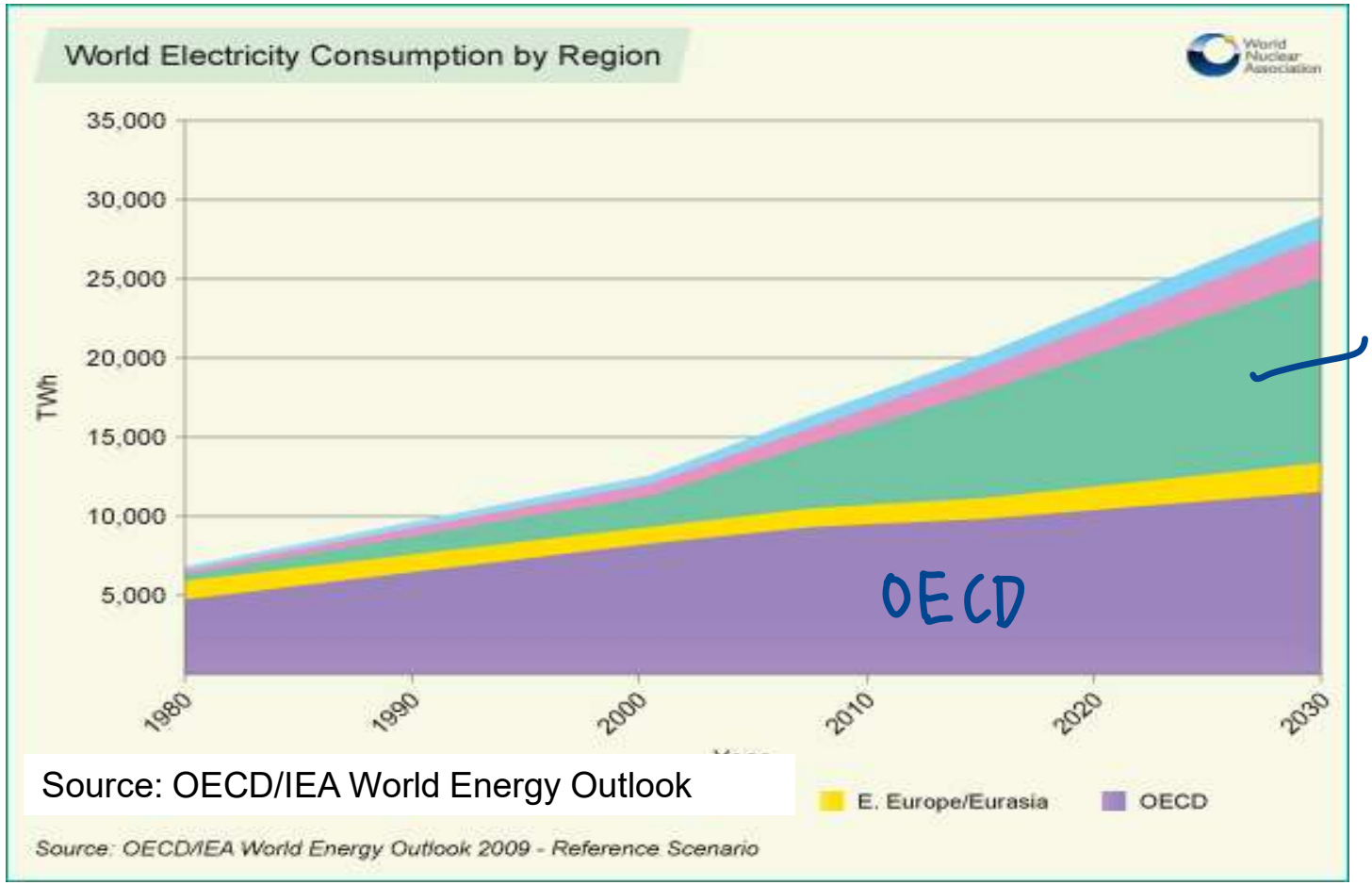


↑GDP,
↑electricity consumption

Driving up electricity consumption in a country will cause its per capita GDP to grow

Source: CIA World factbook

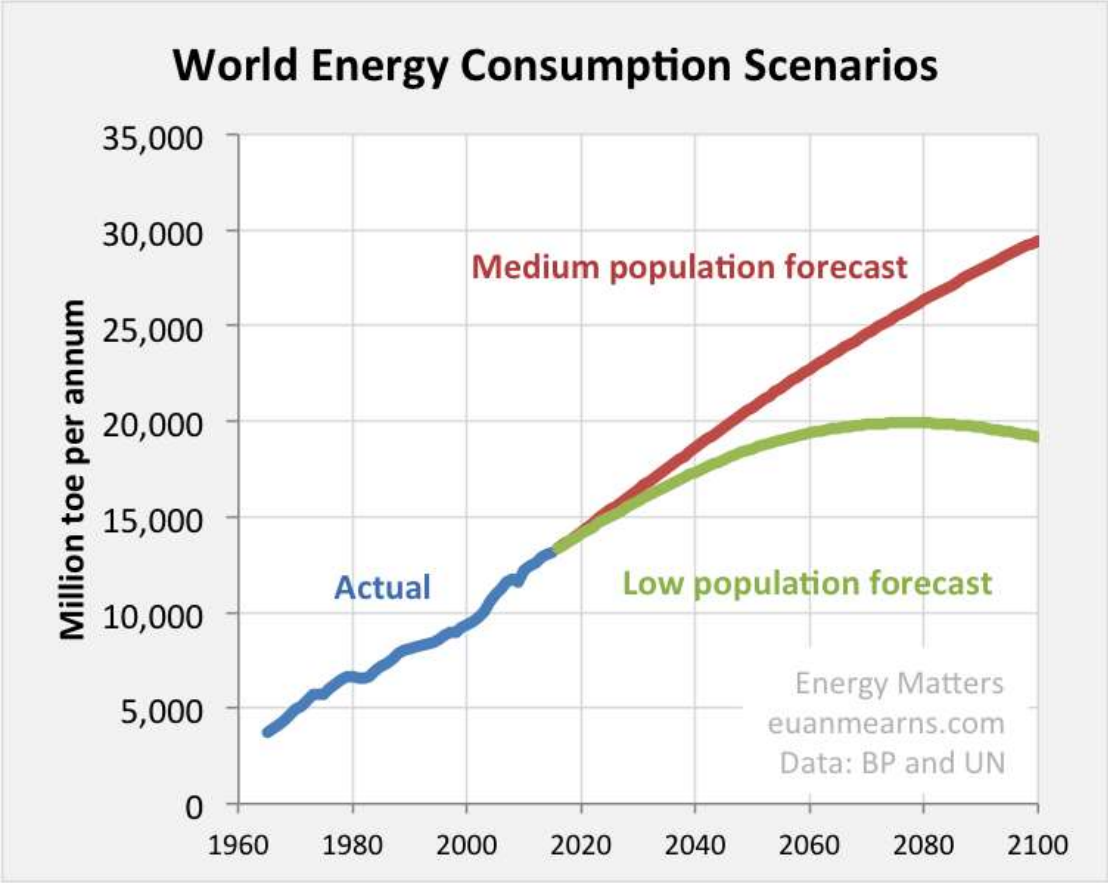
Historical World Energy consumption and Trends



World energy demand in recent years is characterized by bullish demand in Asia, while developed countries have fairly stable energy consumption

How much electricity is consumed per capita?

World Energy Consumption: Projections

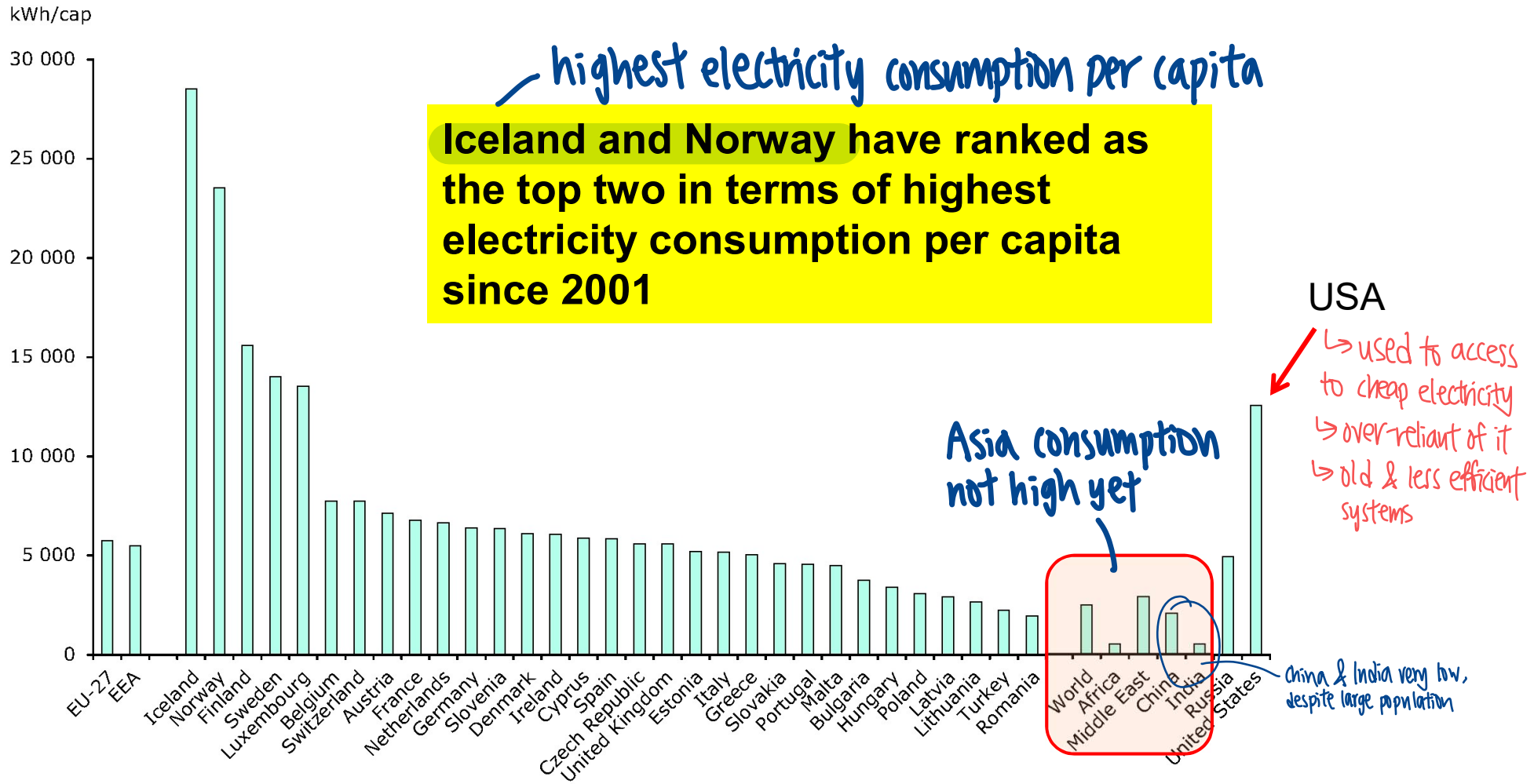


EIA projects that global energy consumption will increase nearly 50% over the next 30 years (reference case).

Although petroleum and other liquid fuels will remain the world's largest energy source in 2050, renewable energy sources will grow to nearly the same level.

Source: EIA, Energy matters euanmearns.com
Data: BP and UN

Electricity consumption per capita (selected countries)

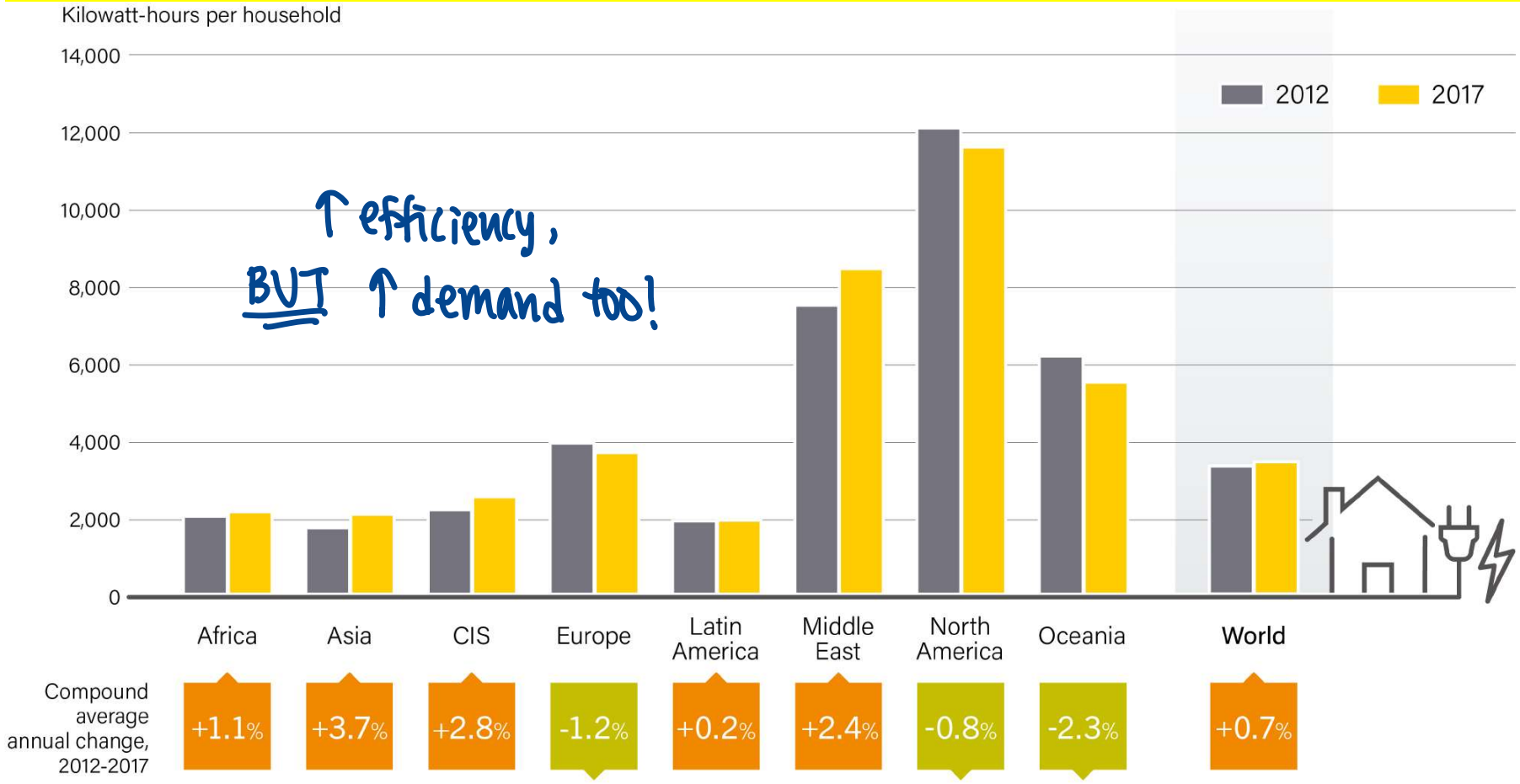


Energy consumption is projected to increase by approximately 11% in the High Economic Growth case

