Course: Global Energy Transitions and Climate Policy

lecture 4. Systems Integration of Renewable Energy Sources

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The Agenda Today

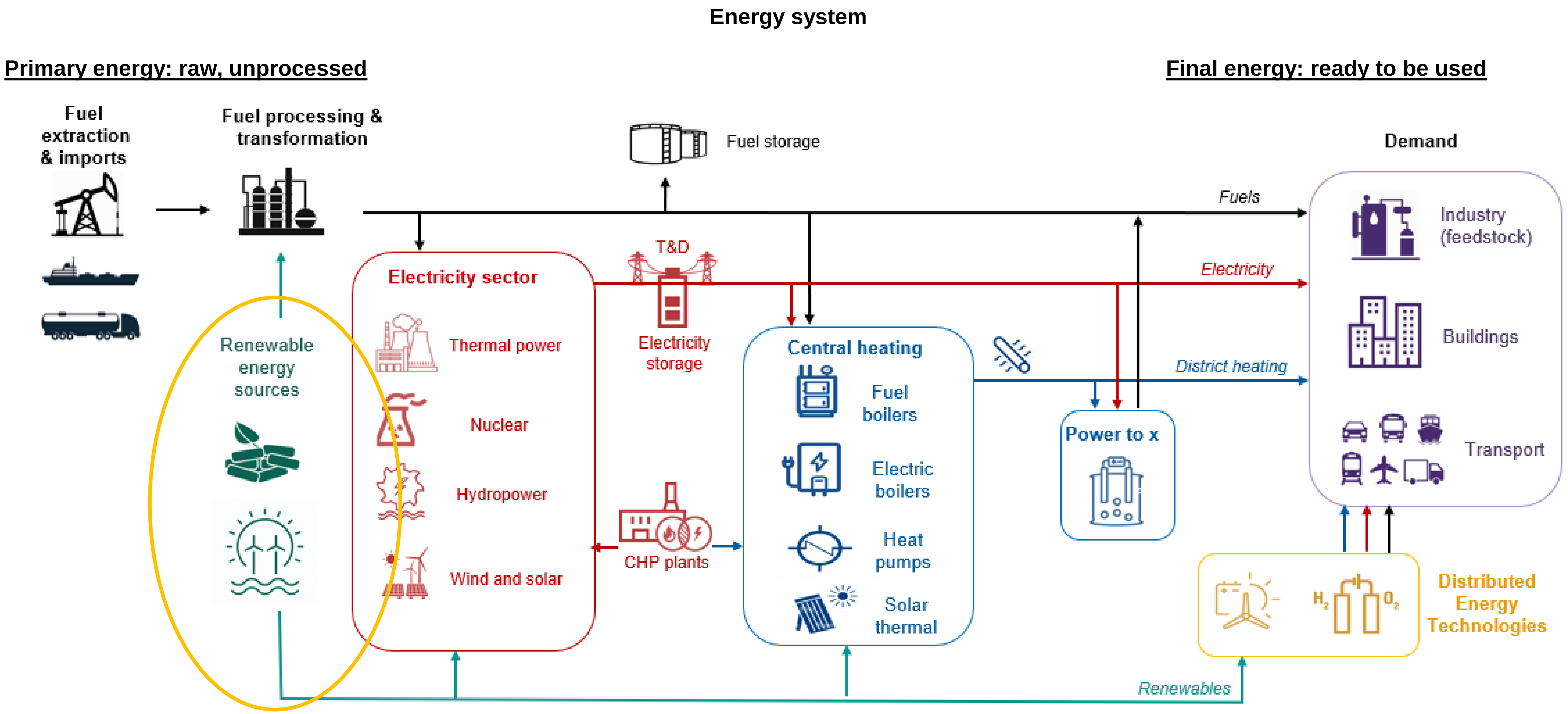
Part 1: Renewable Energy Systems

- Energy and climate change (continue)
- Global trends in penetration of renewable energy
- Potentials and challenges

Part 2: Energy storage systems

Image: https://esa-africa.com

Terminology (reminder)



Lecture 3.1.

Renewable energy systems

Energy Consumption History (recap)

- World primary energy use in 2015
- Huge dependence on fossil fuels

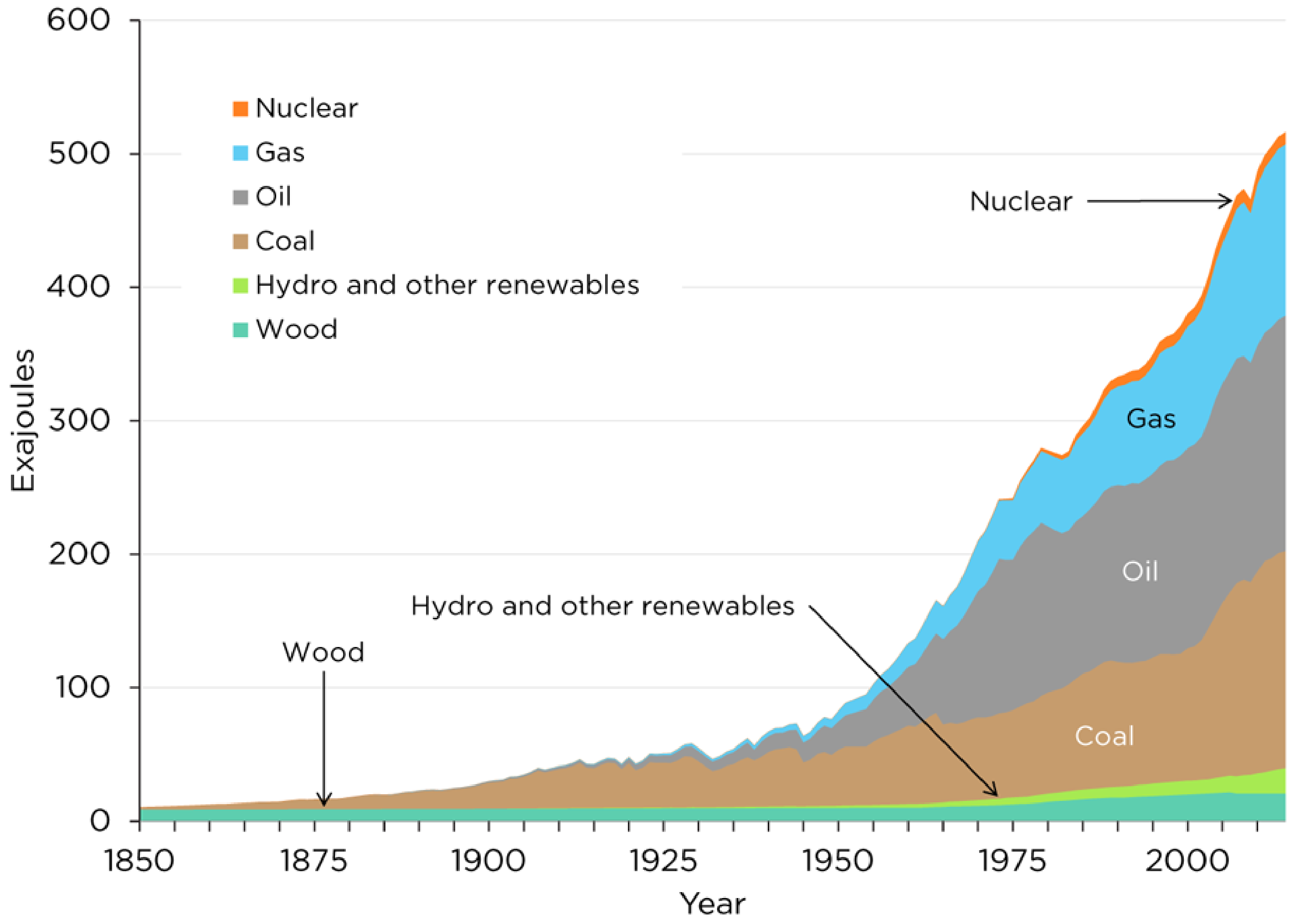
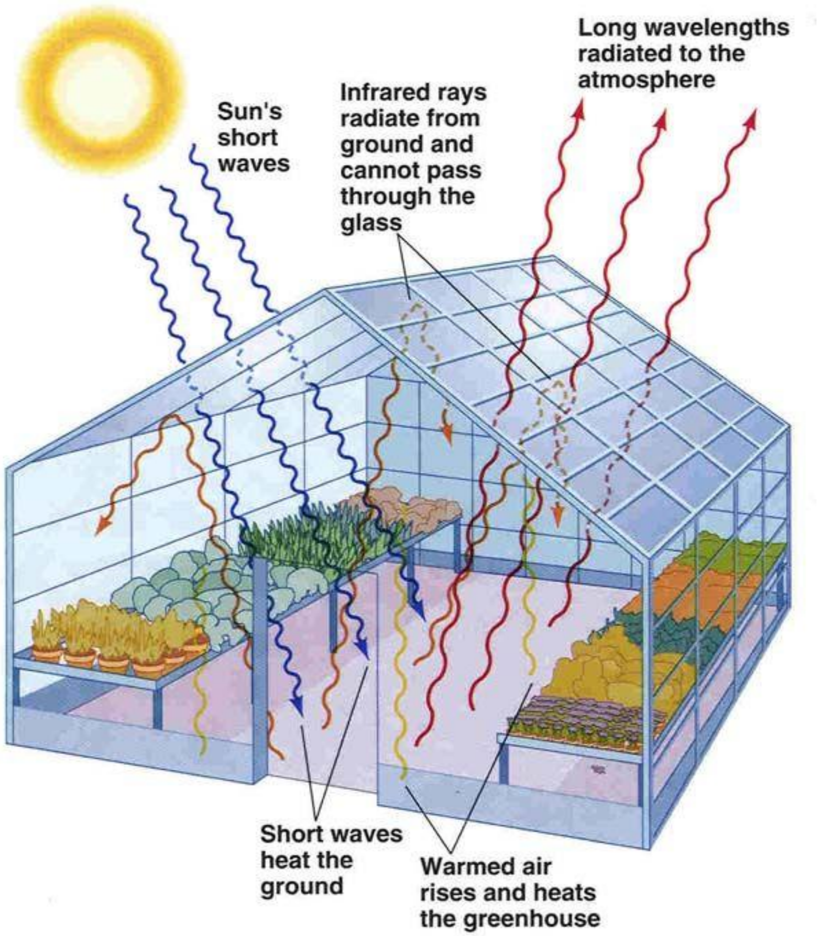