Source: European Environment Agency report

Average electricity consumption per electrified household

Despite efficiency improvements, household electricity use is up overall, due largely to a growing number of electrified households and rising demand for appliances and electronics

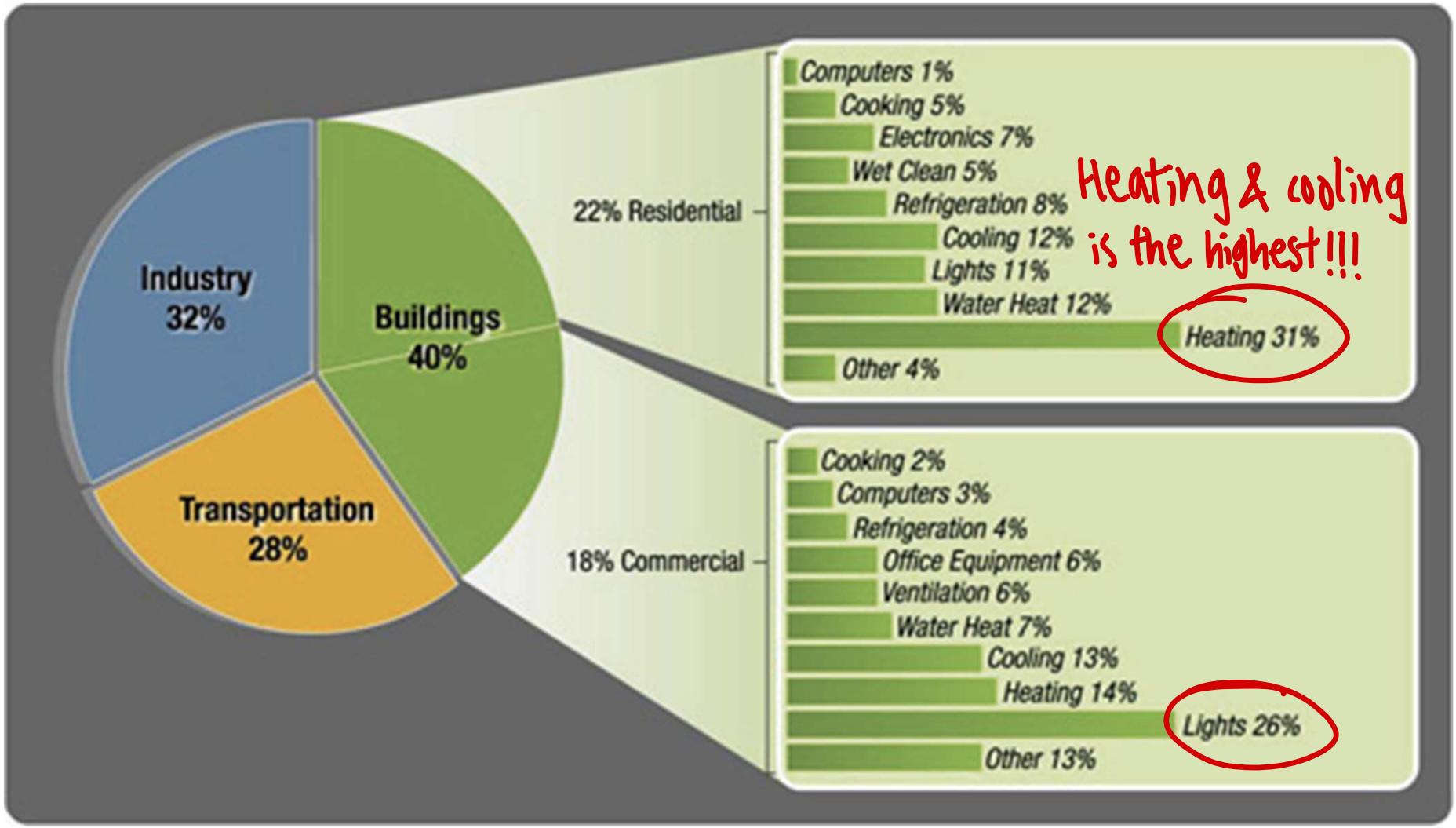


Note: CIS = Commonwealth of Independent States.

Source: Enerdata.

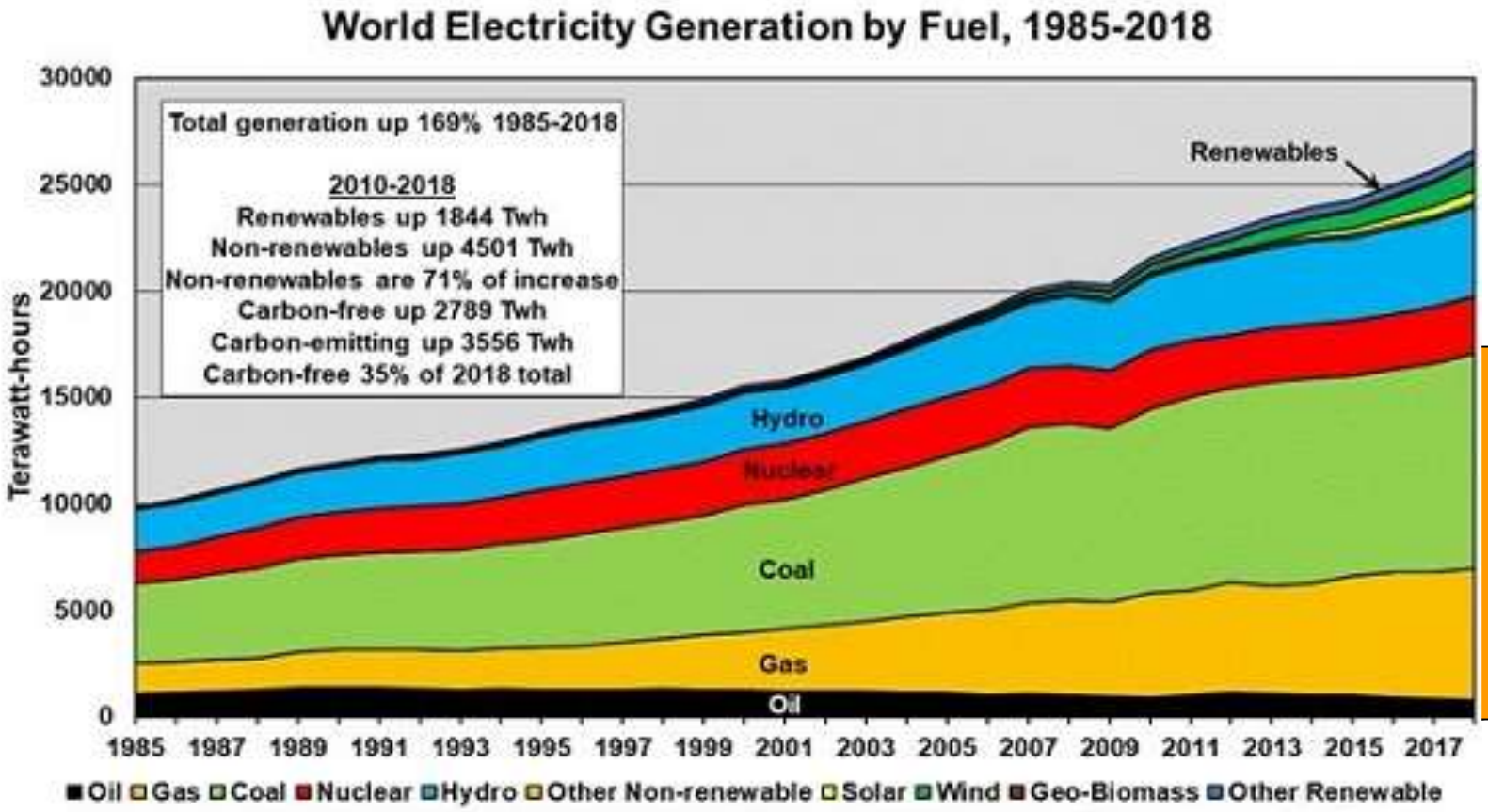
How is this electricity used ?

Electricity consumption by sector



Source: US Department of Energy Buildings Energy Data Book

World Electricity Generation by Fuel (Terawatt hours - TWh)



Fossil fuels!!

most used.

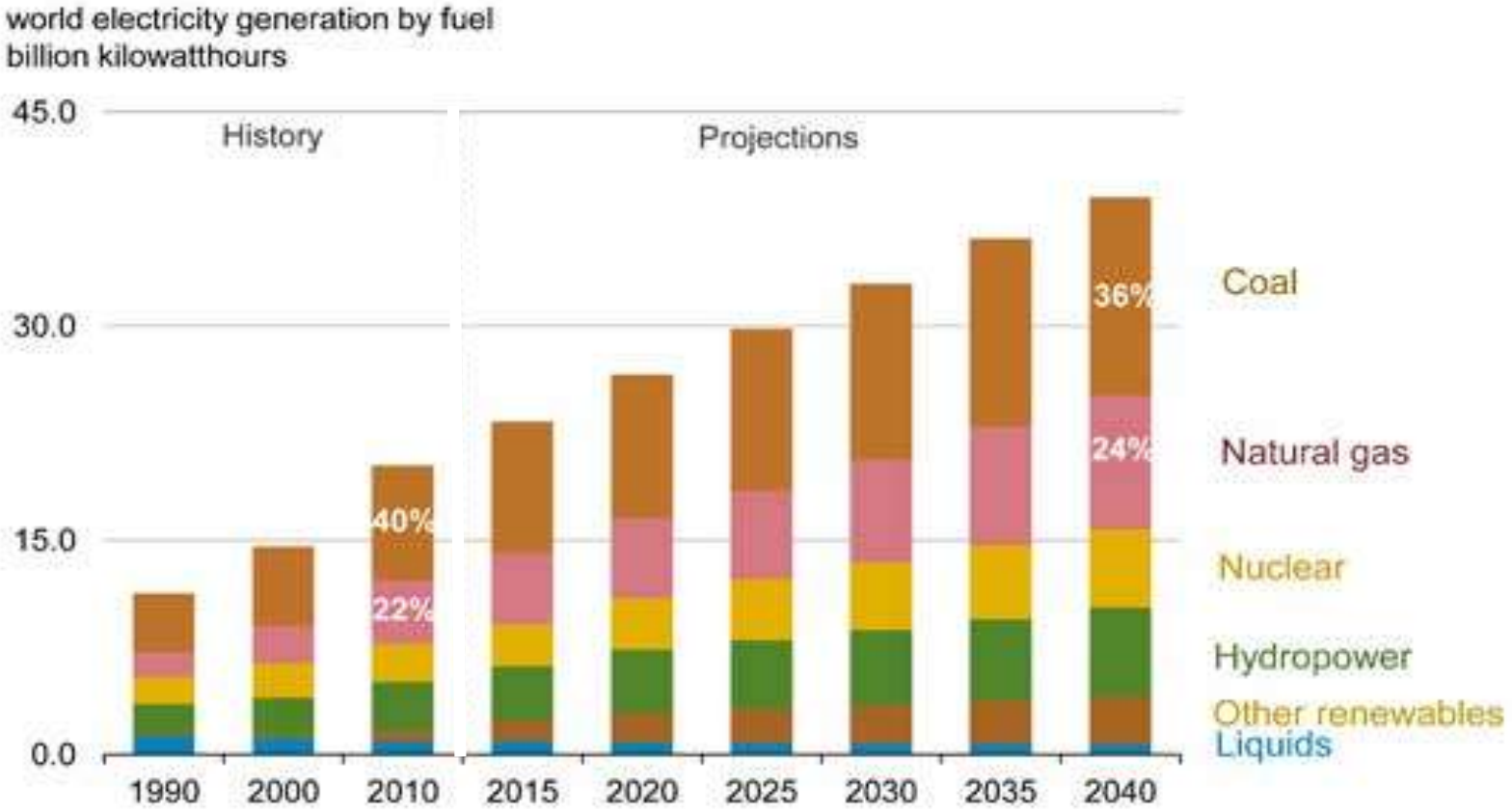
Note that electrical energy consumption has been increasing at a rapid rate

Source OECD Factbook 2019

What are the future projections?

World Net Electricity Generation by Fuel: Projections

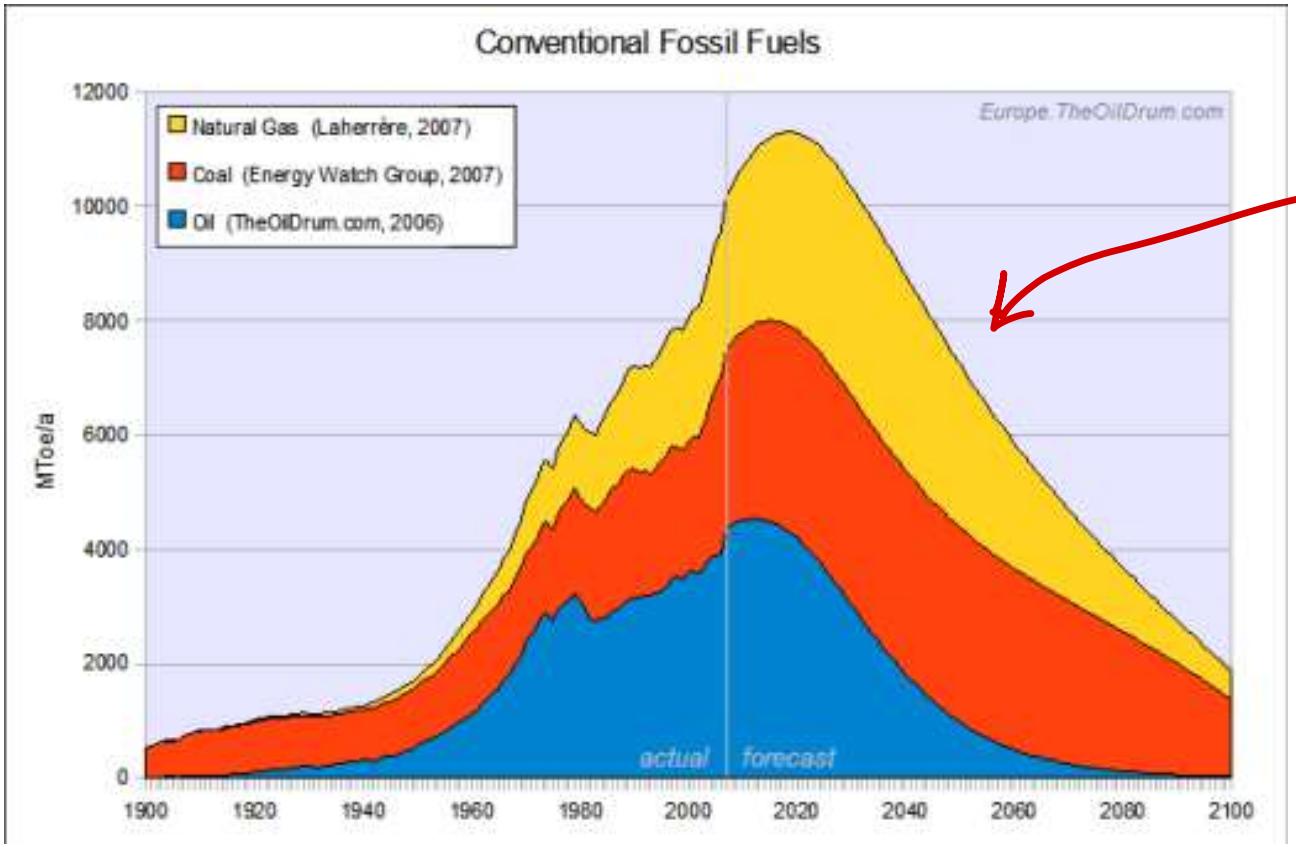
In electricity generation, renewables and natural gas are the fastest growing sources, but coal still fuels the largest share in 2040



Source: EIA, International Energy Outlook

Do we have enough resources to supply this electricity demand?

Availability of conventional Fossil fuels is expected to decline

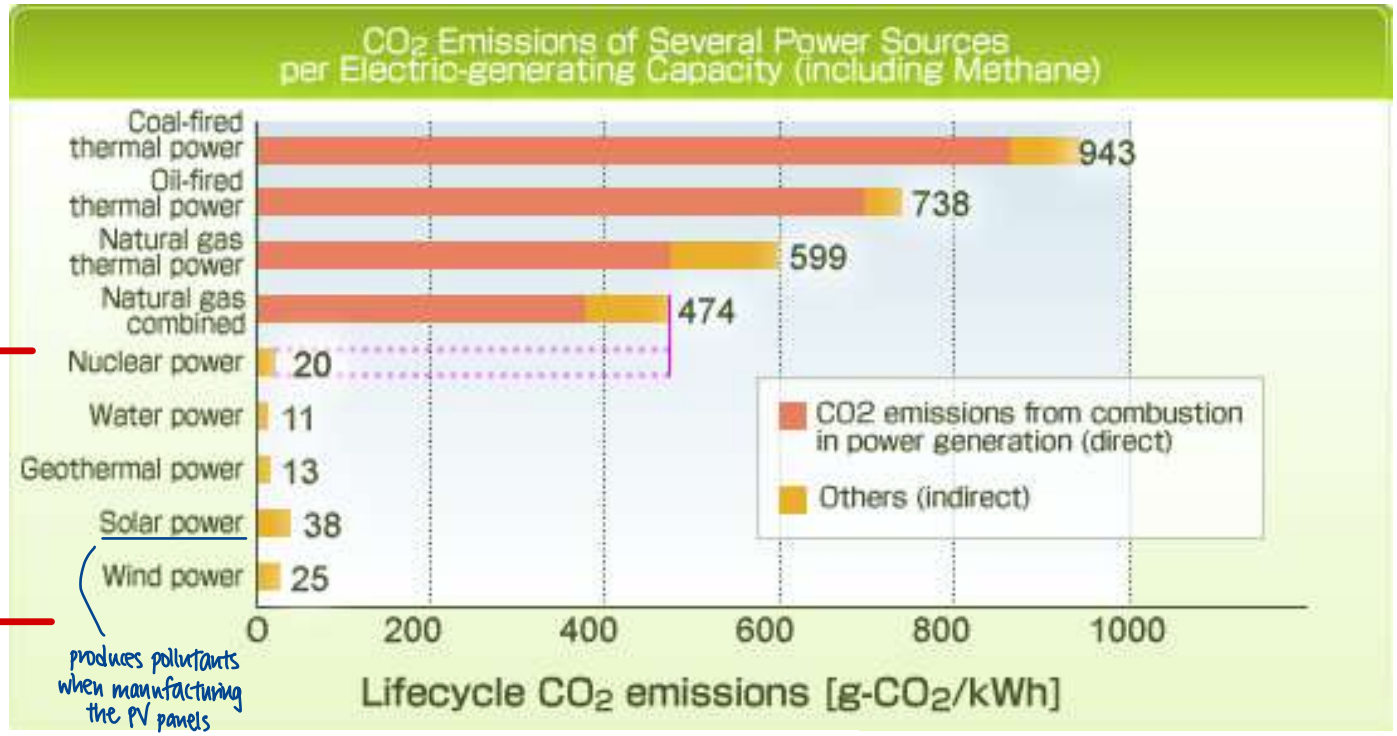


supply will start to diminish.

As the production increases due to a growing trend in consumption of energy, the supply of these fossil fuels will start to diminish.

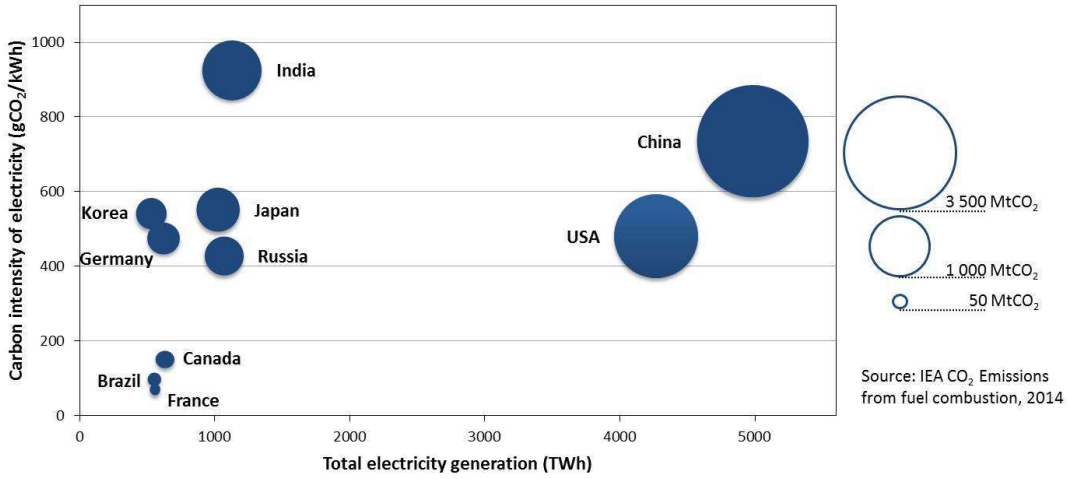
Source: Earth Trends, Environmental Information, World Resource Institute

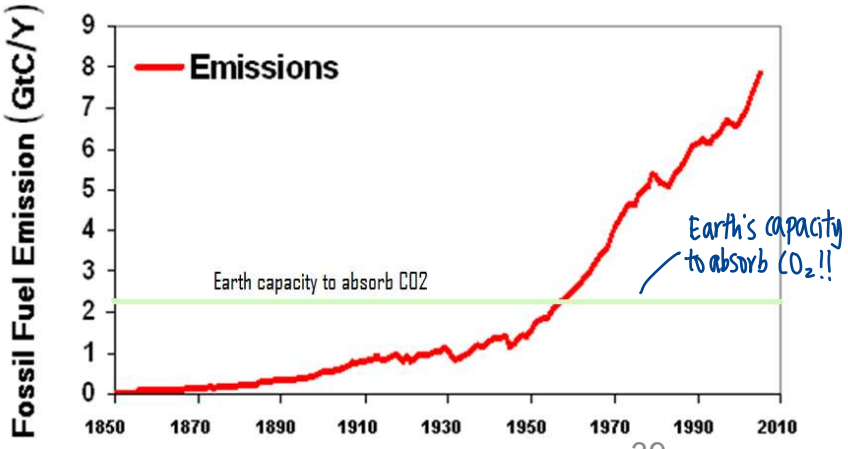
World Co_2 Emissions From Electricity Generation



renewables are less polluting

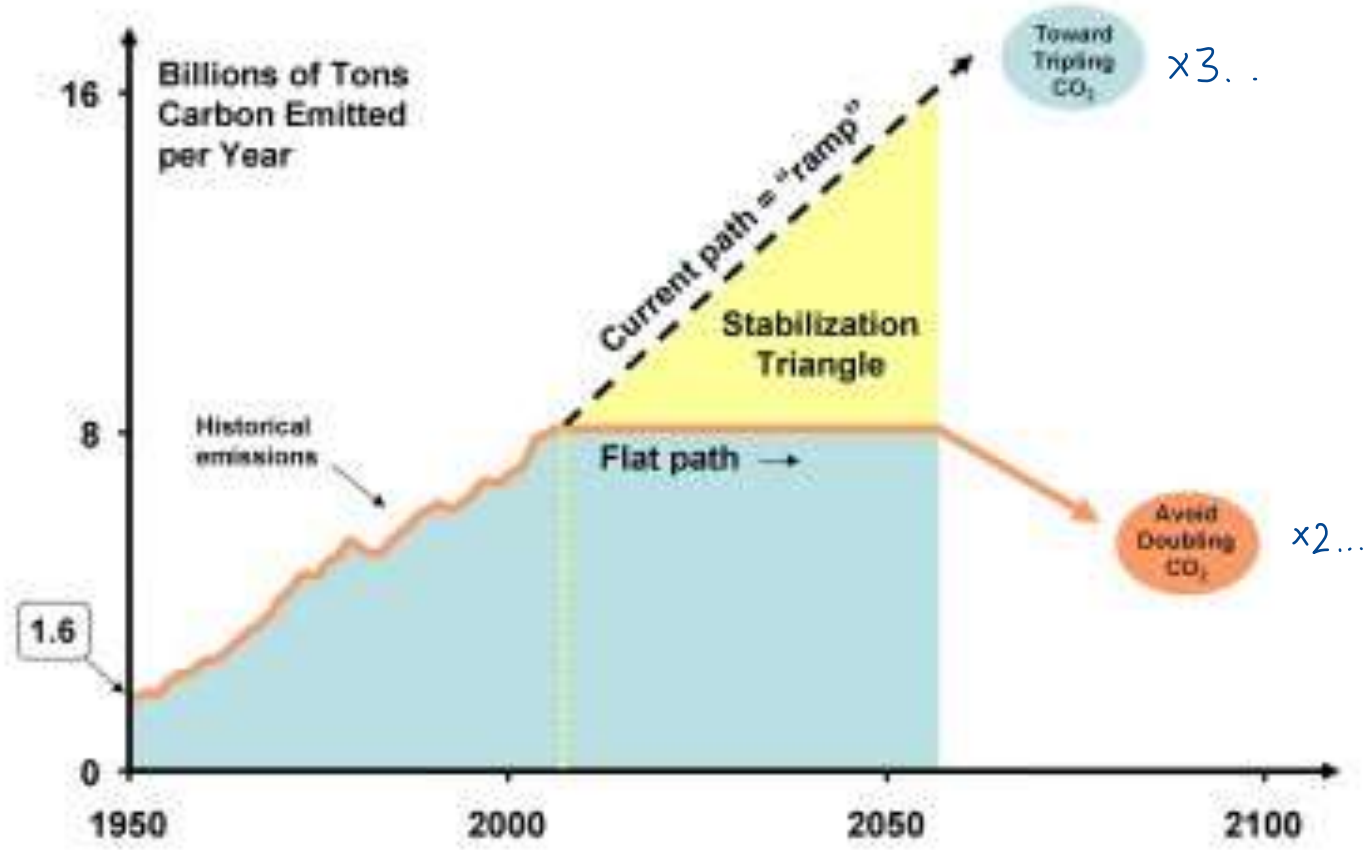
produces pollutants when manufacturing the PV panels





Source: EIA, US Department of Energy

Variation in Carbon

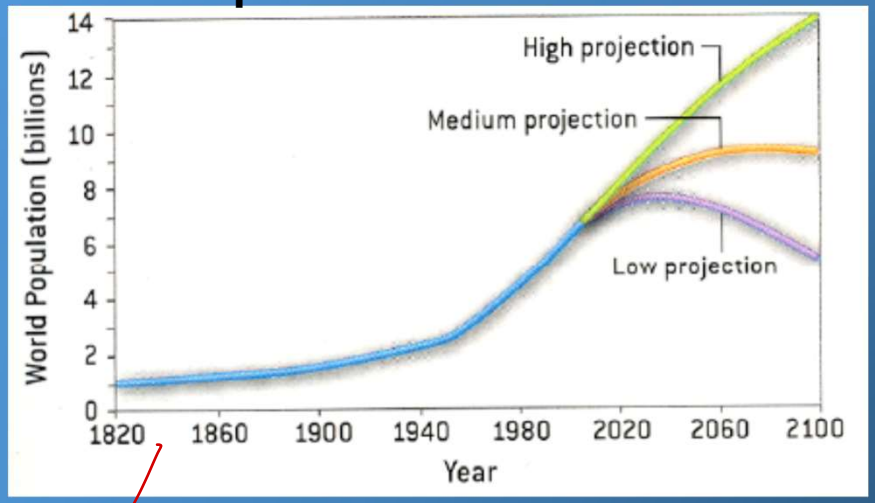


There is an urgent need to curtail CO_2 emissions!

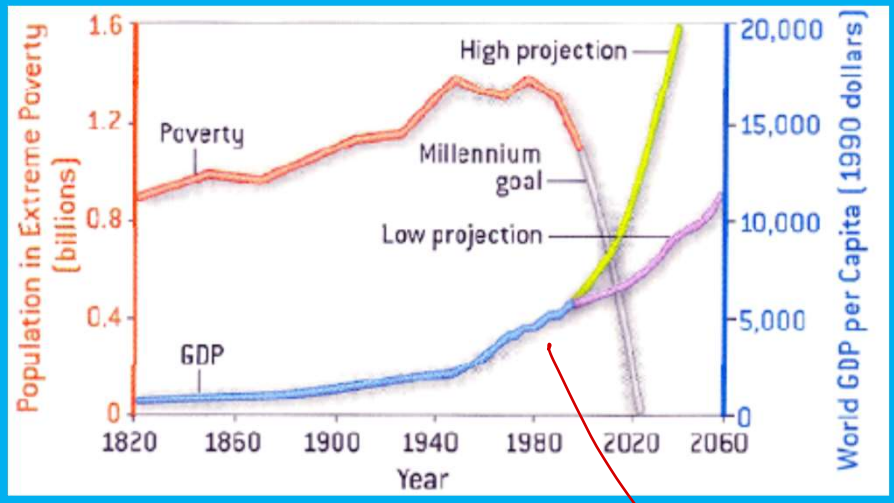
Source: Earth Trends, Environmental Information, World Resource Institute

Future projections ….