Image: http://ourrenewablefuture.org/

Greenhouse Effect



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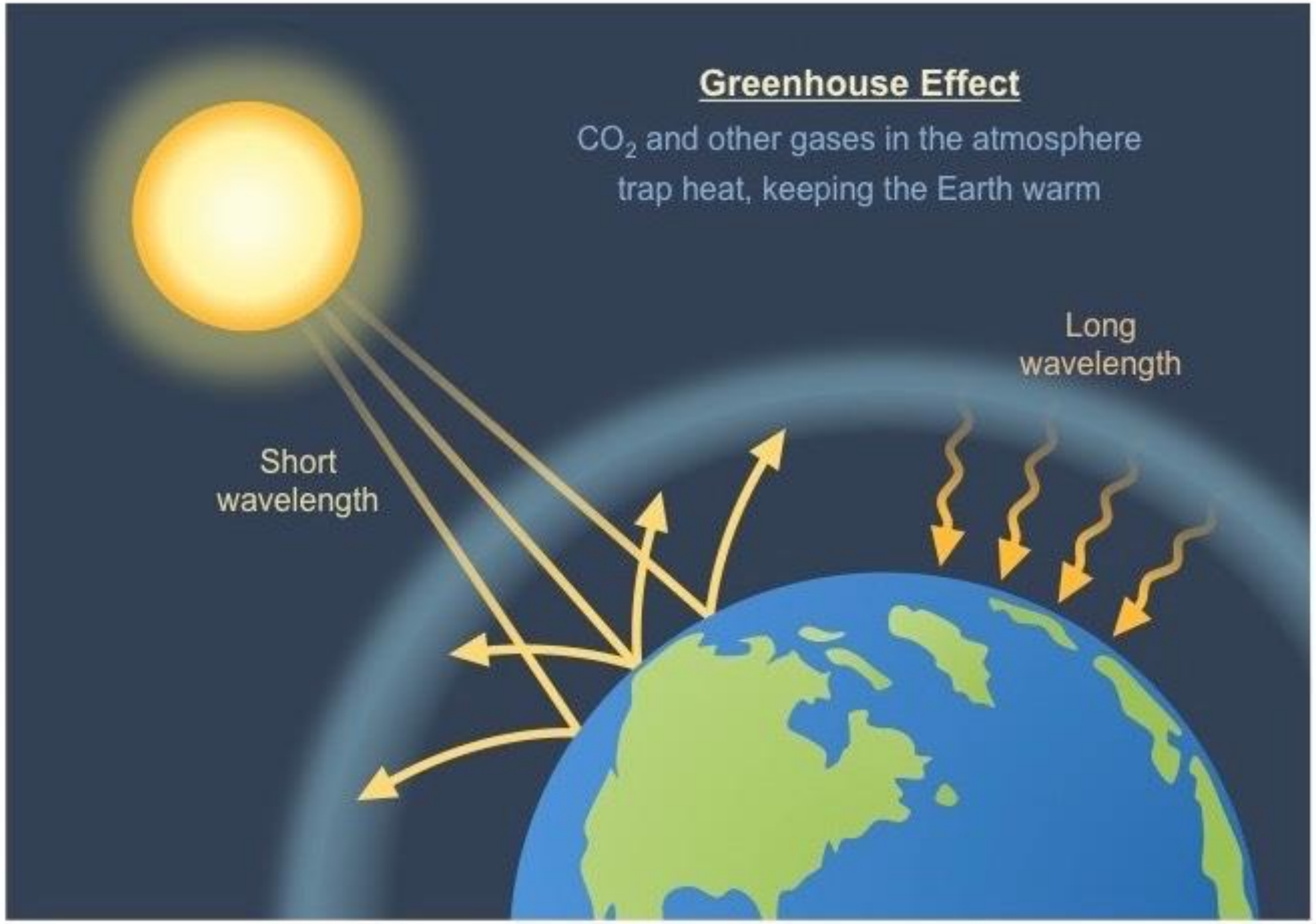

Image: http://steemit.com/

Greenhouse gases: CO2, CH4, N2O, O3, CFC, H2O vapor

Global Carbon Cycle

- Carbon pools: oceans, soils, plants, earth's crust

- Human induced GHGs the biggest imbalance in the cycle

Human induced GHGs = 7.7 Pg or Gt (billion tonnes)

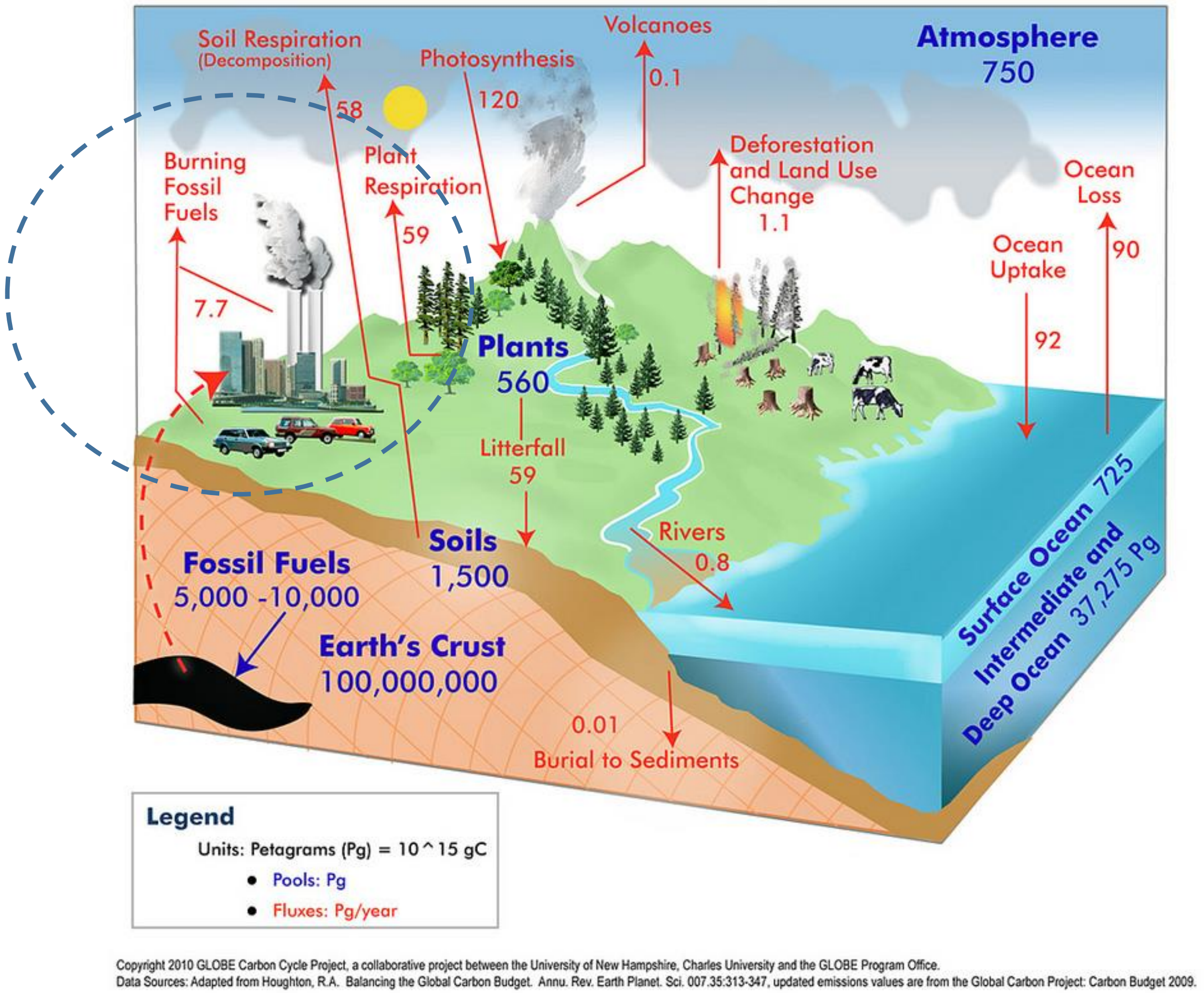

Image: http://pinterest.com/charleswelsh

Image: http://puassignmentmtng.rkorakot.me

Temperature Rise

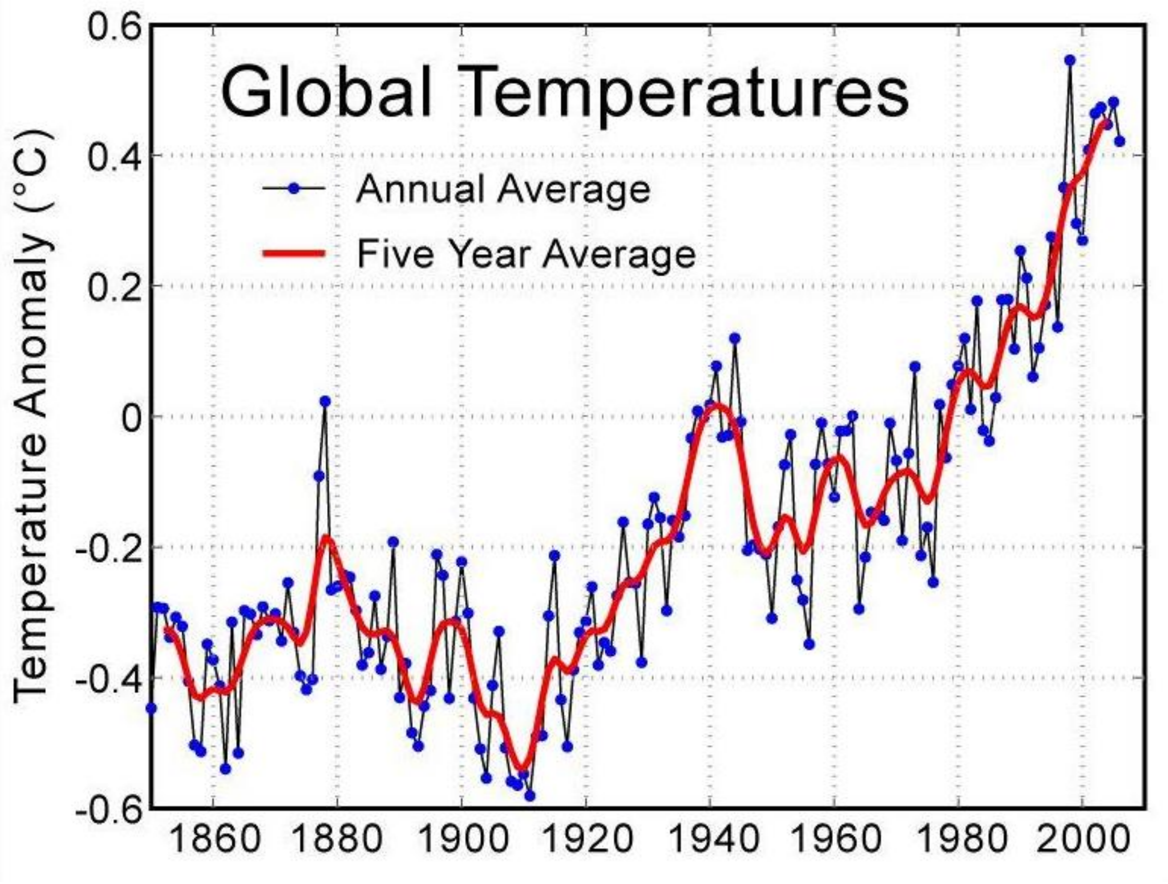

Image: http://newscientist.com

- The target: try to keep the temperature rise well below **2°C** by the year 2100

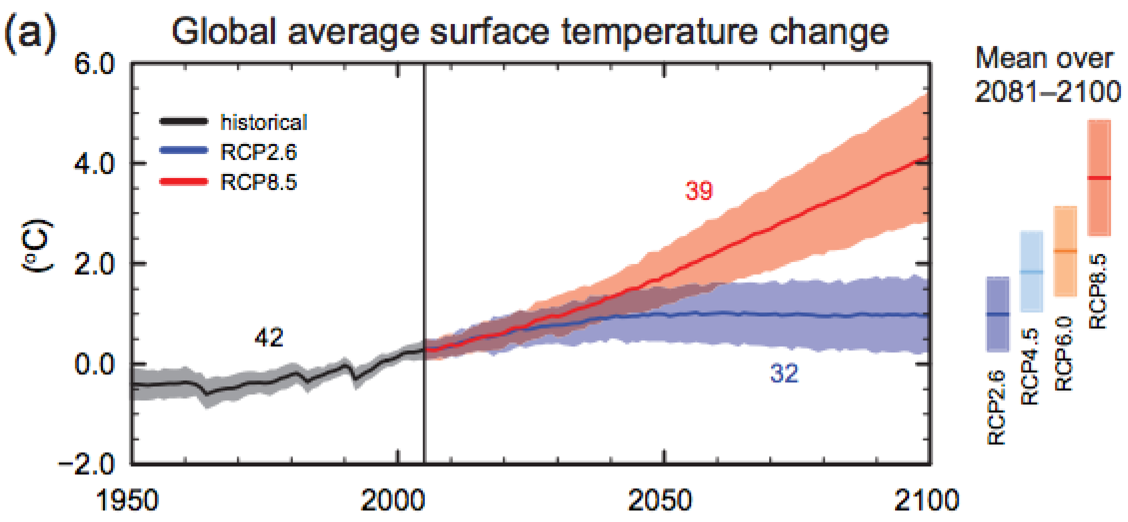

Image: http://vox.com

Climate Change Effects

Question:

discuss the main climate change

Impacts and consequences

in your group

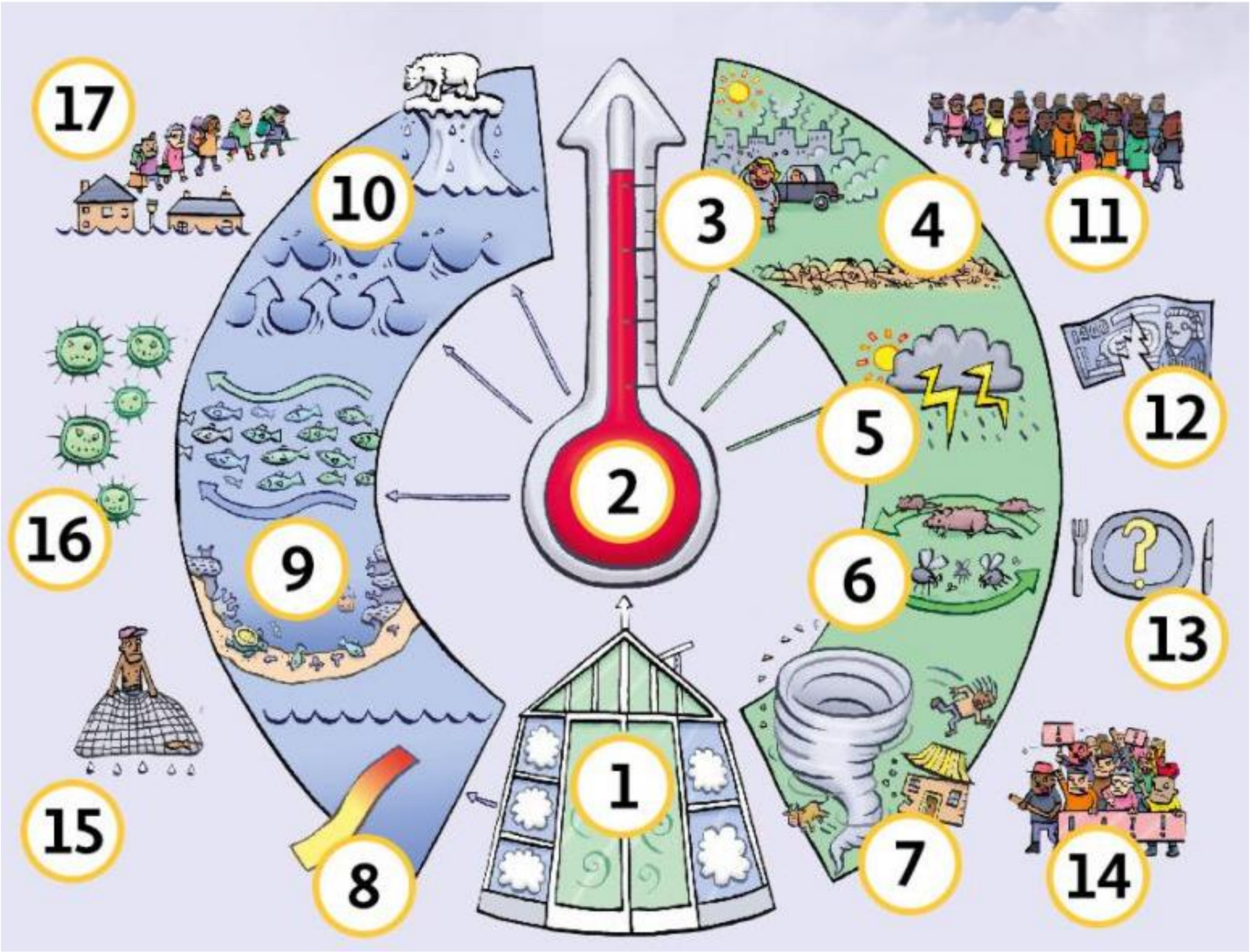

Image: http://vox.com

Climate Change Effects (cont.)

- **Direct effects:**
- Higher temperatures
- Agriculture failure
- Altered weather patterns
- Homelessness
- Ocean acidification
- Marine ecosystem shift
- Sea level rise

- **Indirect effects:**
- Mass migration
- Economic disruption
- Malnutrition
- Social unrest
- Displacement
- Infectious disease spread

Image: http://ecological.blog.com

GHGs may generate a Hothouse

- **Hothouse state:**

Human is not able to stop the process ➔ Domino Effect

Environment

Earth at risk of entering ‘hothouse’ state from which there is no return, scientists warn

'In the context of the summer of 2018, this is definitely not a case of crying wolf... the wolves are now in sight'

Josh Gabbatiss Science Correspondent | @josh_gabbatiss | 4 hours ago | 15 comments

Like
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The Independent Online

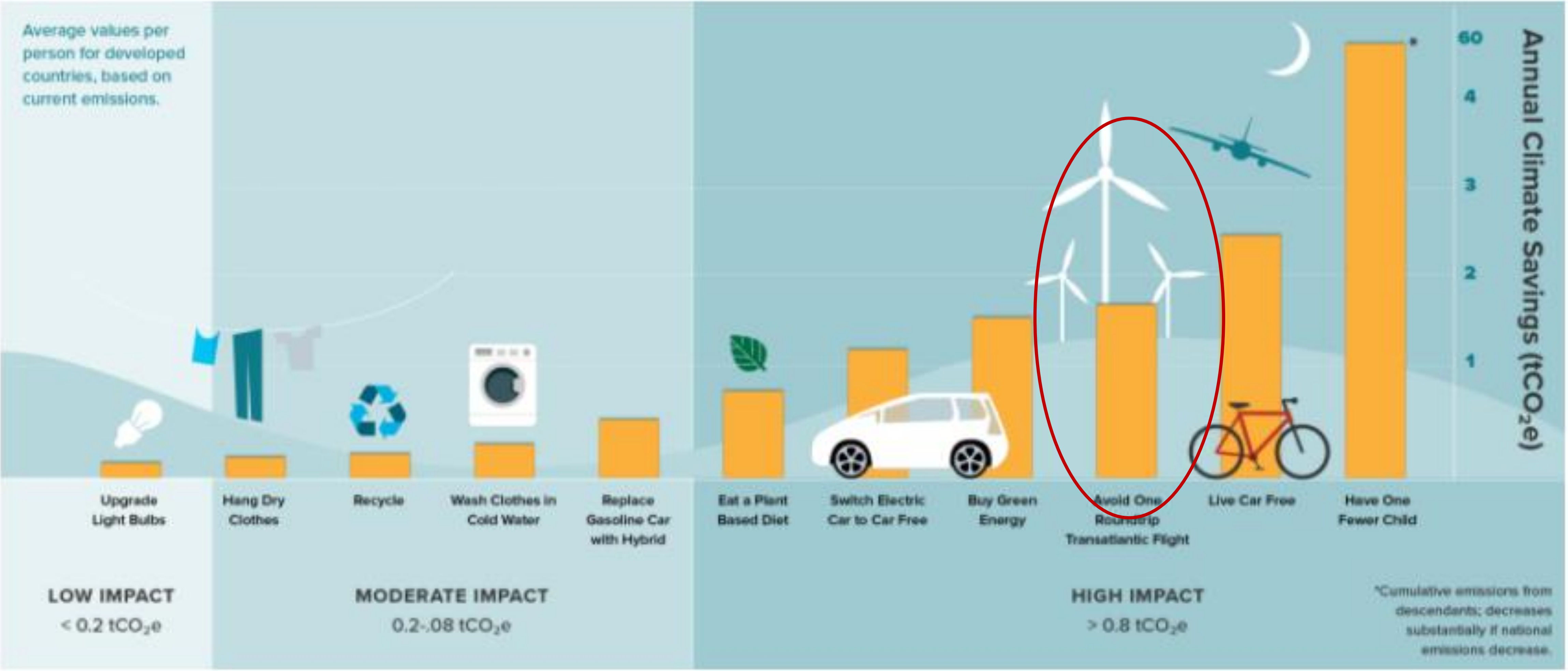
What is the solution?

"If there are to be problems, may they come during my life-time so that I can resolve them and give my children the chance of a good life."

Kenyan proverb

https://www.weforum.org/

Measures for reducing carbon footprint



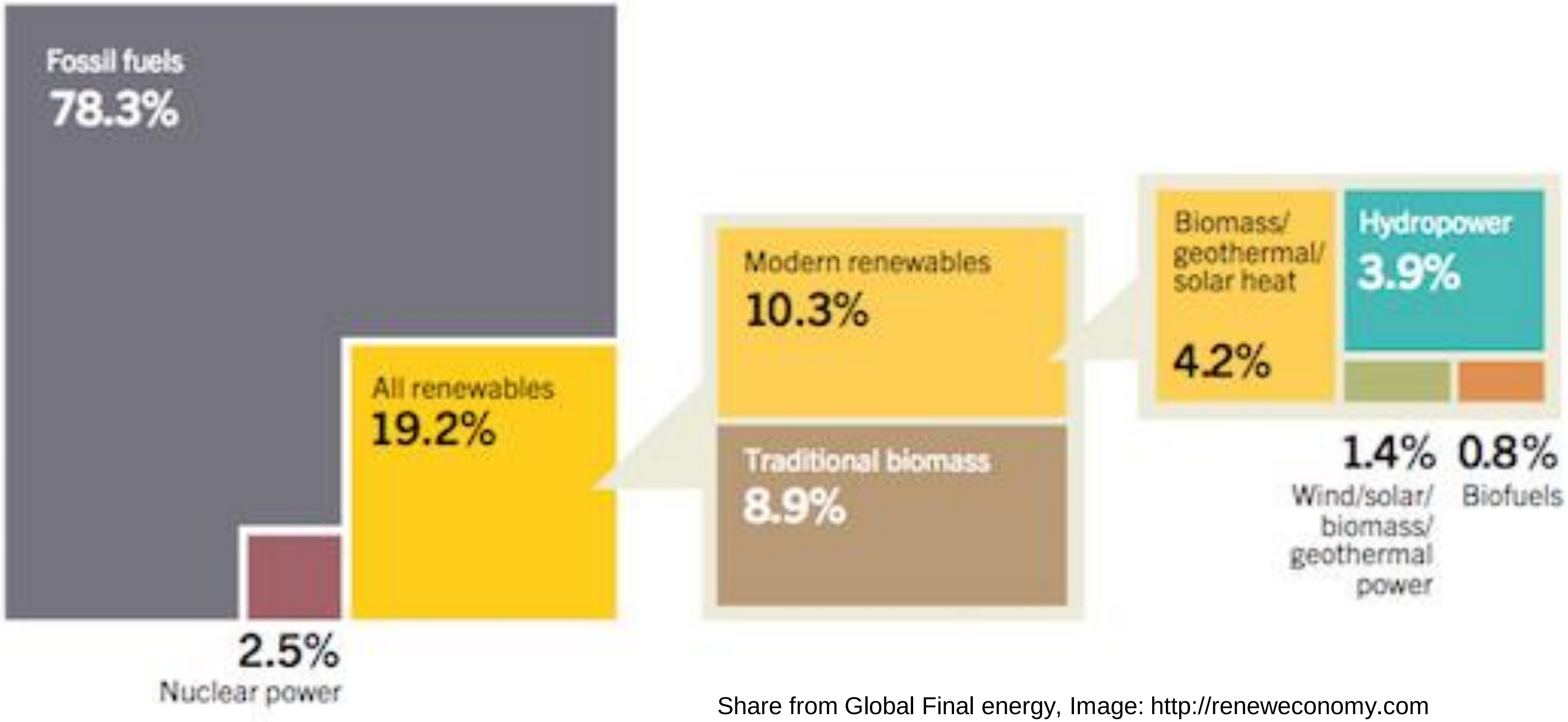
https://greenrestoration.ie/principles-of-carbon-footprint-reduction/carbon-footprint-breakdown/

Renewable Energy in the Energy Mix

- Available and replaceable in a sustainable way

Types of renewable energy:

- Solar
- Wind
- Biomass
- Hydro
- Geo-thermal
- Ocean/wave/tidal
- …



Share from Global Final energy, Image: http://reneweconomy.com

Renewable Energy Potential

- World annual energy needs:

  16 TW-yr

- Solar and wind two biggest

  renewable energy resources

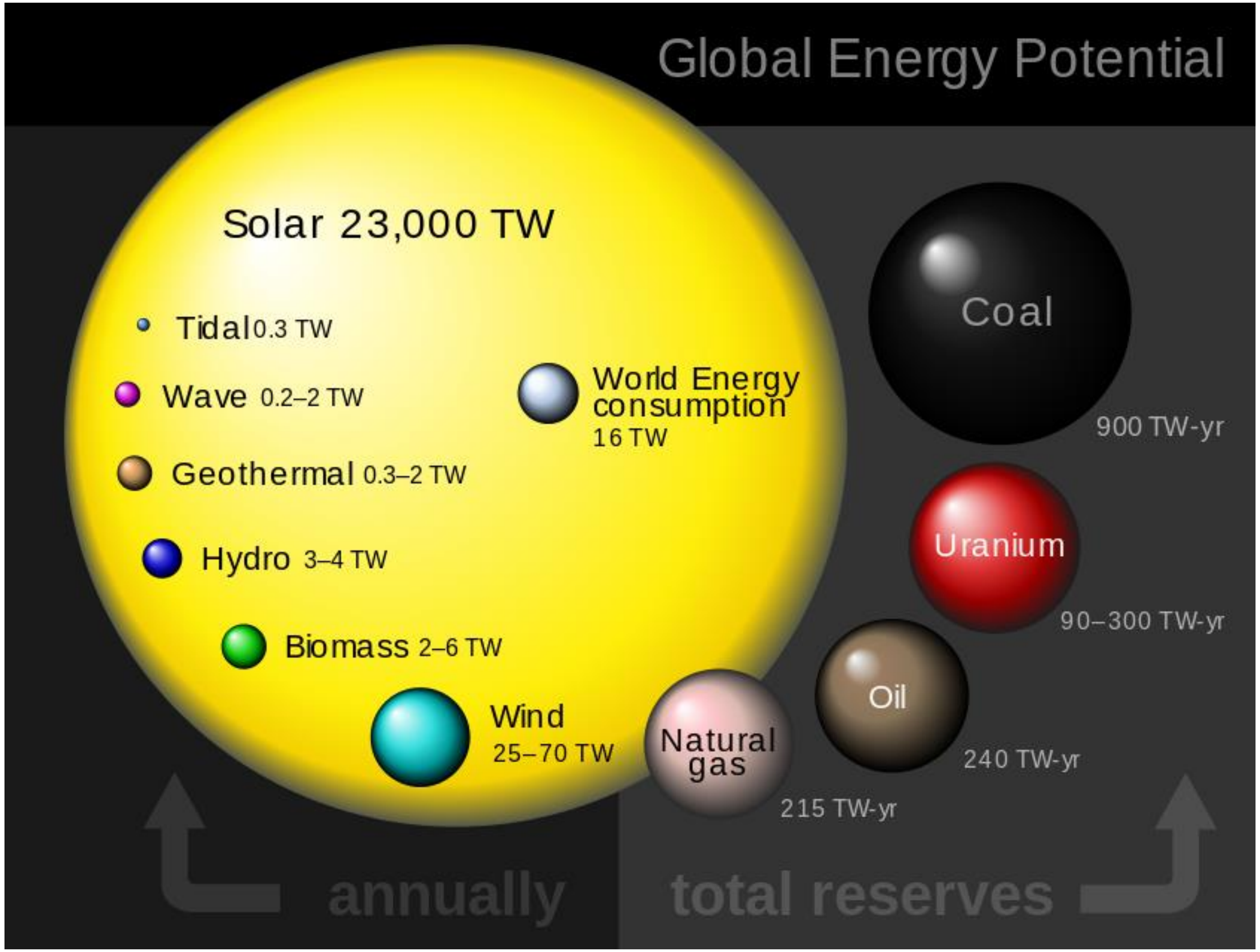


Image: http://waitbutwhy.com

Solar PV

- Small-scale: household
- Large scale: solar PV farms
- Modular, quick, no water needs, maintenance-free
- Distributed and off-grid generation
- Often peak-demand following
- Economically competitive:

In many places in the world, the cheapest option for new capacity

Globally 627 GW installed by 2019

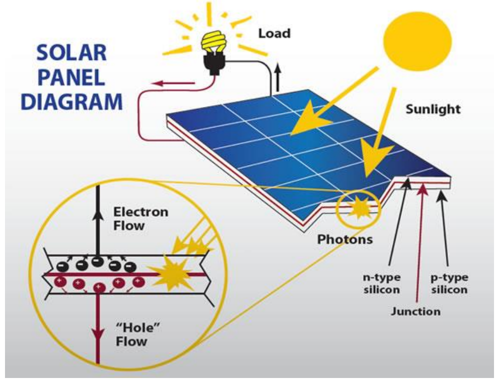
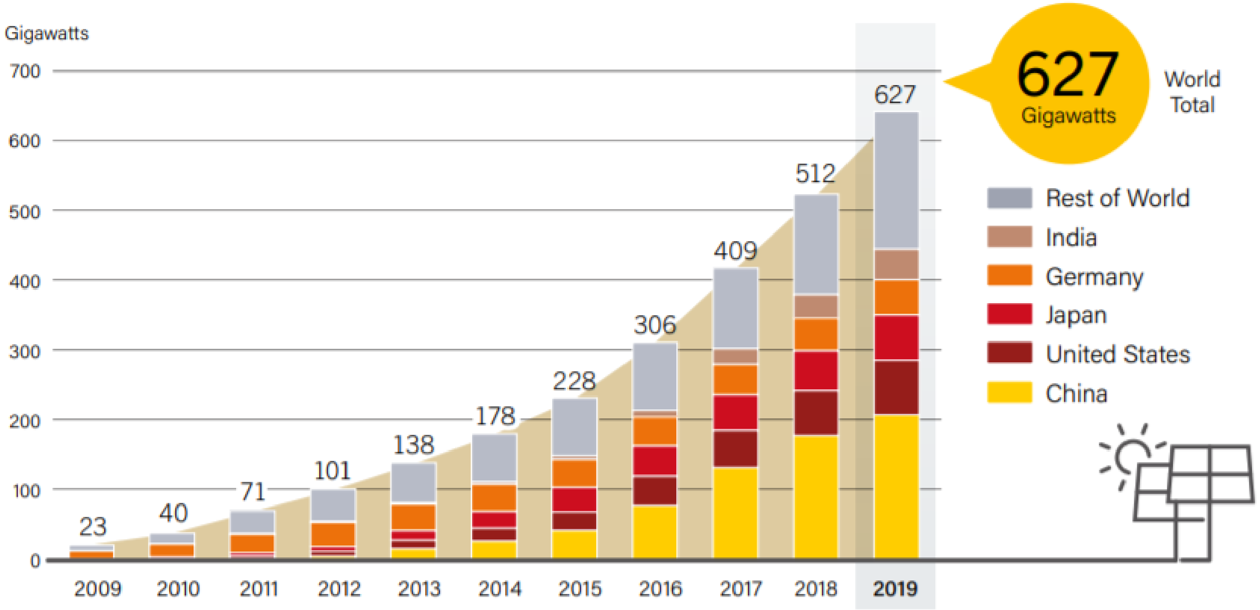


FIGURE 29. Solar PV Global Capacity, by Country and Region, 2009-2019

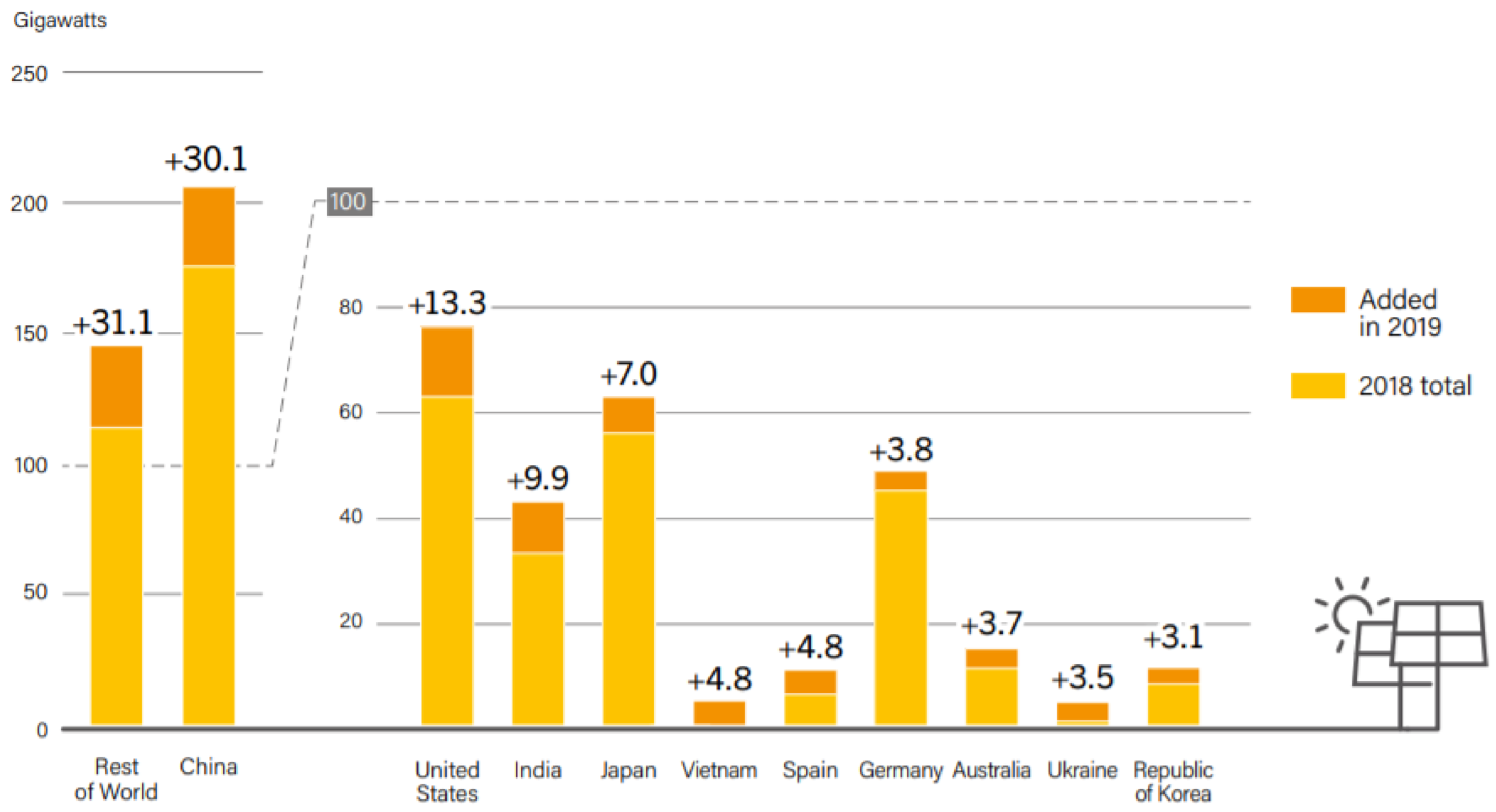


Images: http://dosolar.com.au above and https://ren21.net

Solar PV Capacity Additions

- 40% growth in 2019 compared to 2018
- As cheap as 0.014 $/kWh: a choice also for developing countries

FIGURE 30. Solar PV Capacity and Additions, Top 10 Countries for Capacity Added, 2019