Population growth is expected to slow down

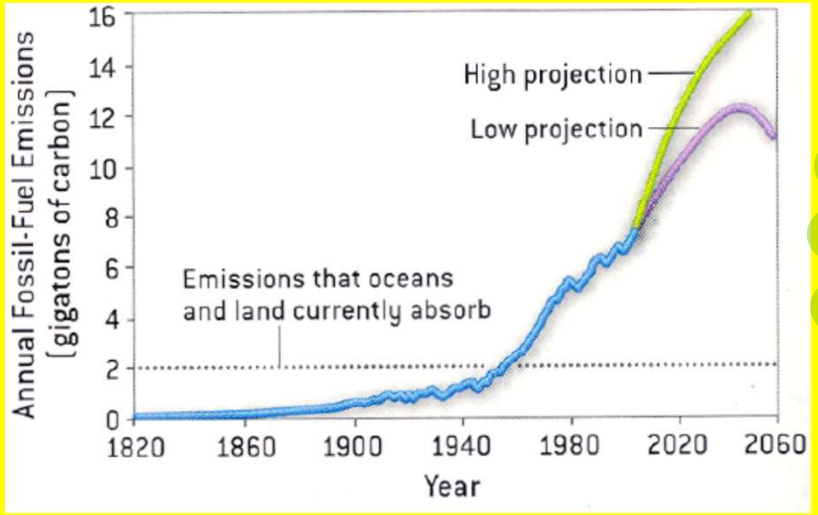


Global population below poverty line is expected to drop rapidly



↑ population, ↑ elec. consumed

↑ GDP ⇒ ↑ elec. consumed



Carbon emissions are projected to continue rising

Source: Earth Trends, Environmental Information, World Resource Institute

Issues related to reliability and security of supply

Rising security and reliability concerns

- Blackouts and Terrorist Threats

Great Northeast blackout – USA (August 14, 2003)

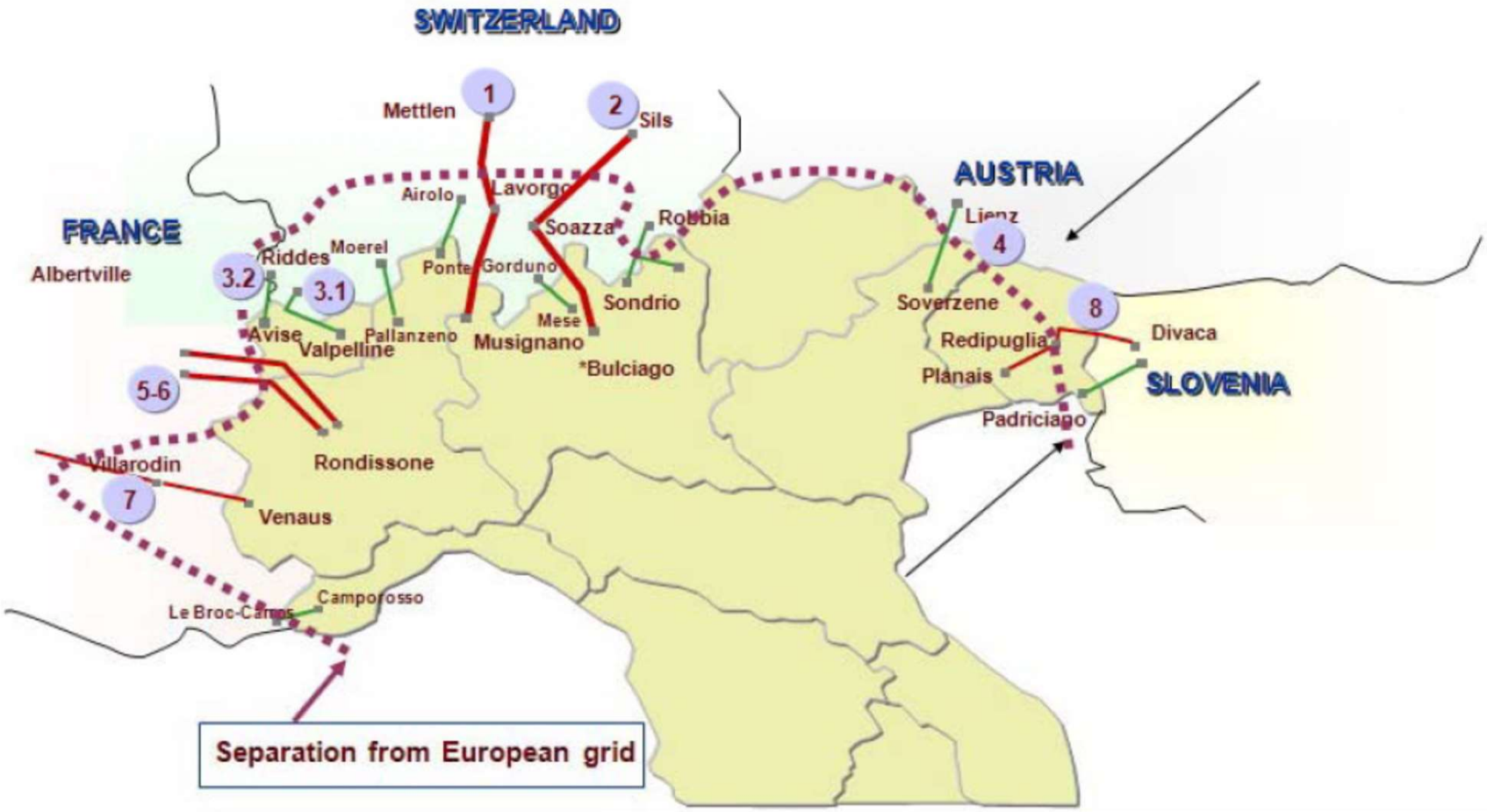
- **World's second most widespread blackout in history till August 2003**
- **Affected 45 million people in USA and Canada**

↳ "interconnected" systems ⇒ once fault happens, MANY people affected.

↳ over-reliant on traditional sources (renewable won't have such issue as Sun will always be present)

Rising security and reliability concerns

Italian & Swiss Blackout - 28 September 2003



Affected 56 million people

- **Loss of 28,000 MW**
- **Recovery in Southern Italy after 20 hours**

Rising security and reliability concerns

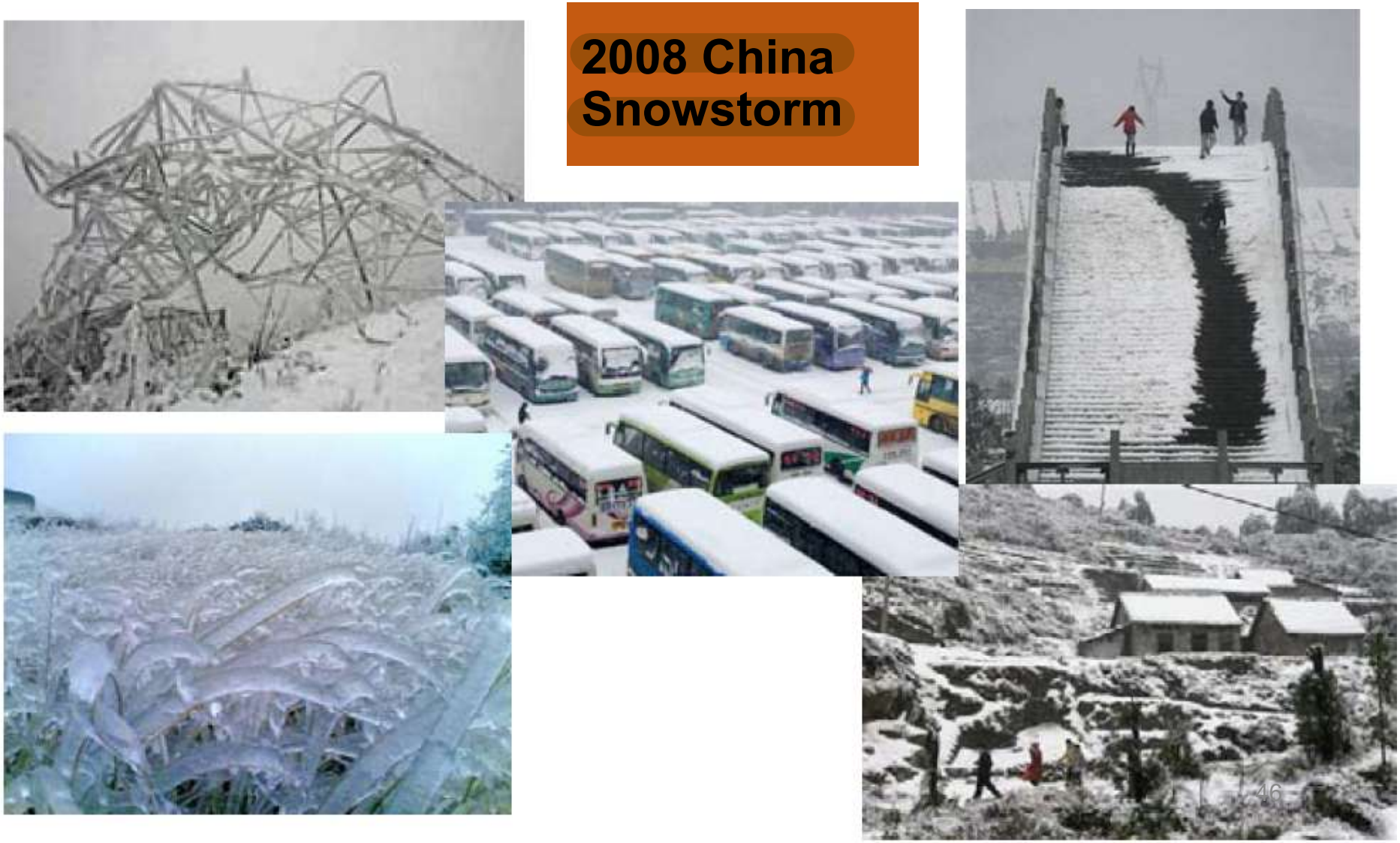
India: 700 million without power in 'biggest ever blackout'

- Power cuts plunge 20 of India's 28 states into darkness as energy suppliers fail to meet growing demand in July 2012

- An estimated 32 GW of generating capacity was taken offline
- Affected 700 million people

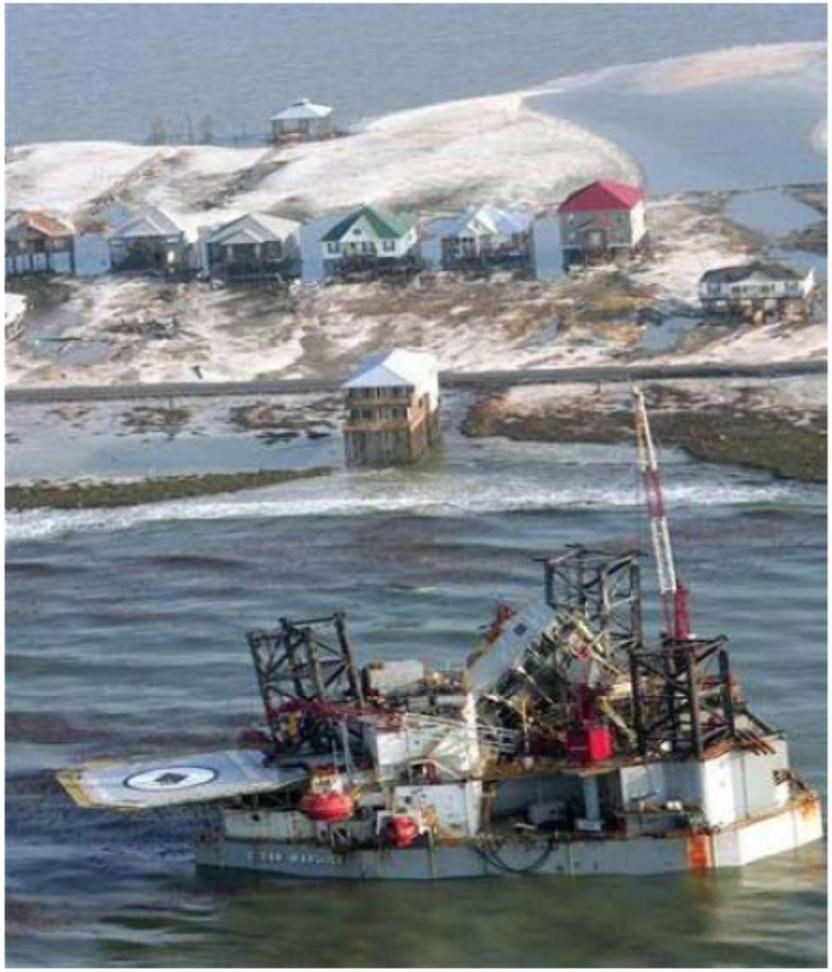
Rising security and reliability concerns

- Extreme weather events



Rising security and reliability concerns

- **Hurricane damage in the United States**



Gulf of Mexico damaged oil rig

A submerged oil refinery in Alabama

Changing structure of electrical energy systems

- **So What *IS the Problem?***
- The electric grid was created at a time when :
- pollution was without consequences
- energy was cheap
- the larger the generator size, the higher the efficiency

need new modern, adapted systems.

These design points are no longer valid!

Power system is largely based on the 1950s technology and not designed for the modern era!

Outcome of unexpected weather events cause rethinking

- Grid failure and hurricane damage in the US (Katrina, Rita, etc.) caused rethinking about tightly interconnected systems
- The snowstorm experience gave Chinese planners a pause about the philosophy of "bigger is better"
- **Diversification and redundancy are getting more interest from planners**

Renewable energy power plants are getting more attention due to energy security issues and environmental concerns

Why Should We Use Renewable Energy

- **Limited availability** of Non-renewable resources
- **Rising world energy consumption**
- **Security of Supply** (extreme weather, faults)
- **Sustainability**
  - Energy
  - Environment
  - Society
  - Economy

Energy Demand

By 2050:

- 9 billion people, *2.5 billion more than today*
- 2 billion cars, *double the number today*
- China and India will dominate Asia's energy demand, with China alone accounting for 40% of primary energy needs and 60% of emissions

Every 1% growth in GDP takes at least 0.5-1% more energy, and that rate has been growing rapidly in recent years towards 1:1 ratio as emerging economies develop heavy industries

Three hard truths will shape the future of the ecosystem

- Surge in energy demand
- Declining supply of Resources
- Rising Environmental stresses

We are entering an era of revolutionary transitions!