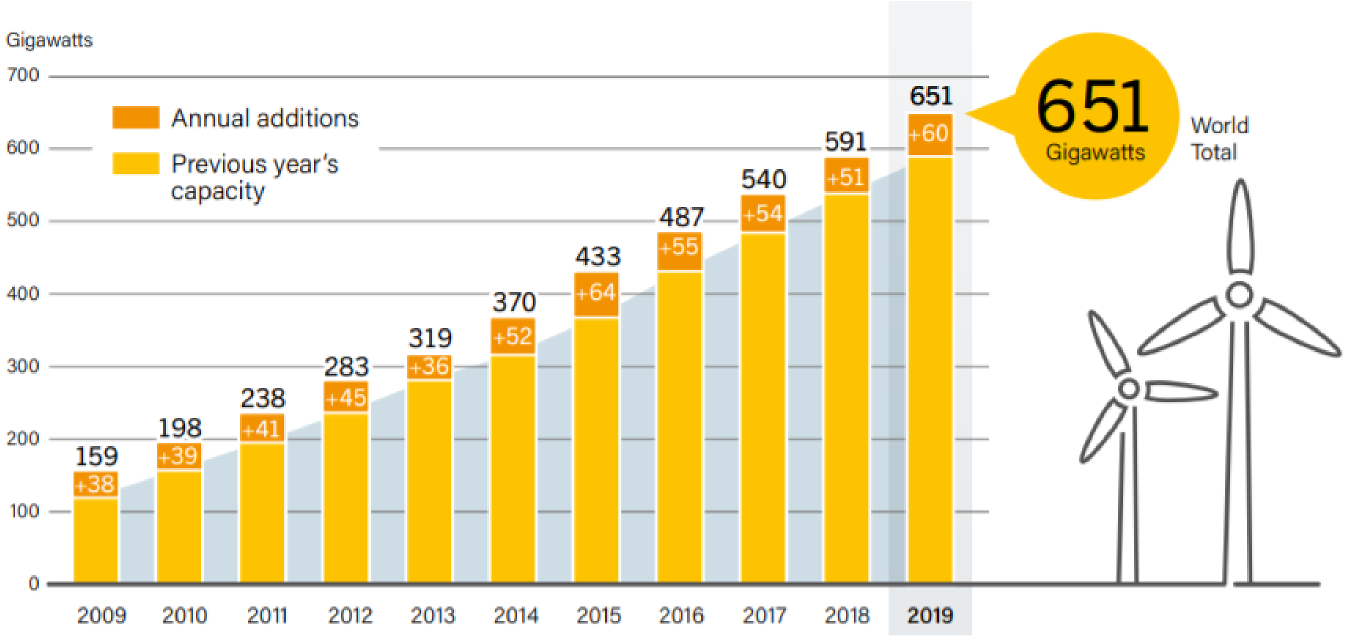
https://ren21.net

Wind Power

- Modular and distributed
- Onshore and offshore
- Large scale production (wind farms)
- Economically competitive
- Technology improvements

(higher capacity factor, bigger turbines)

- 651 GW global capacity by 2019
- China the leading country



- India, the third country in capacity additions in 2019

https://ren21.net

Investments in New Power Capacity

FIGURE 52. Global Investment in New Power Capacity, by Type (Renewables, Coal, Gas and Nuclear Power) 2019

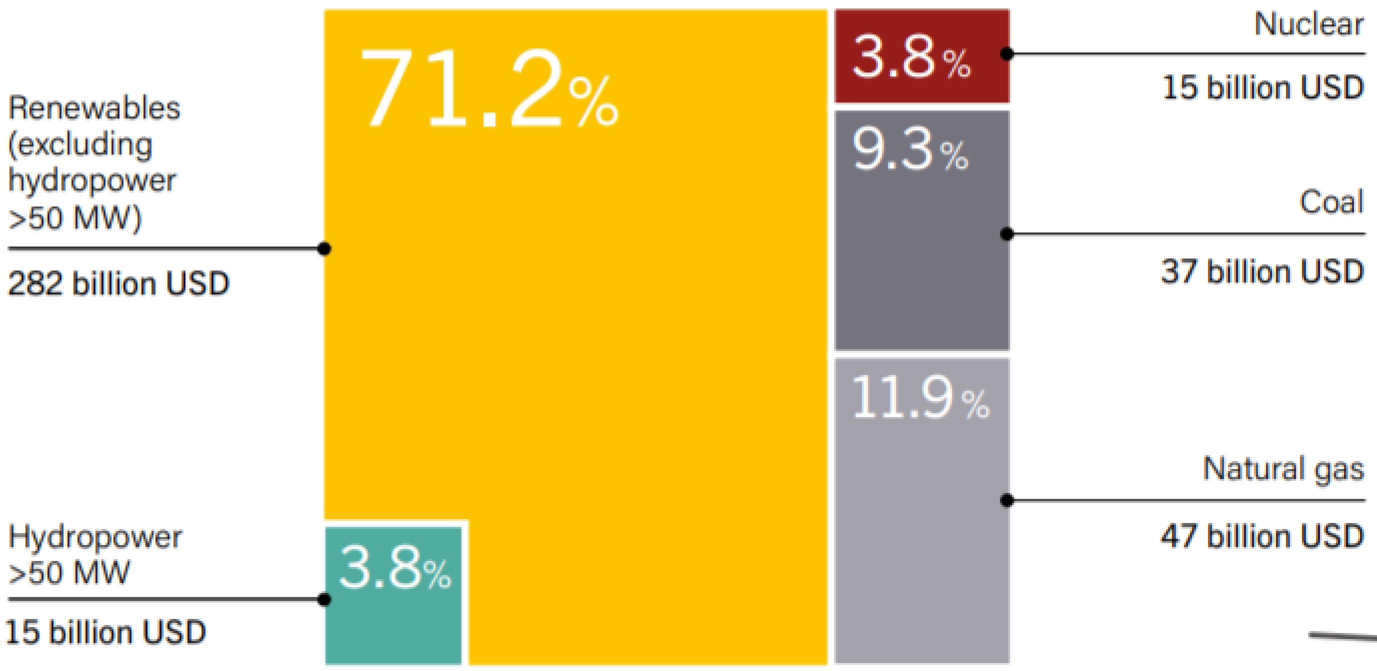


Image: http://ren21.net

Share of Wind and Solar in Electricity

- RE more in the electricity sector
- 60% of electricity in Denmark from mainly wind and solar

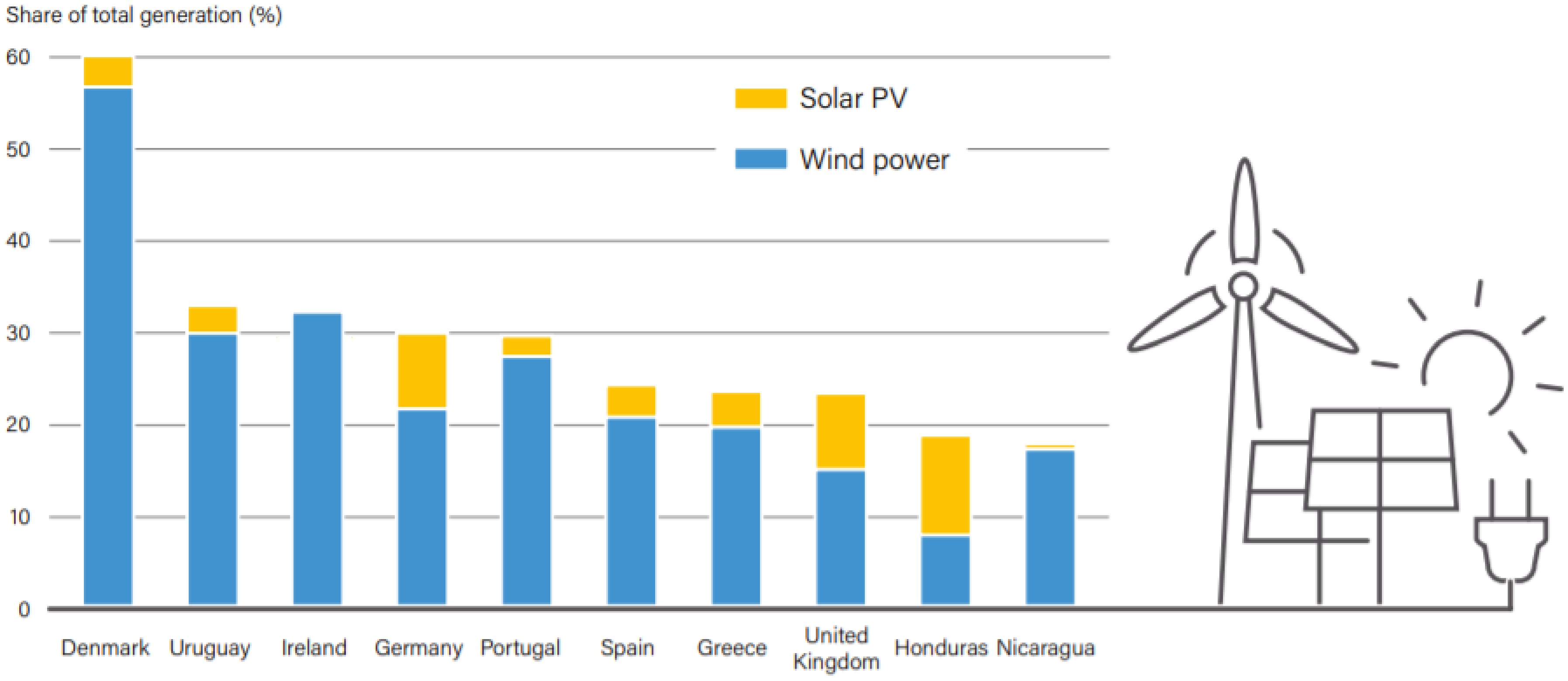


Image: http://ren21.net

Levelized Cost of Electricity (LCOE)

- Indicator for the cost of one unit of electricity generated by a power plant
- Net present value (NPV) of the costs over lifetime divided by total electricity generated

$$LCOE = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}}$$

$$LCOE = \frac{\sum \frac{(I_t + M_t + F_t)}{(1 + r)^t}}{\sum \frac{E_t}{(1 + r)^t}}$$

I: investment costs

M: maintenance costs (disposal, etc.)

F: fuel costs

E: total electricity generated

LCOE of Renewables vs. Conventional

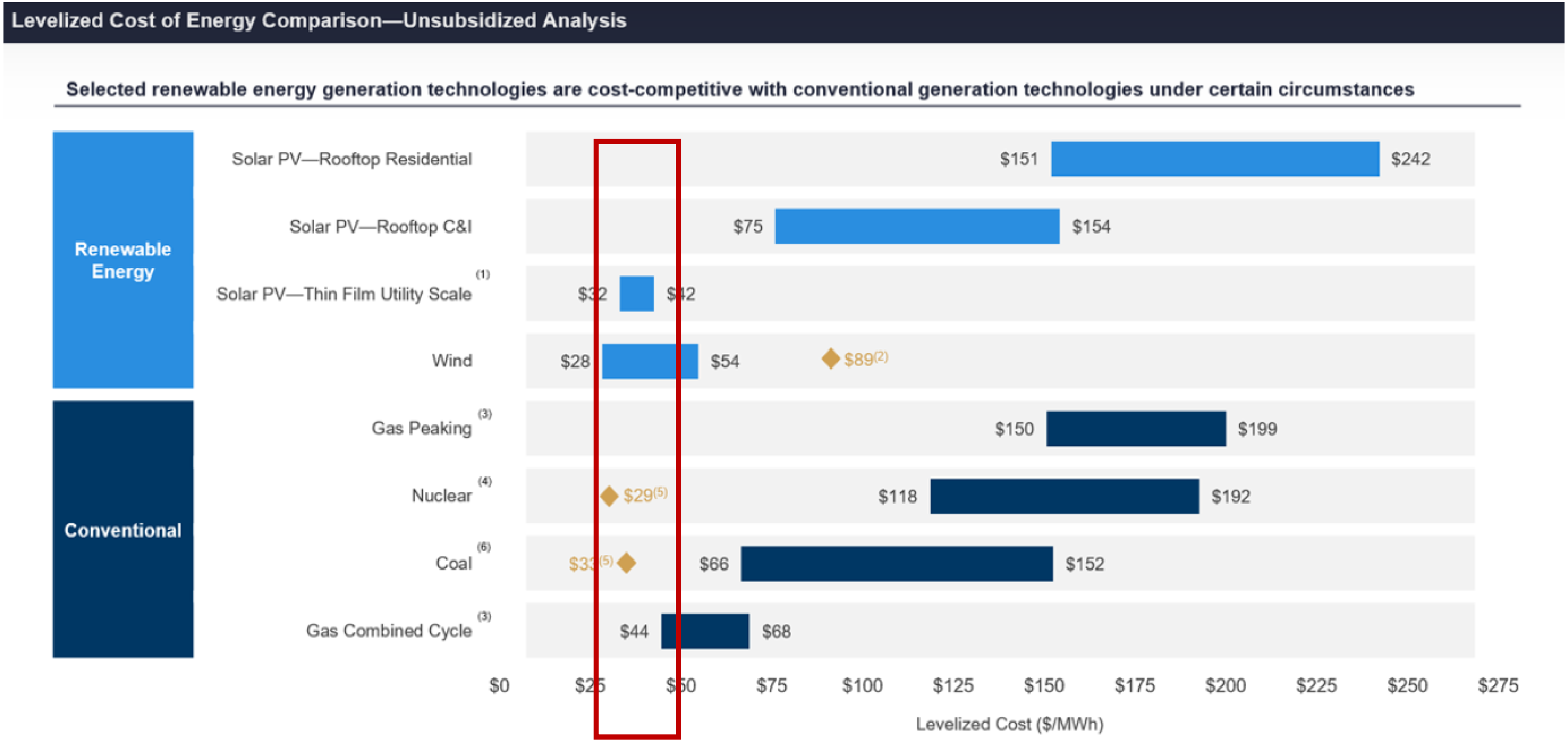


Image: Lazard Consultancy

Challenges in Integration of Renewables

- Question:

what are the main challenges in increasing the share of renewables in our final energy use?

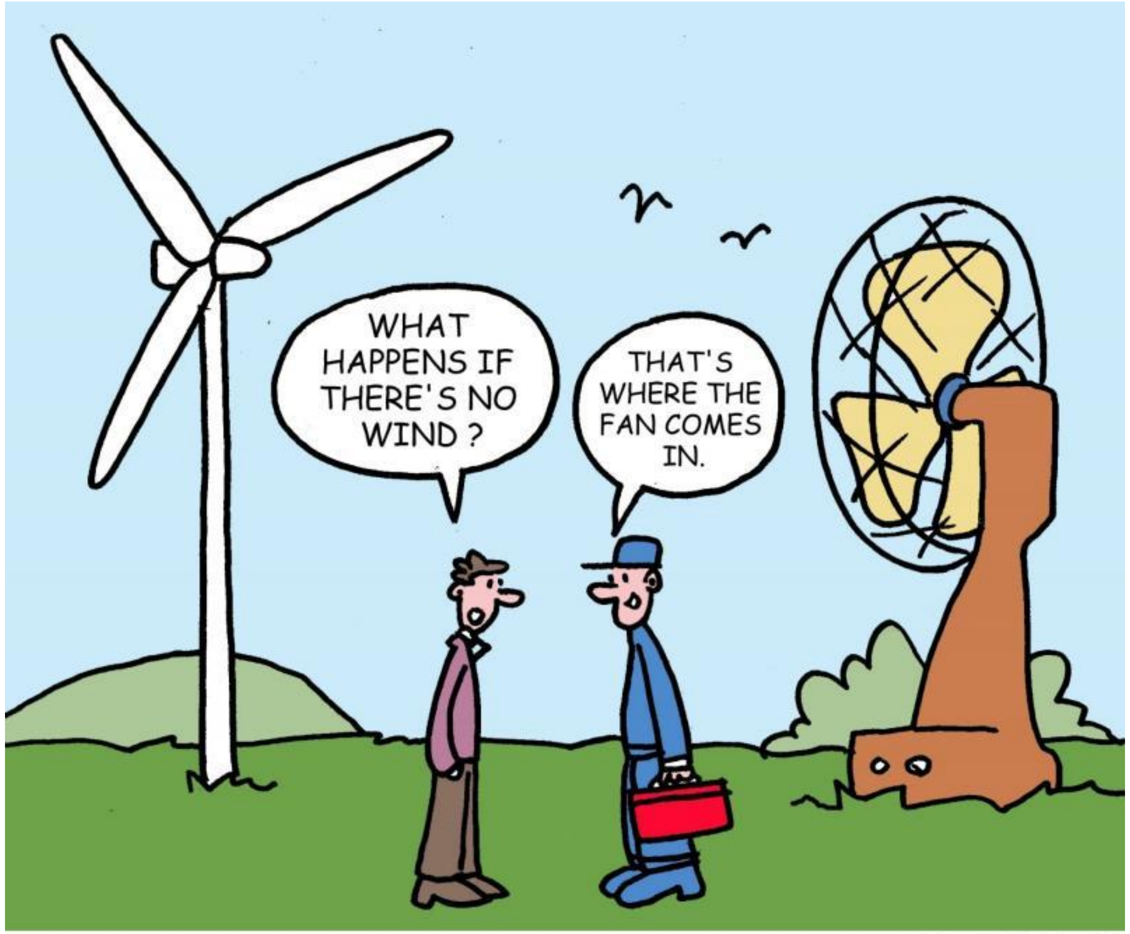
Some Intermittency Challenges

- Variable renewable energy (solar and wind)
- Temporal and locational variability
- Need for huge backup capacity in high shares of VRE
- Grid connection (windy areas far from the grid)
- Reliability, firm capacity (e.g., peak time): backup capacity
- Capacity credit (capacity value): capacity available at peak time (wind and solar = 10-15%)
- Ramp-up and ramp-down of thermal plants = additional cost for them

What's the challenge?

- Challenge in large scale integration of variable renewable energy (wind, PV)

Mothersagainstwindturbine.com



CartoonStock.com

https://uncomfortableknowledge.com/decarbonization-of-electricity-production/

Energy storage systems

“I can't change the direction of the wind,

but I can adjust my sails to always reach my destination.”

Attributed to **Jimmy Dean**

Solutions for Intermittency Challenge

- **Grid interconnectivity:** connecting homes/communities/cities/ countries together to balance variability
- **Electricity storage:** storing excess electricity to be used later
- **Demand response:** changing electricity demand to respond to variability
- **Power-to-heat:** converting electricity to heat
- **Power-to-fuel:** converting electricity to fuels (like hydrogen, methane, etc.)
- …

What is electricity storage?

Storing electricity to be used later (in the same form) at a reasonable response time

- Electricity storage = electrical energy storage (EES)

Electricity storage in this study:

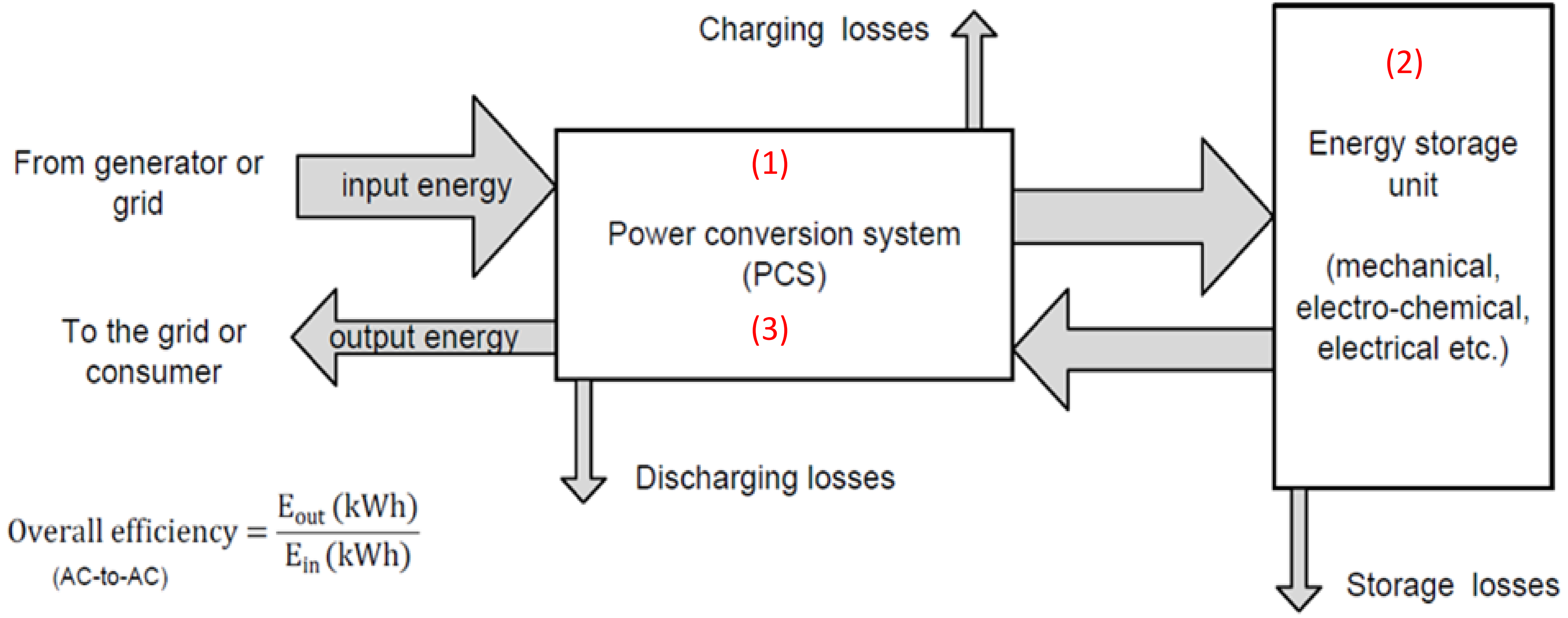
Stationary, grid-connected, Utility scale (medium to large scale), rechargeable

Not including:

Electric vehicles (dump charge), energy management, fuel storage, residential scale end-user, etc.

Functionality of EES (in general)

1. **Charge:** receiving power, converting it to a type of storable energy
2. **Storage unit:** storing energy and preventing from losing its value over time
3. **Discharge:** converting energy back into power, when required

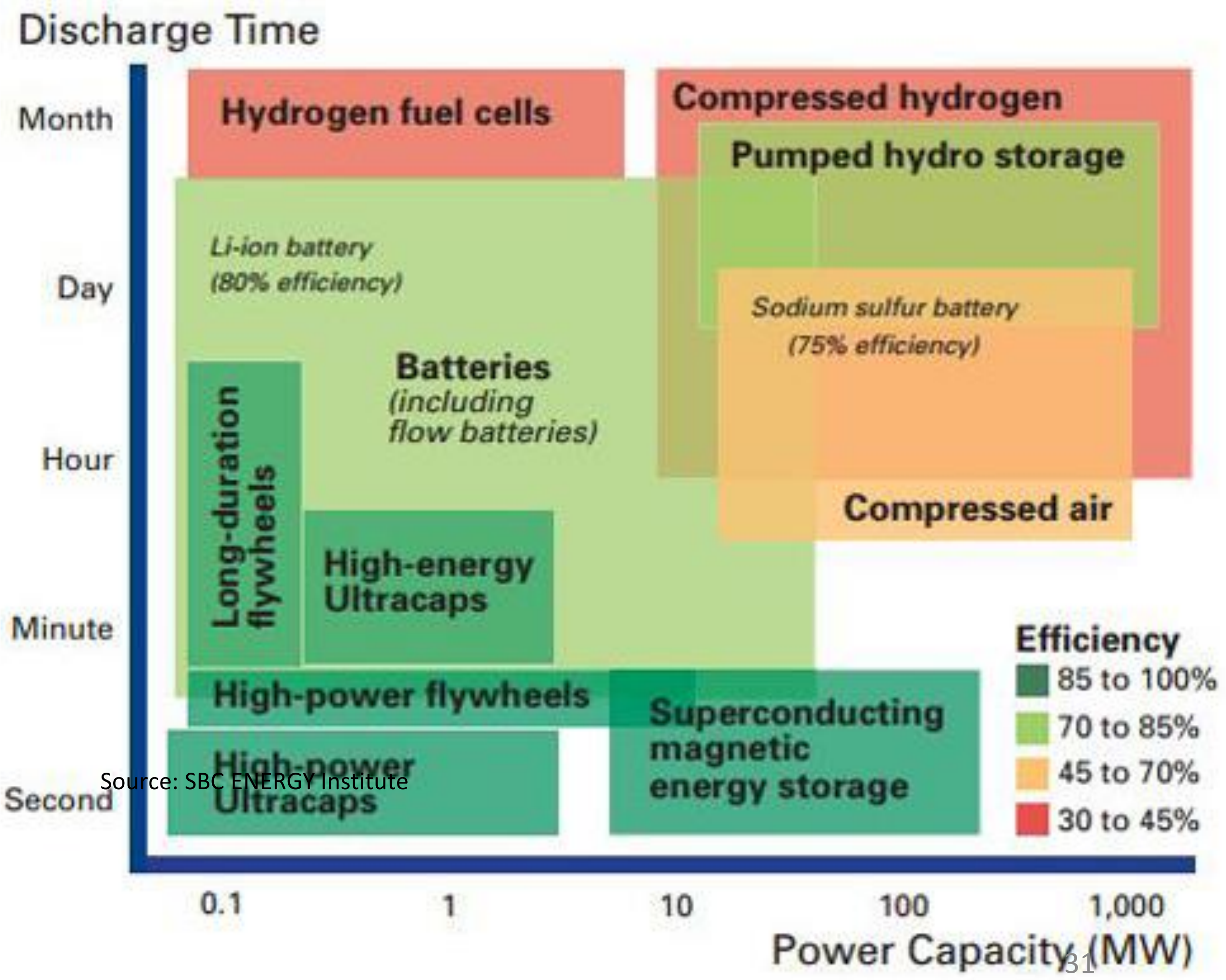


Motivation for further research on EES

- Variable renewables and need for integrating them
- Deregulated markets and high capital cost for peak demands
- High investment costs of grid infrastructure for reliability improvement
- Price improvement of EES technologies (e.g., batteries)
- Smart energy systems and the need for smart use of energy …

Electricity storage technologies

- Mechanical:
  - Pumped hydro-electricity storage (PHS)
  - Compressed air energy storage (CAES)
  - Flywheel
- Electrochemical:
  - Batteries (lead-acid, NaS, Li-ion, etc.)
  - Flow batteries (e.g. VRFB)
- Other (chemical, electromagnetic, …)
  - Hydrogen storage, SMES ultracapacitors, etc.