Hence we need to explore renewable and sustainable sources of electricity

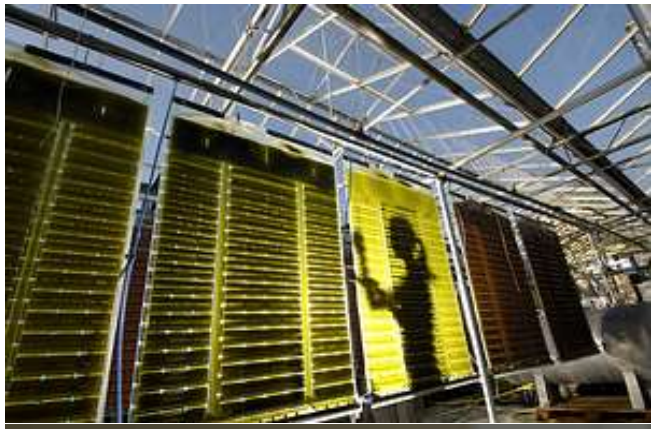
Solution: Renewable Energies on a Large Scale

A combined use of renewable energy sources could meet our current energy needs:

- ***Solar energy (photovoltaic and thermal)***
- ***Hydroelectric energy***
- ***Wind energy***
- ***Geothermal energy***
- ***Ocean Thermal energy***
- ***Ocean wave energy***
- ***Tidal and currents energy***

These technologies are available today …

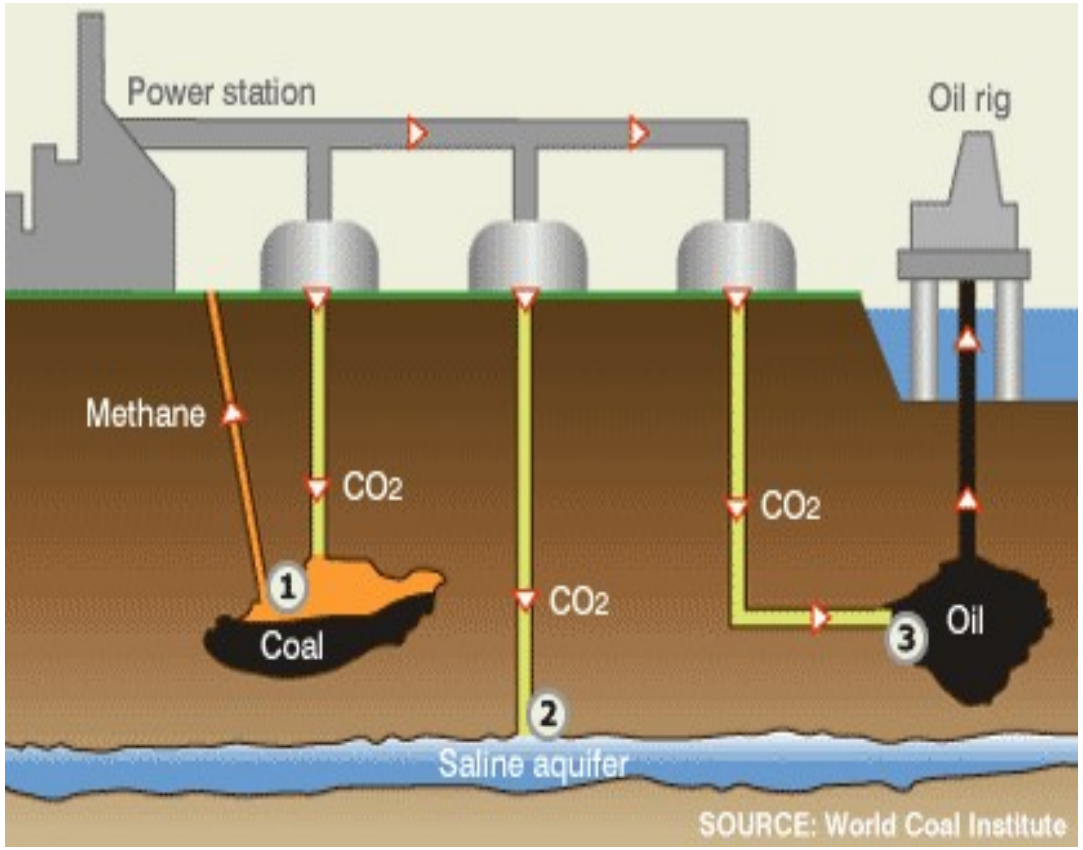
We must however rapidly make the shift going away from fossil fuel based energies



Solution:
Biofuel Generation (for example - from Algae)

- The current biofuel production process is highly unsustainable (land use, energy requirements) => negative impact on agriculture
- Biofuel generated from algae could solve these issues:
  - ***saving in energy***
  - ***saving in land use***
  - ***high yield*** (grows quite fast)
- **Fuel of the future?**

Solution: Carbon Sequestration



↓ CO_2 emissions.

- Long-term storage of CO2 and other forms of Carbon
- Sequestrating carbon emissions underground is a safe process
- Similar technology used for the extraction of natural gas can be applied
- The carbon will remain trapped for millions of years

Source: World Coal Institute

How do we achieve the balance between increasing demand for electrical energy and sustainable development?

- **Electricity supply mix away from fossil fuels**

- development of wind, solar, biomass, geothermal, and energy from the oceans

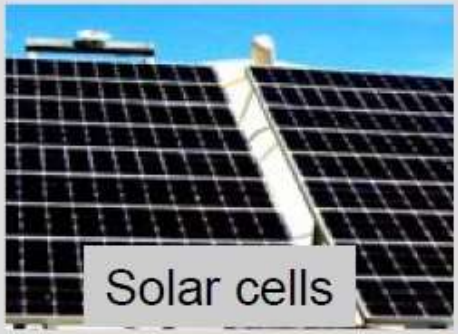
- **Expanded focus on energy efficiency**

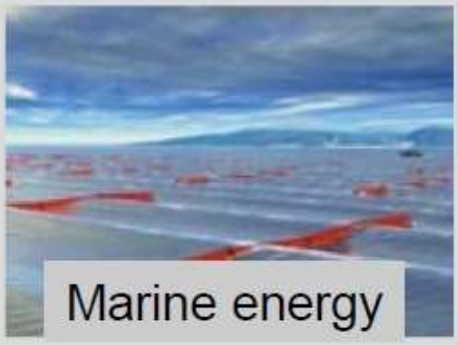
- **Smart electric power grid**

- Greater application of IT, artificial intelligence and communication technologies

The Revolution Is Coming!

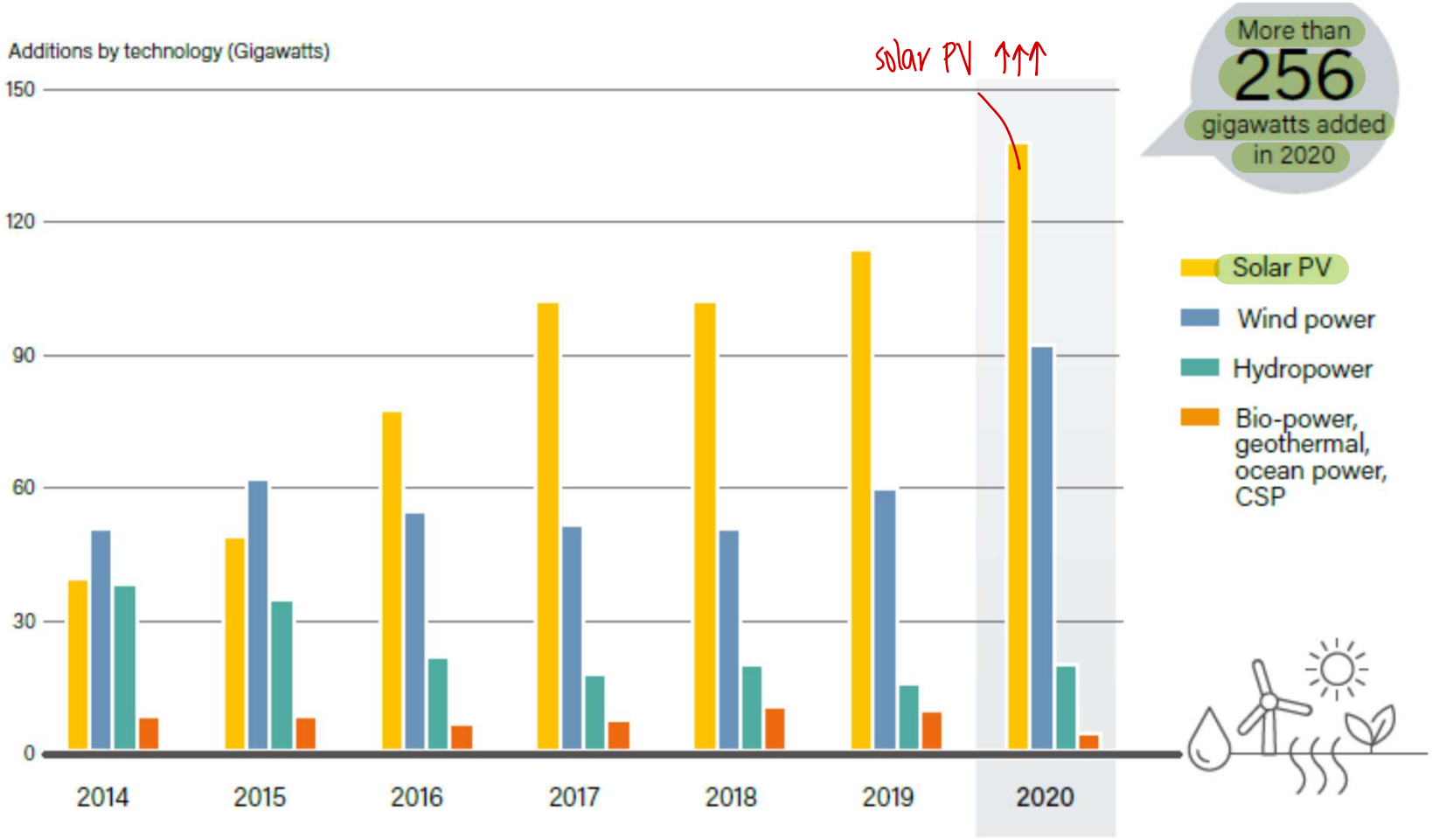
Candidate sources for distributed generation





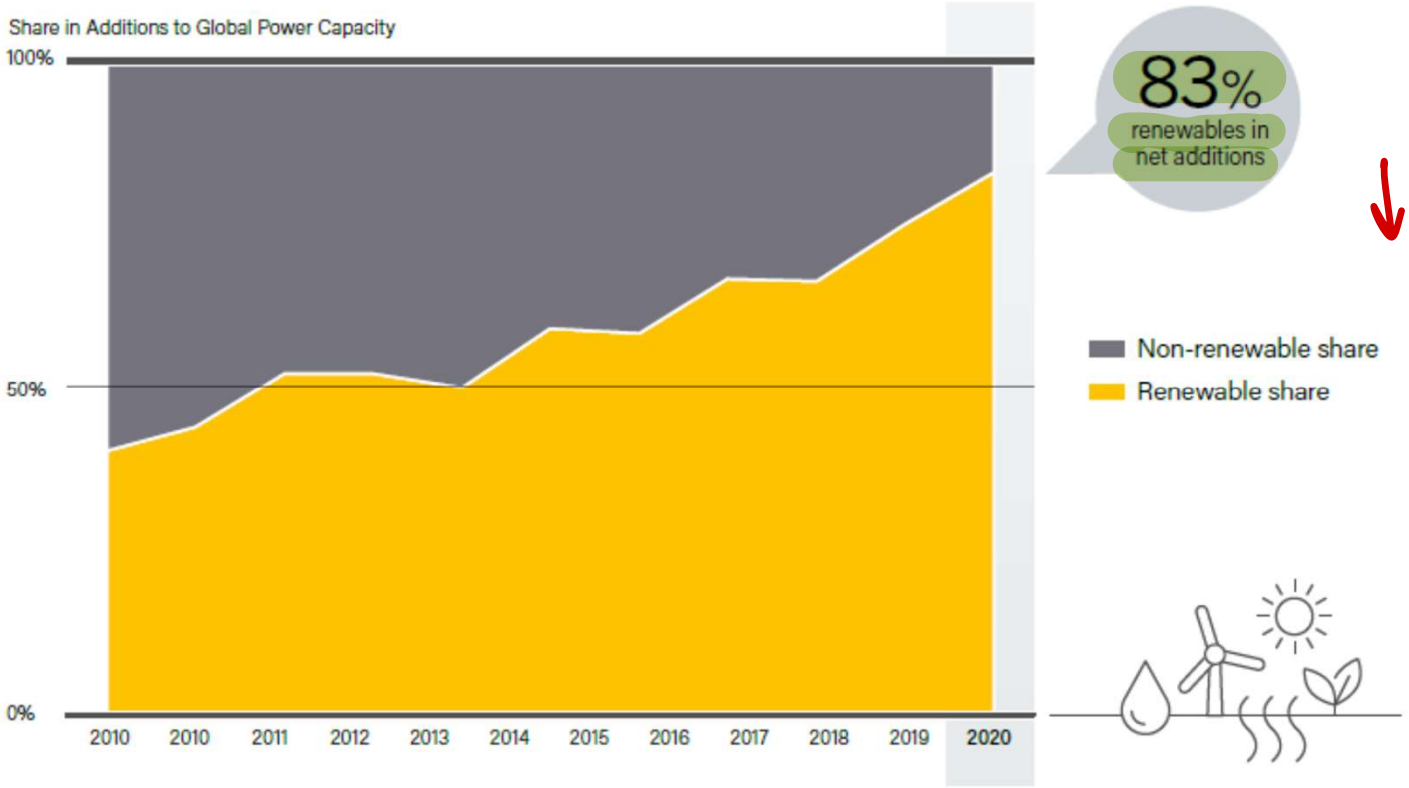
Total Installed Capacity and Growth Rates