Source: SBC ENERGY Institute

Pumped hydropower storage (PHS)

- The most common EES
- The largest PHS is 3000 MW
  (Bath County PHS, USA)

+ High efficiency (75-85%)
+ No fuel and emissions
+ Long discharge time (8-24 hr)
+ Low O&M requirements
+ Low generating costs
+ Long lifetime

- Large and long projects
- Site-specific
- Environmental permitting
- Capital intensive

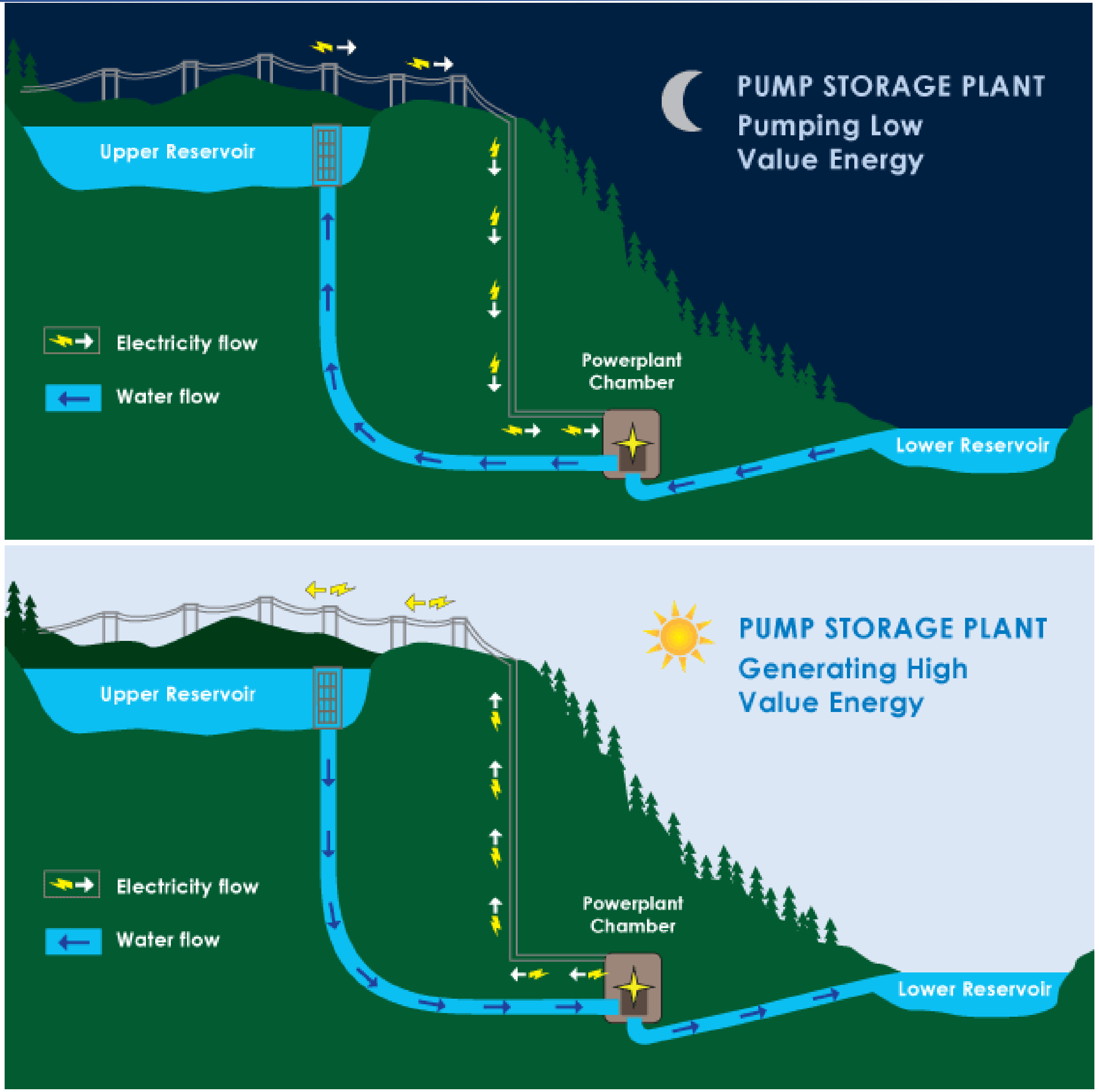
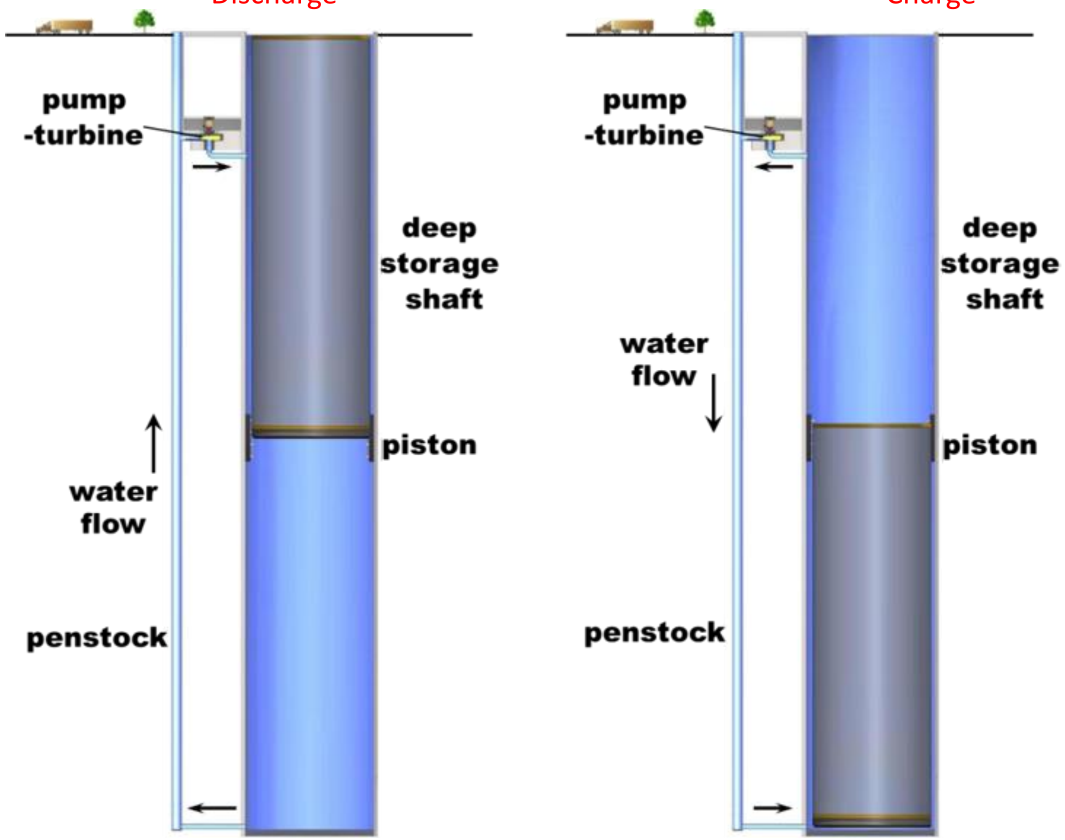


Image source: cleanbalancepower.com

EES technologies: Prospects for PHS

- Underground PHS, sea water reservoir, multi-purpose reservoir, pressurized water (Link to a PHS project, Link to the video of a pressurized PHS)

Pressurized PHS



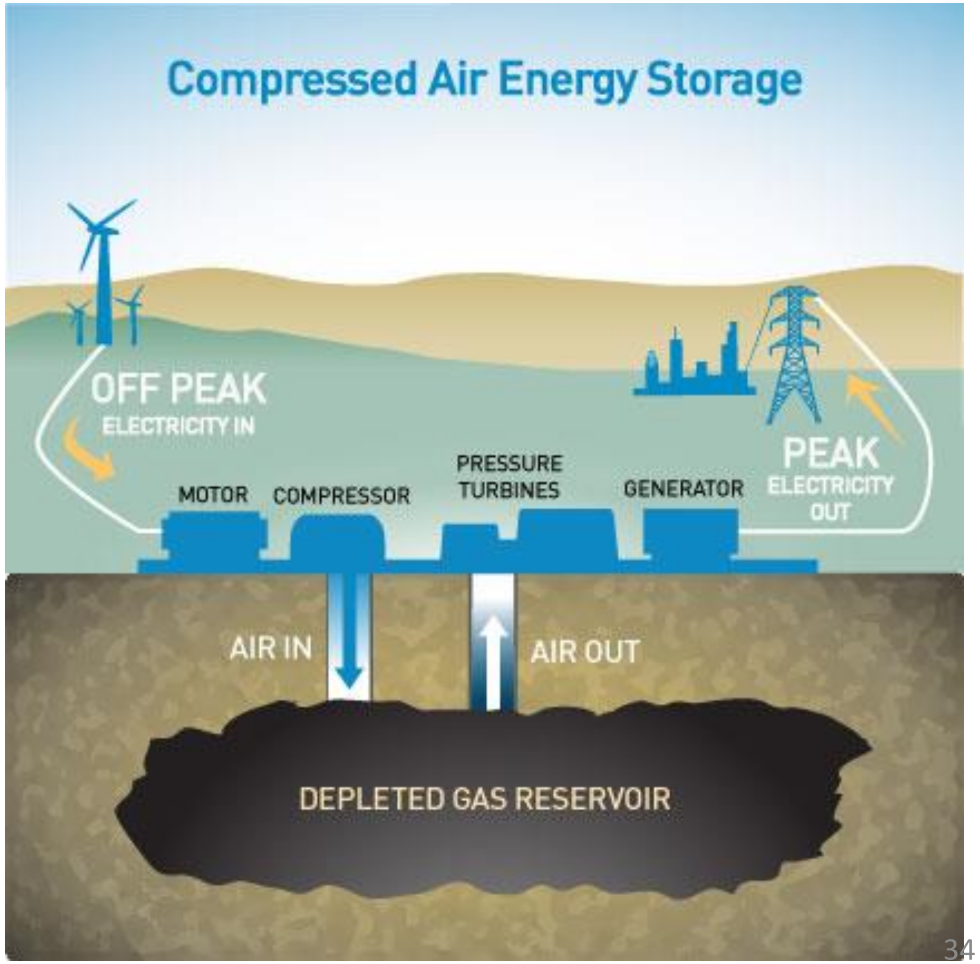
www.gravitypower.net

Sea water PHS

Yanbaru Okinawa PHS, Agency of Natural Resources and Energy, Japan

Compressed air energy storage (CAES)

- Second commercial technology for large-scale storage
- Two operating plants worldwide: 320 MW in Germany and 110 MW in USA
- Pressurized air is stored in salt caverns,
  natural aquifers, depleted gas reservoirs
  or aboveground vessels
- Advanced CAES without fuel needs