Annual additions of Renewable Power Capacity, by technology and total, 2014-2020



Source: REN21's Renewables 2021 Global Status Report

Annual Additions in Power Generating Capacity



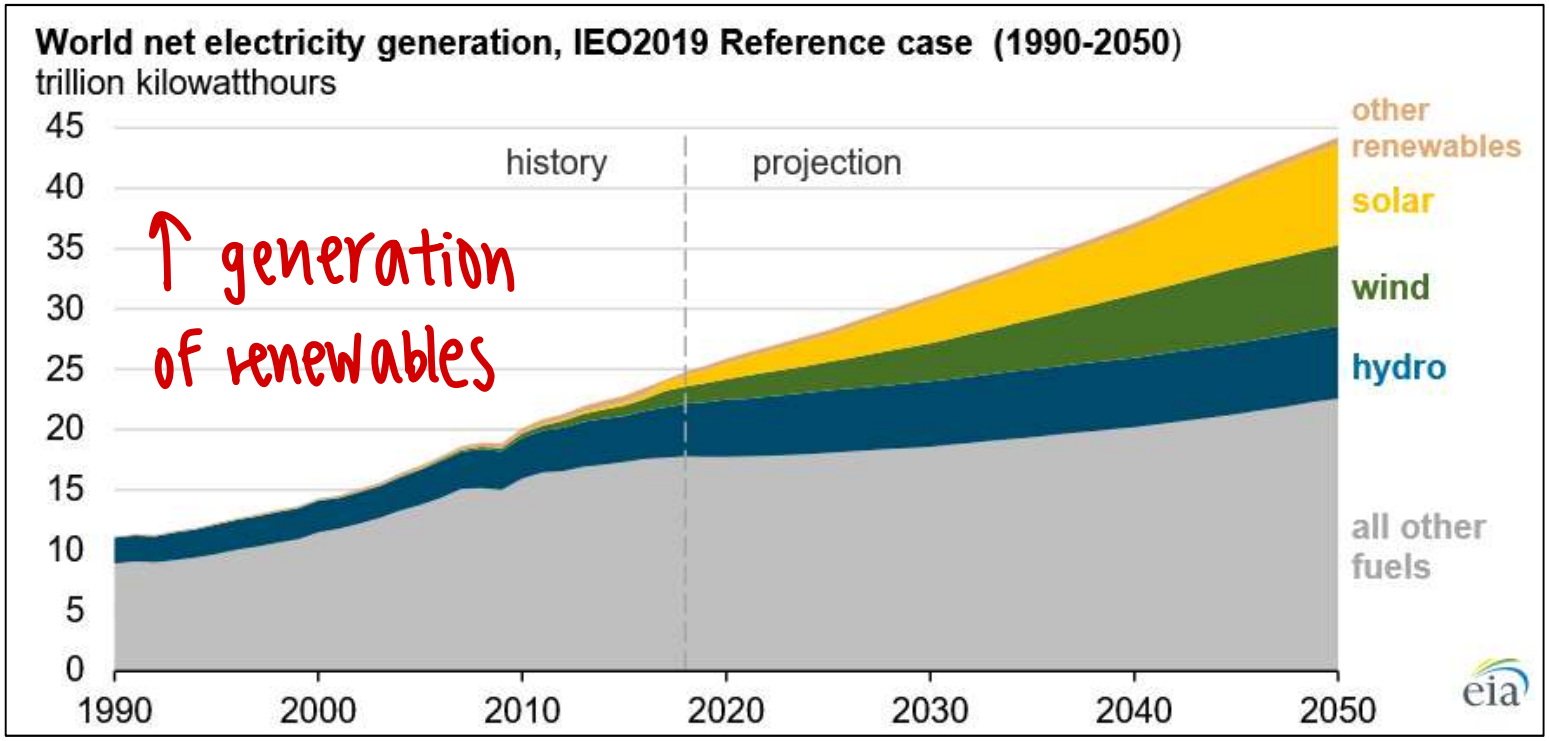
↓ non-renewables added,
↑ renewables added!!

Share of renewables in global total power generation capacity is growing steadily!

Source: REN21's Renewables 2021 Global Status Report

solar > wind > hydro > other fuels

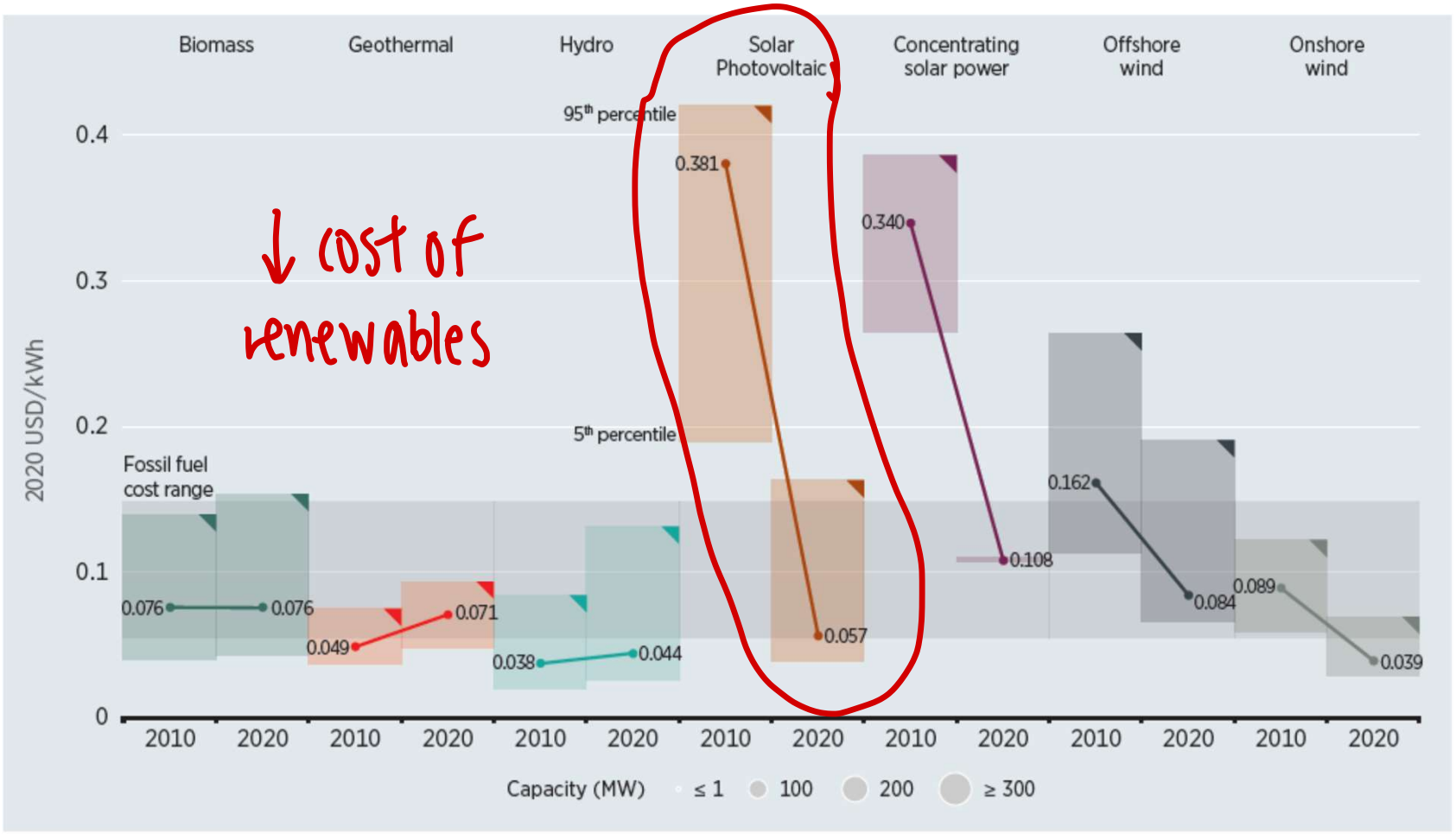
Renewable Energy Generation: History and projection



- Globally, renewables made up 29 percent of electricity generation in 2020, much of it from hydropower (16.8 percent)
- EIA projects that renewables will collectively increase to 50% of global electricity generation by 2050.
- Of the top three renewable sources, solar's share of generation is expected to grow the fastest and hydroelectric's share to grow the slowest

Source: *U.S. Energy Information Administration, International Energy Outlook 2019*

Renewable Energy Generation: Falling cost



Source: IRENA Renewable Cost Database

Renewable power generation costs have fallen sharply over the past decade, driven by steadily improving technologies, economies of scale, competitive supply chains and improving developer experience. Costs for electricity from utility-scale solar PV fell 85% between 2010 and 2020.

Top Five Countries: Renewable Power Capacity

Total Power Capacity or Demand / Output as of End-2020

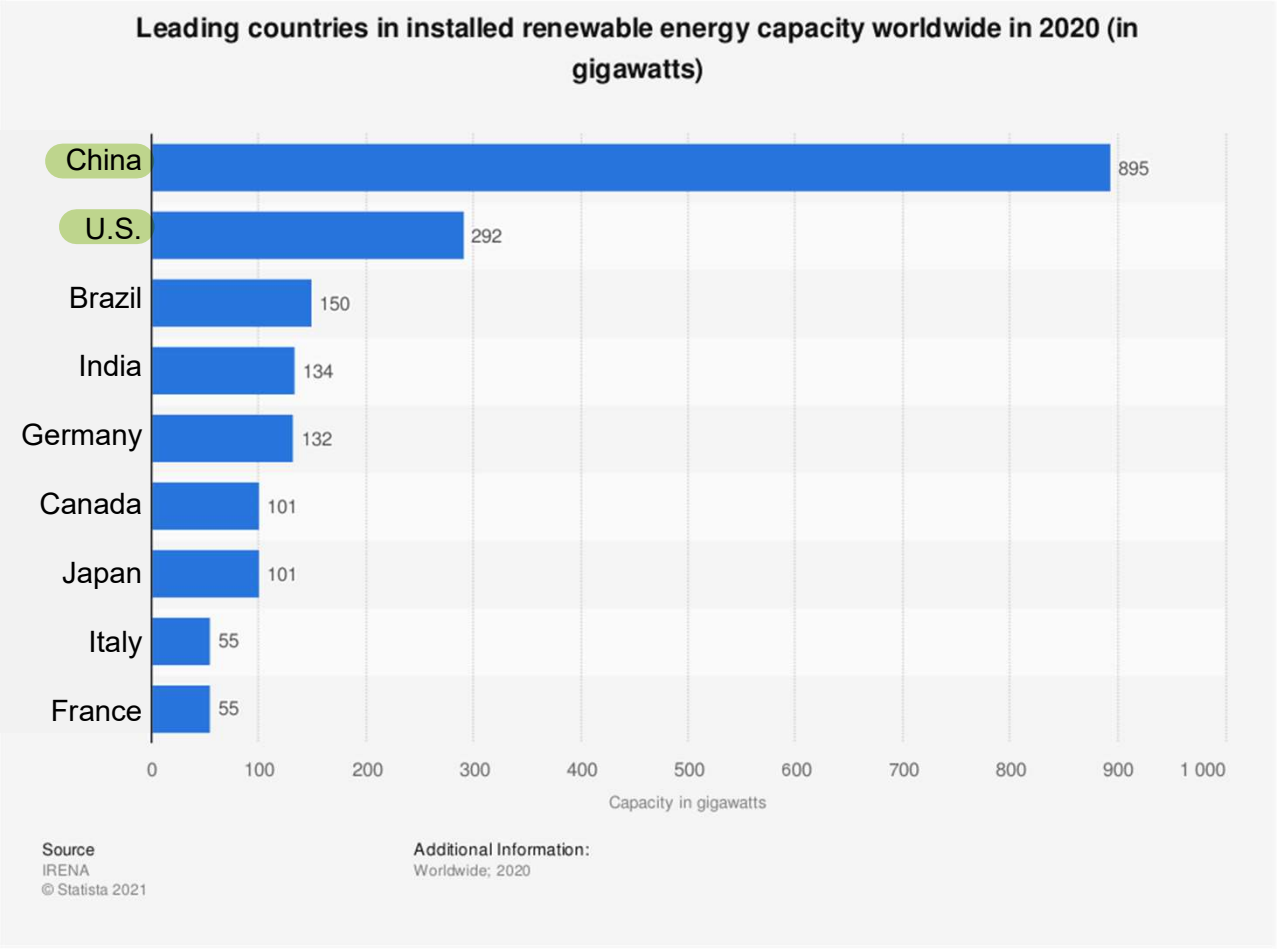
	1	2	3	4	5
POWER					
Renewable power capacity (including hydropower)	China	United States	Brazil	India	Germany
Renewable power capacity (not including hydropower)	China	United States	Germany	India	Japan
Renewable power capacity *per capita* (not including hydropower)[1]	Iceland	Denmark	Sweden	Germany	Australia
Bio-power capacity	China	Brazil	United States	Germany	India
Geothermal power capacity	United States	Indonesia	Philippines	Turkey	New Zealand
Hydropower capacity[2]	China	Brazil	Canada	United States	Russian Federation
Solar PV capacity	China	United States	Japan	Germany	India
Concentrating solar thermal power (CSP) capacity	Spain	United States	China	Morocco	South Africa
Wind power capacity	China	United States	Germany	India	Spain

China is leading the renewable generation of electricity ⇒ BUT consumption rate for renewable energy is LOW...

Source: REN21's Renewables 2021 Global Status Report

Renewable Power Capacities in the World

China leads, with nearly 30% of the world's renewable power capacity (approx. 900 GW)



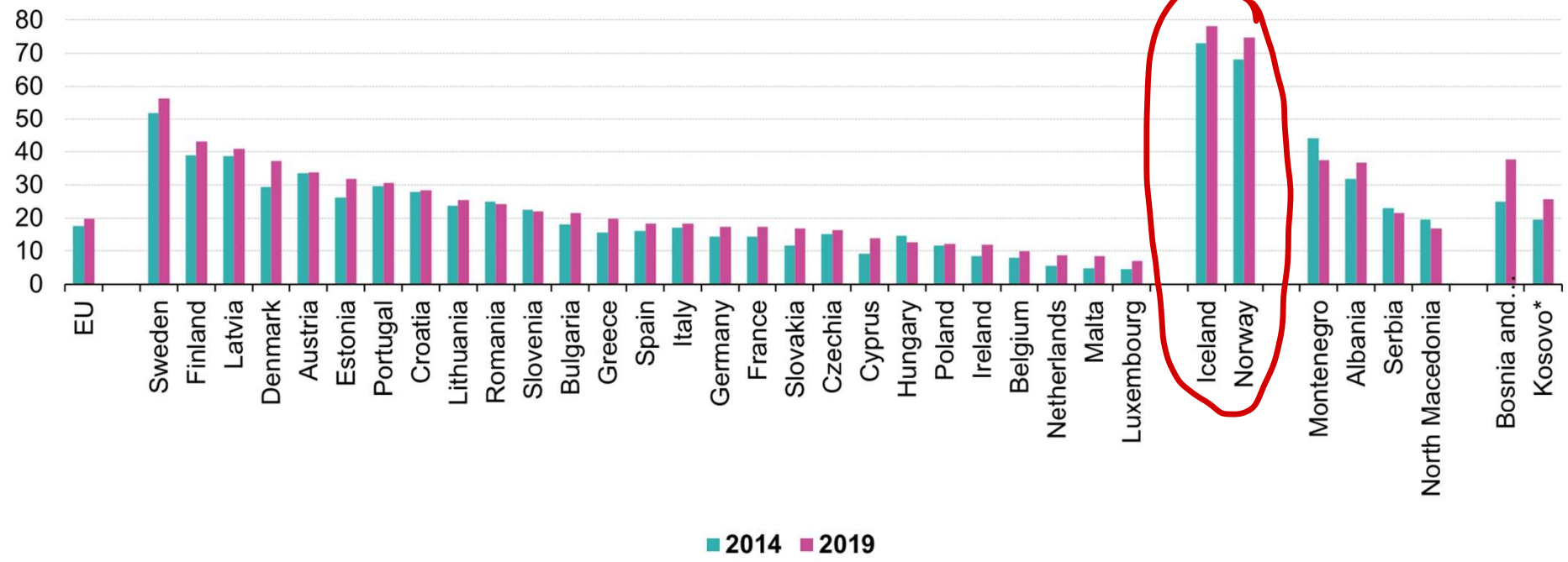
Source: IRENA Renewables 2021 Global Status Report

Share of Renewable energy in total energy consumption in EU

highest consumption in general + for renewables

Share of renewable energy in gross final energy consumption, by country, 2014 and 2019

(%)



(*) This designation is without prejudice to positions on status, and is in line with UNSCR 1244 and the ICJ Opinion on the Kosovo Declaration of Independence.

Source: Eurostat (online data code: sdg_07_40)

eurostat

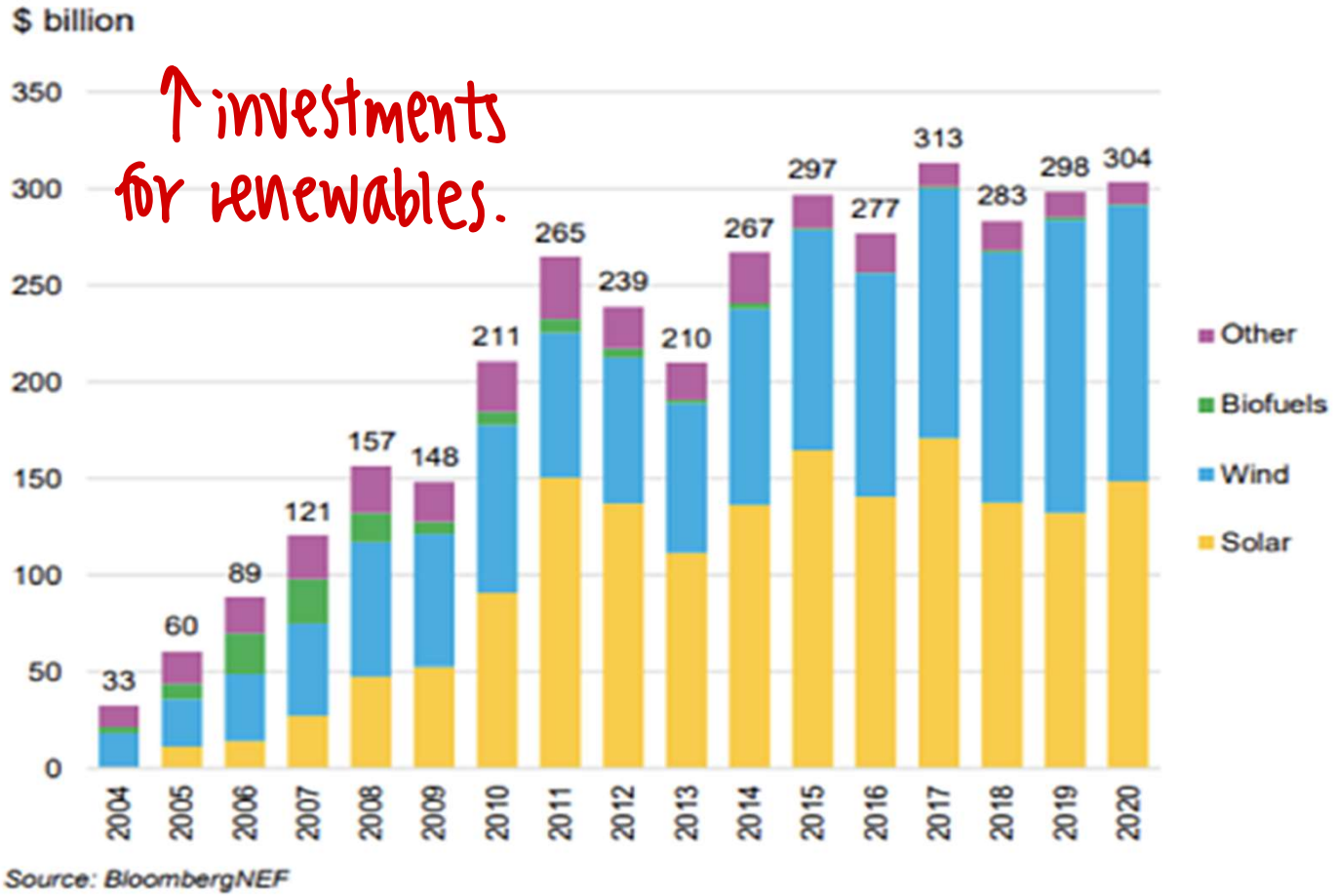
Renewable Energy Jobs by Technology (2012-2020)

The year 2020 demonstrated that not even a global pandemic can slow the advance of renewable energy

- The number of jobs in renewable energy worldwide increased in 2020 (by 500,000), despite the huge economic disruptions caused by the COVID-19 pandemic.
- The crisis, together with the challenges of global warming, reinforced the need for a transition towards clean, reliable energy supply and sustainable, climate-friendly jobs.

Source: IRENA Renewables 2021 Global Status Report

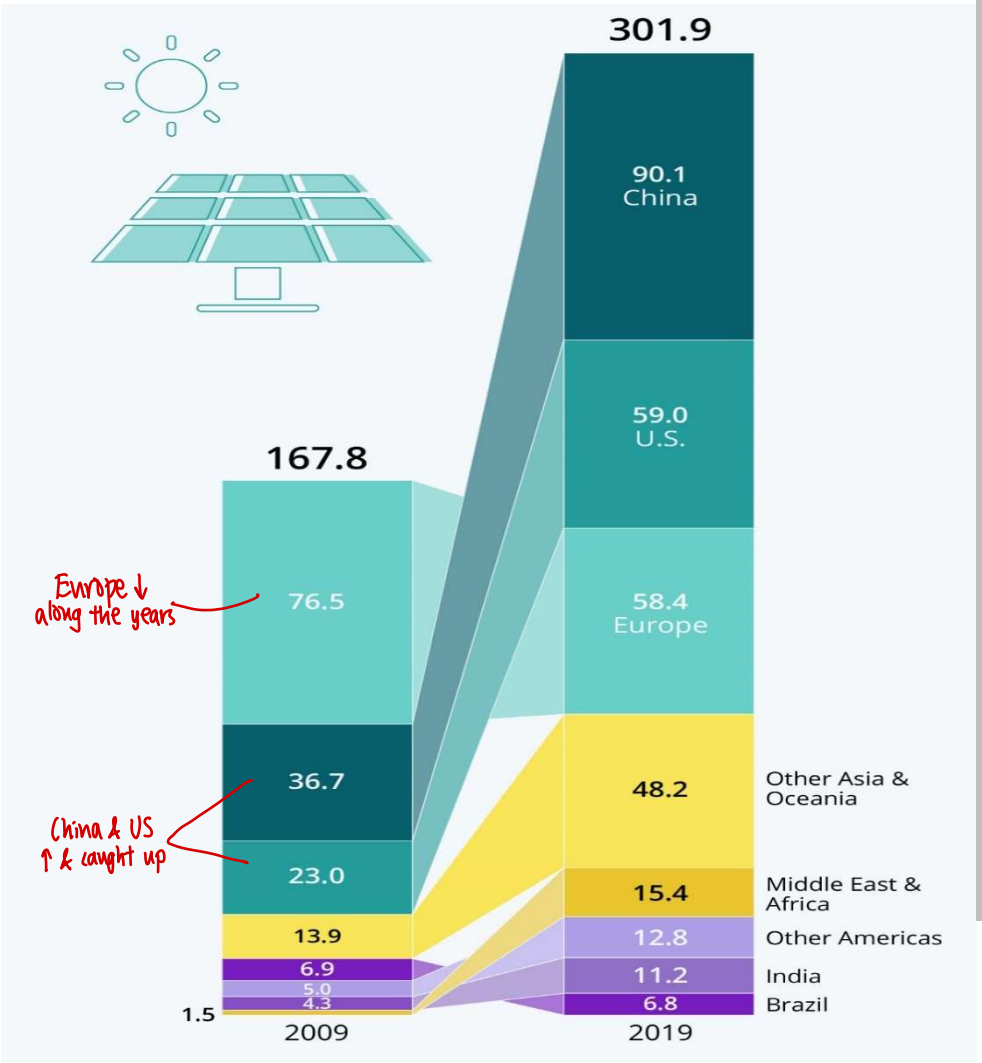
Global New Investment in Renewable Energy



- Most of the European countries have set goals to achieve net-zero emissions by 2030
- Current committed investments in renewables are still not enough to begin to bend the emissions curve with the goal of being Net-zero by 2030.

Source: Bloomberg, NEF

Who is Driving Investment in Renewable Energy?



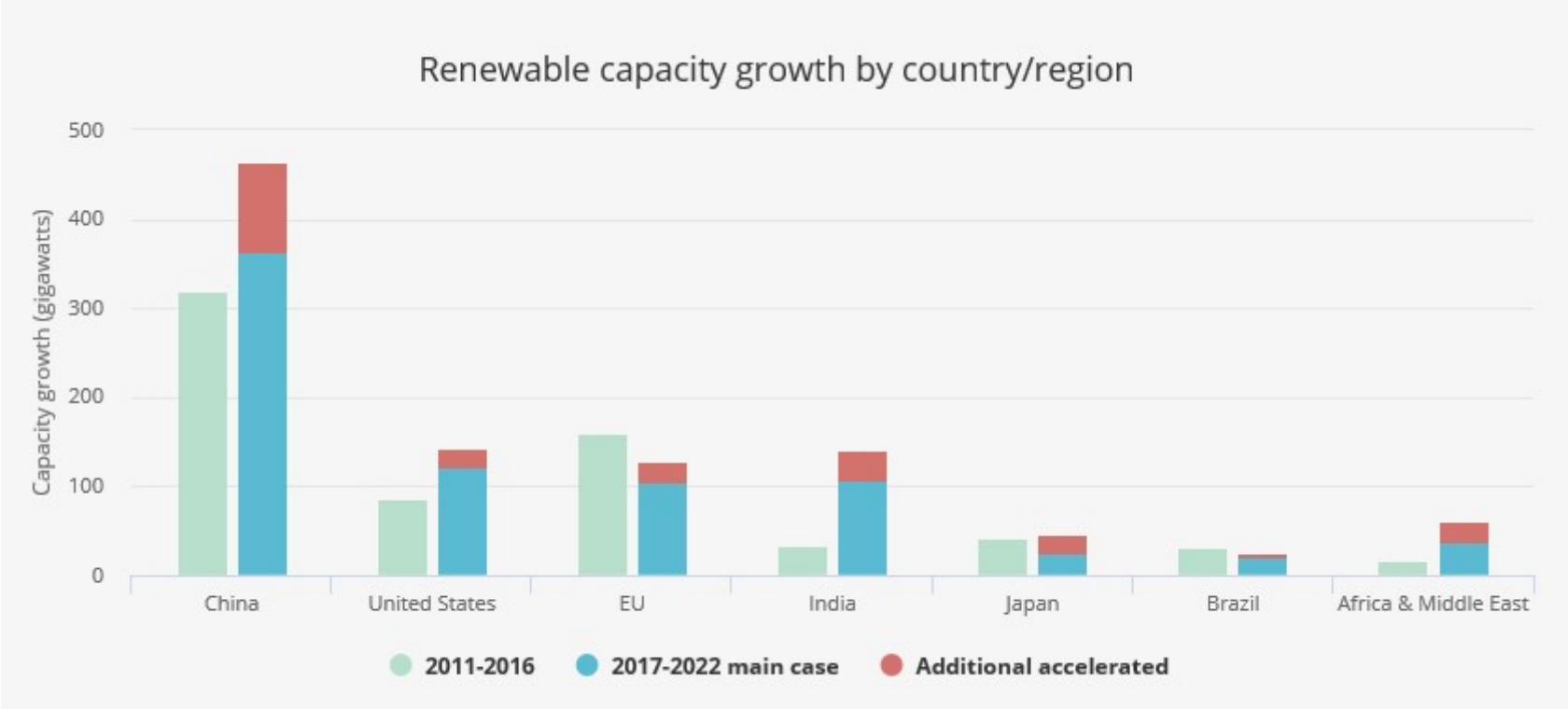
- Global investment in renewable energy has almost doubled in the past decade.
- China and the United States have taken over Europe
- A key Trend reinforcing clean energy investment is the push by oil and gas companies to establish low-carbon portfolios.

Source: Bloomberg, Statista

Investment in Billion US dollars

The data includes spending by companies and governments, investments in private equity and public markets as well as money spent on renewable energy installations and other assets

China is the undisputed Renewable Growth Leader

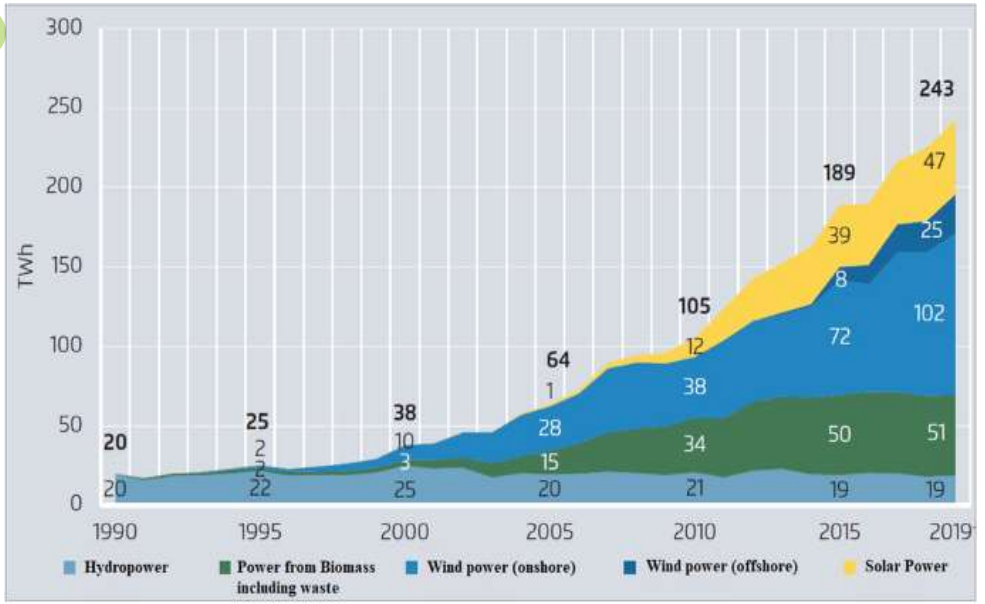


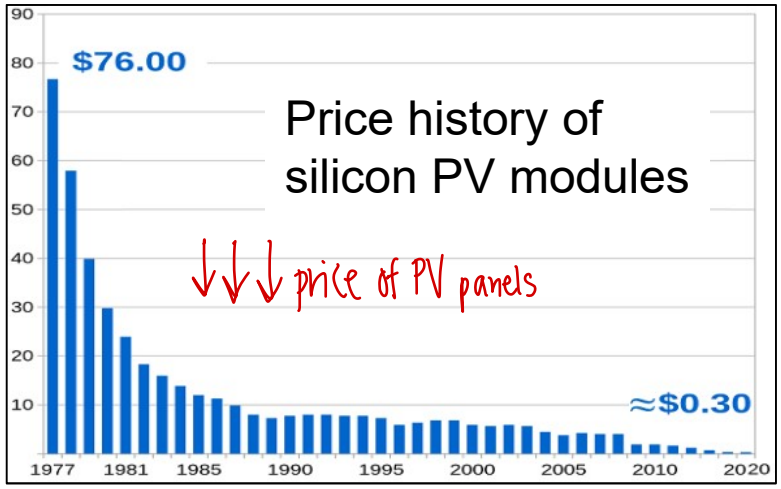
- China is the leader in global renewable capacity growth - largely driven by concerns about air pollution and capacity targets.
- China will bring its total installed capacity of wind and solar power to over 1200 GW by 2030. It expects to grow the share of non-fossil fuels in primary energy consumption to 25%

Source: Bloomberg, Statista

Benefits of Renewable Energy: Case Study of Germany

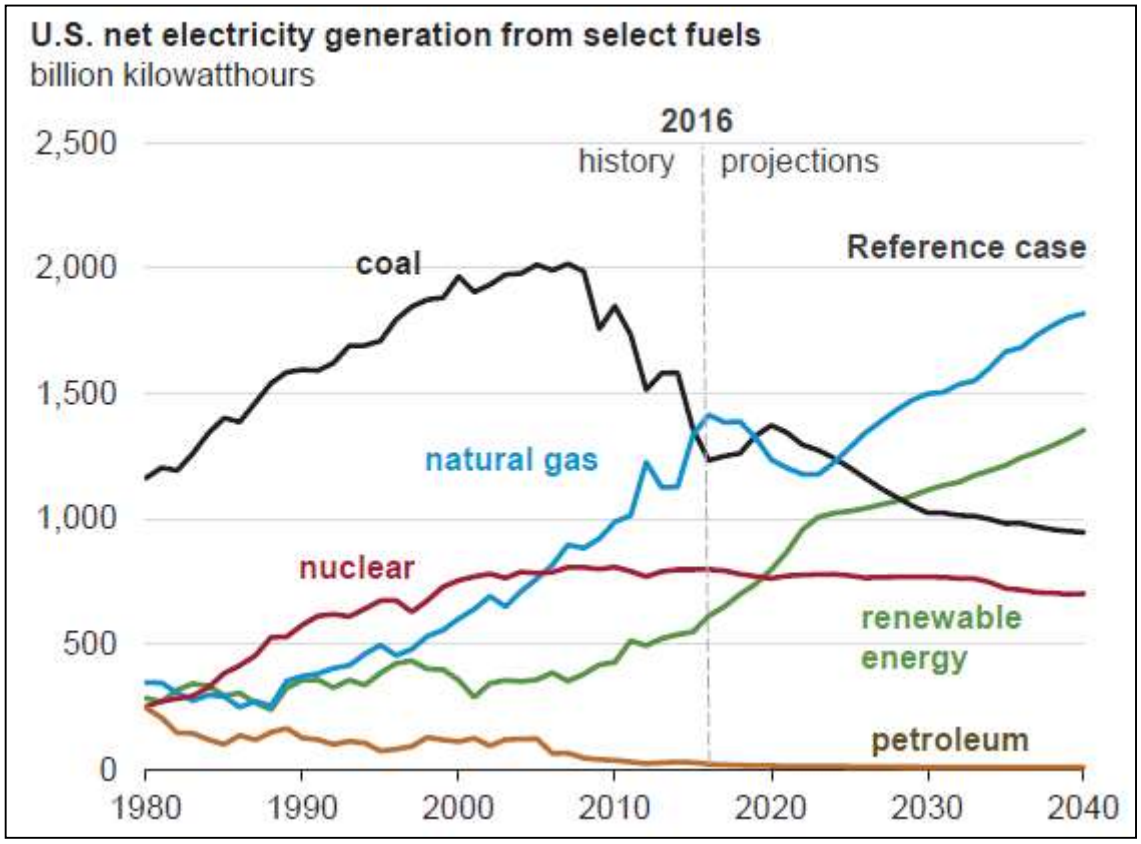
- Germany's renewable energy sector is among the most innovative and successful worldwide.
- The German Energiewende (energy transition) was an exemplary model of a new policy approach and caused a huge reduction in renewable electricity cost — govt. support is crucial.
- Policy encouraged ordinary citizens to invest in decentralized solar and wind power plants
- Net-generation from renewable energy sources increased from 6% in 2000 to about 40% in 2019





Source: REN21's Renewables 2021 Global Status Report

Growth of Renewable Energy projects in USA

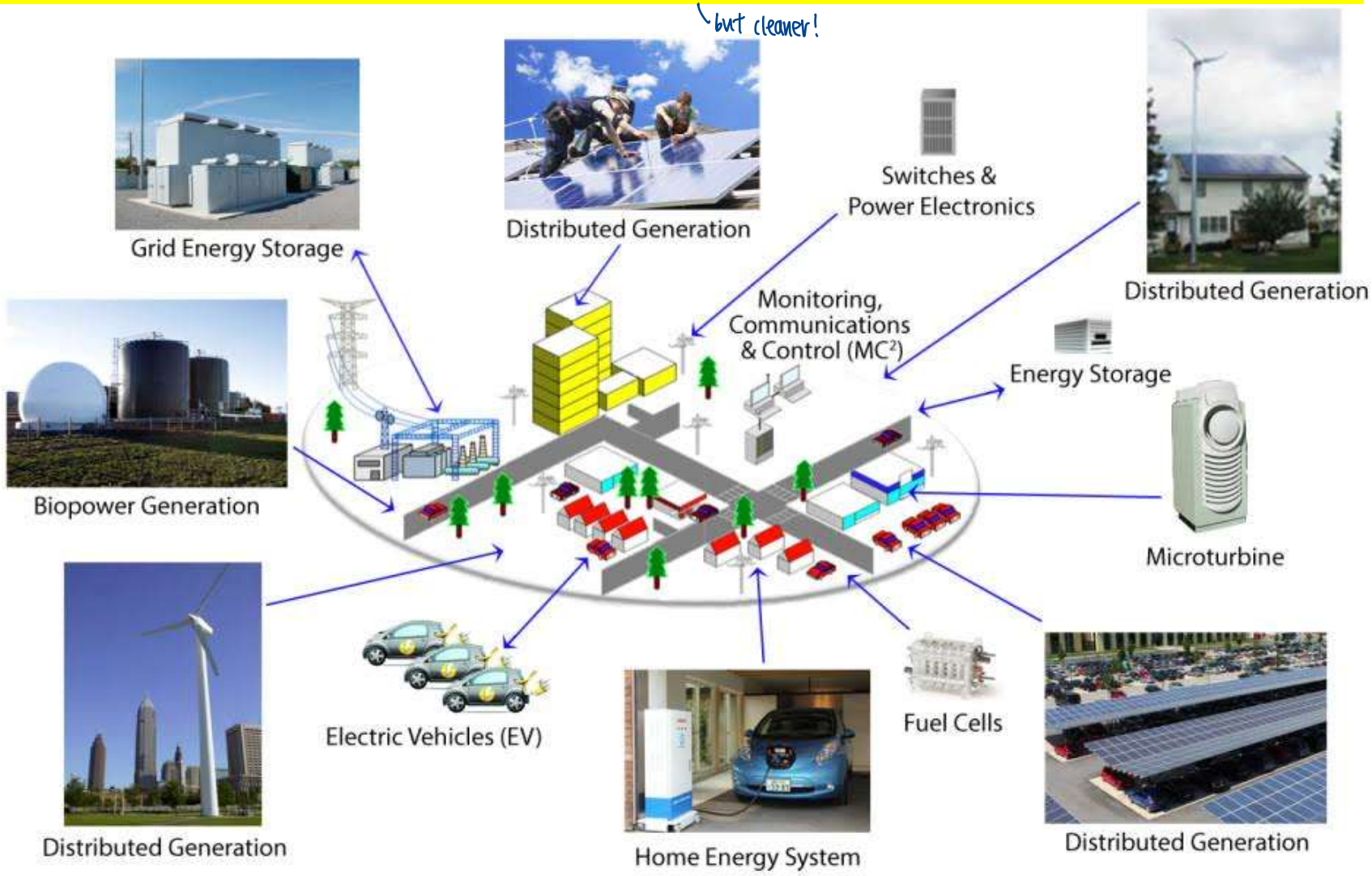


Fuel prices and current laws and regulations drive growing shares of renewables and natural gas in the electricity generation mix—

Source: EIA, International Energy Outlook 2018

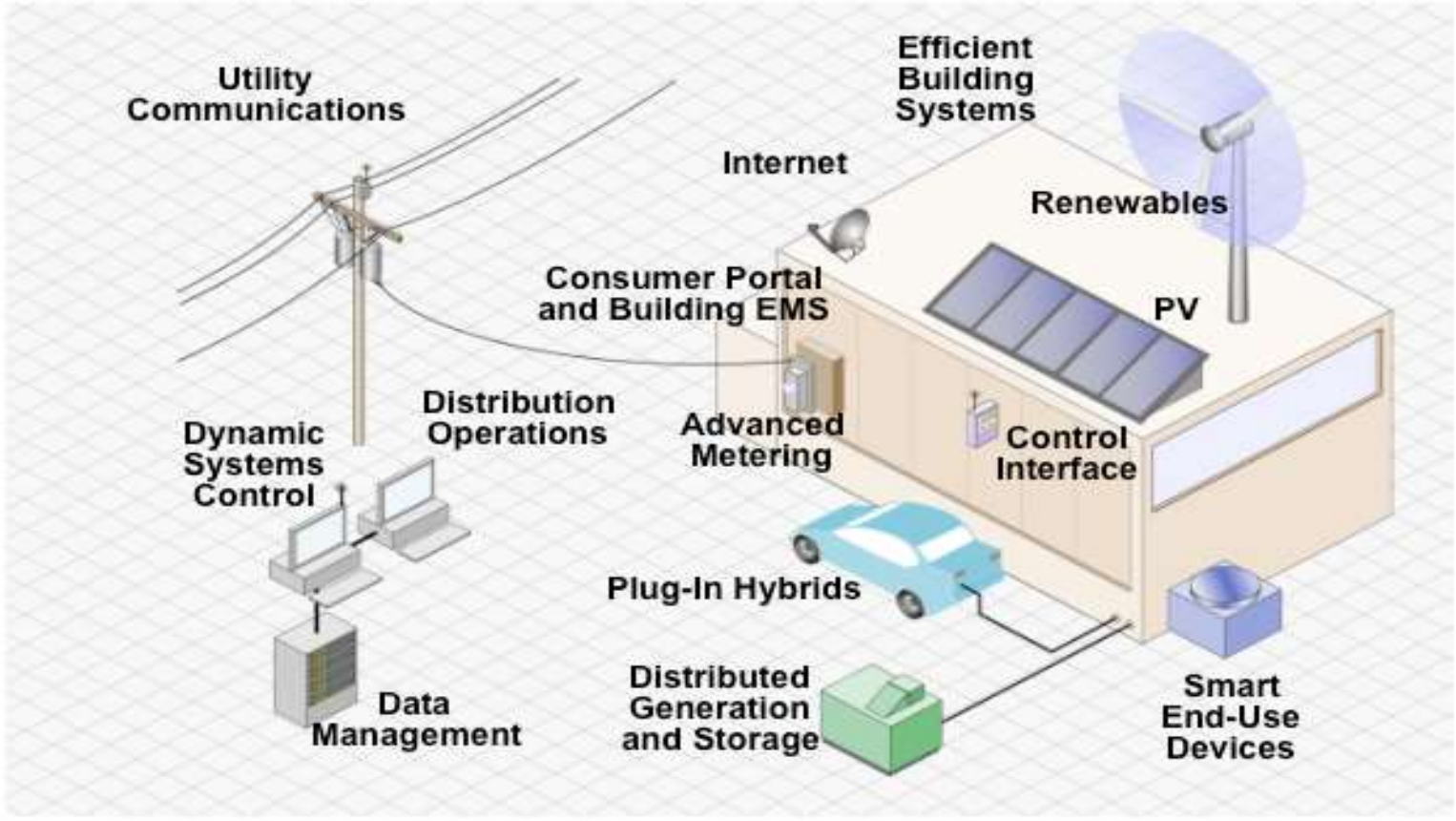
The Revolution Is Coming!

Future power grids will have diverse generating sources that incorporate renewables (renewables + traditional non-renewables but cleaner!)



The Revolution Is Coming!

Investments in “Smart Grid” electricity infrastructure will be needed



Renewable Generation and Smart Grid

A higher penetration of renewable energy sources could play a major role in reducing fossil fuel use.

Distributed energy sources for higher reliability and security

Smart techniques for optimal operation of these complex systems

Renewable Generation – Key Messages

Renewable energy can contribute in a major way towards meeting the global energy demand, while reducing the negative impacts of current production and use.

Renewable energy can help enhance reliability and security at global, national and local levels

Cost of electricity produced from renewables continued to fall in the last 3 years

Policy changes (i.e. tax incentives, subsidies, Carbon credits) are required