\+ Long discharge time

\+ Proven and commercial technologies

\+ Large scale plants possible

\- Fuel and emissions (conventional CAES)

\- Rather low efficiency (42% without and 54% with recuperator)

\- Costs uncertain if fueled with natural gas

PG&E (www.pge.com)

Flywheel energy storage

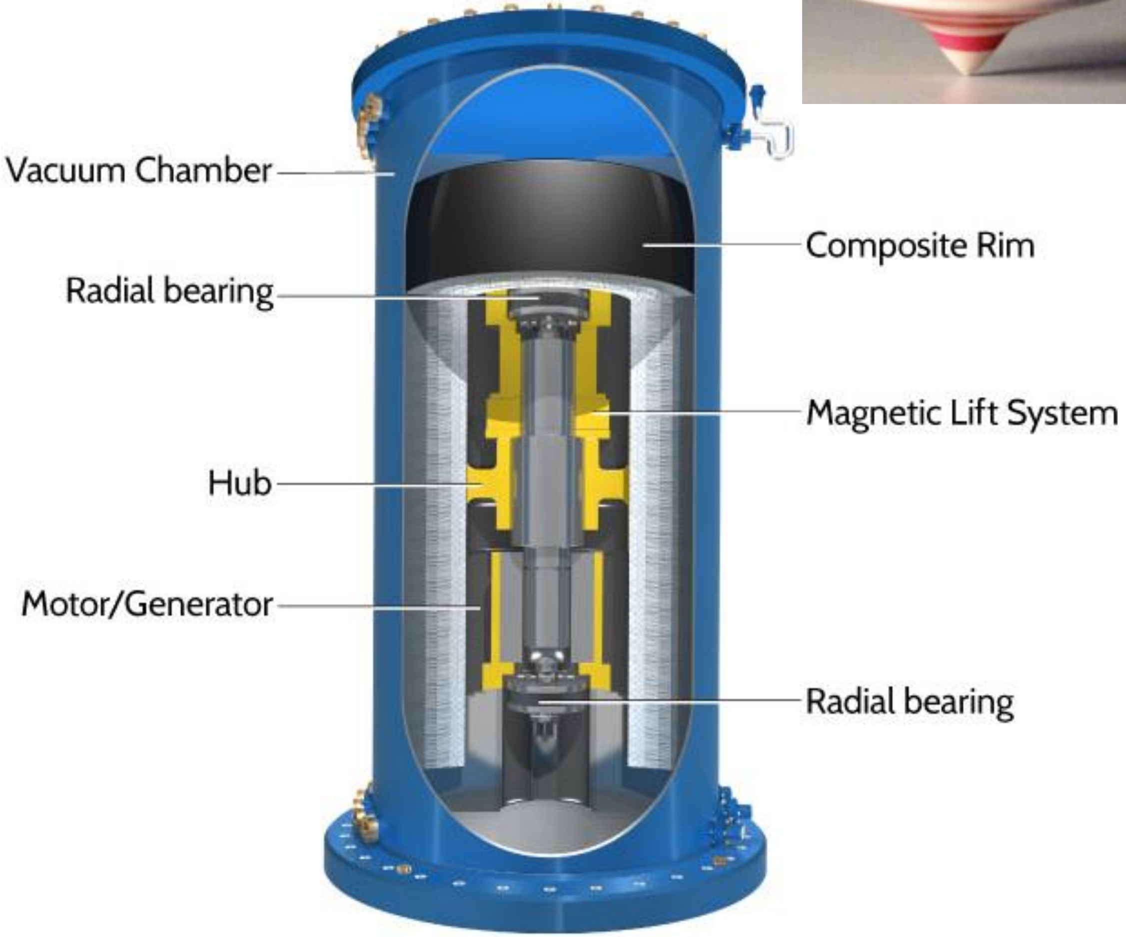
- Commercially available
- Based on the use of rotational energy
- Suitable for power quality services and ride-through
- Applicable to mobile services

  (rail vehicles and automobile industry)

+ High efficiency (85%) and long life cycles
+ Low response time (millisecond)
+ No fuel, spill, hazard,…
+ Scalable, 20 MW plant in New York for

  frequency regulation

  Not suitable for energy-related services



Beacon Power

Electrochemical batteries

- A wide range of technologies available (based on material and process): lead-acid, Ni-Cd, Li-ion, NaS, ZEBRA, etc.
- Suitable both for power and energy-related services
- Most concerns related to toxicity, material intensity, air conditioning needs, etc.
- From rather low efficiency to improved efficiency (e.g., Li-ion)
- Limited life cycle and lifetime resulting in high replacement

costs (e.g., lead-acid)

- Large batteries so far around 30-40 MW

  (70 MW NaS project in future to Italy)

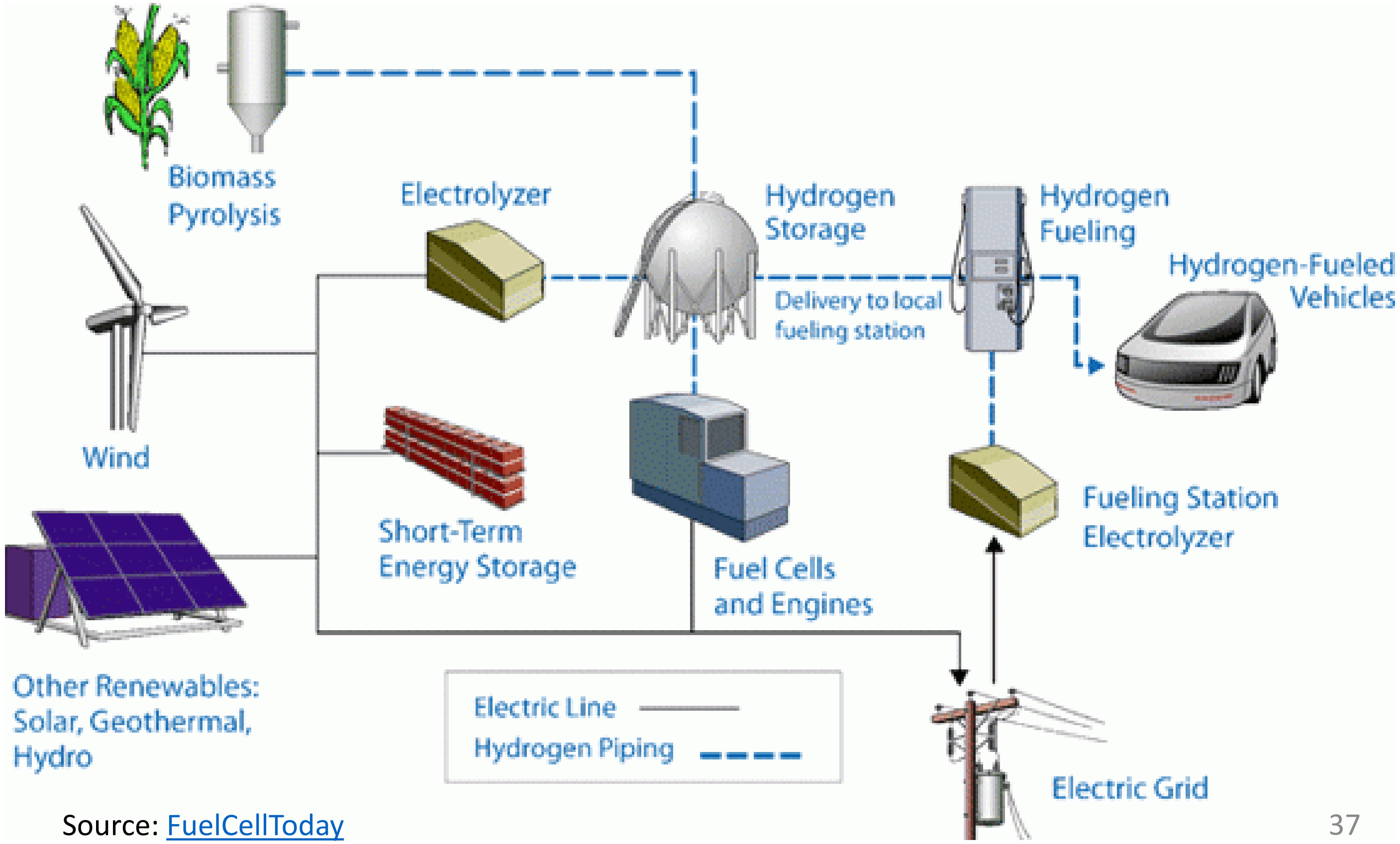
34 MW NaS battery connected to 51 MW wind farm, NGK Insulator, Japan

Hydrogen energy storage

- By electrolysis process, water is decomposed to hydrogen and oxygen
- Hydrogen storage in tanks, reservoirs, even natural gas pipelines (up to 5%)
- Stored hydrogen can be utilized in fuel cells or thermal engines

+ Long-term storage
+ Technology available
+ Different energy carriers
+ High energy density

- Low efficiency (35-42%)
- High capital and O&M costs

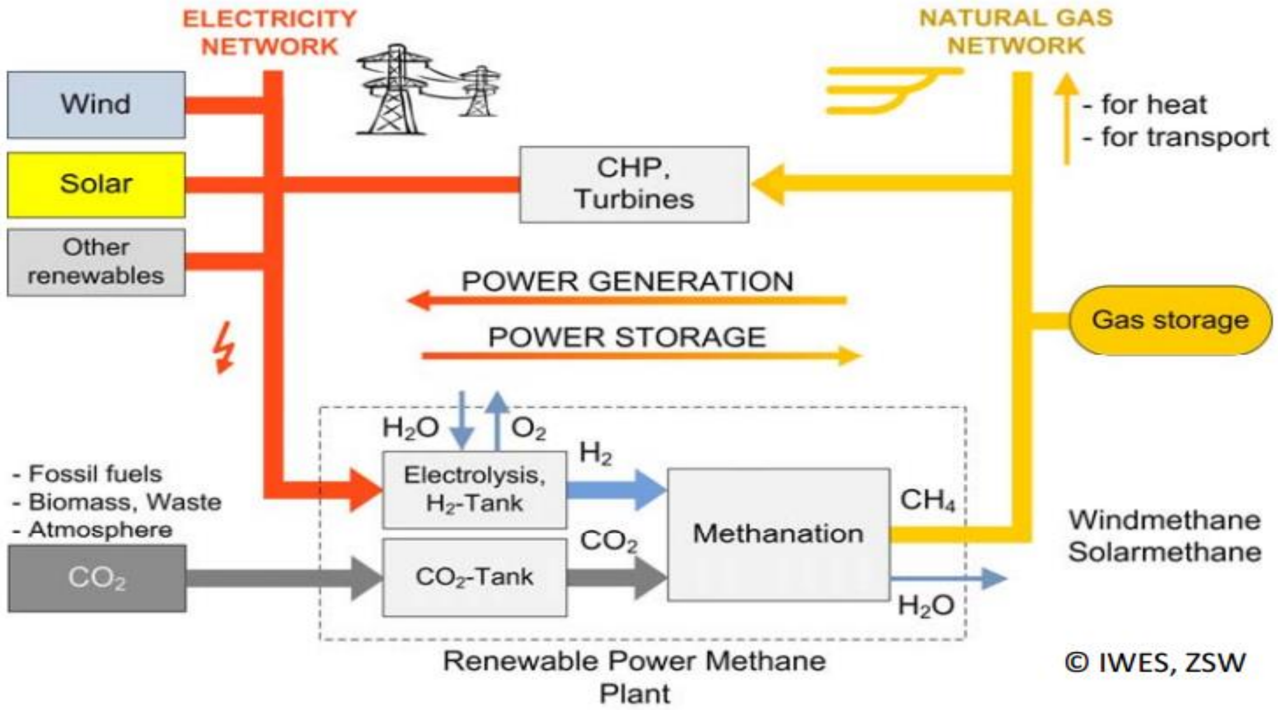


Source: FuelCellToday

Power to gas energy storage

- Hydrogen reacts with CO2 and produces **synthesized methane** (natural gas)
- Can be integrated with carbon capture and storage (CCS) processes

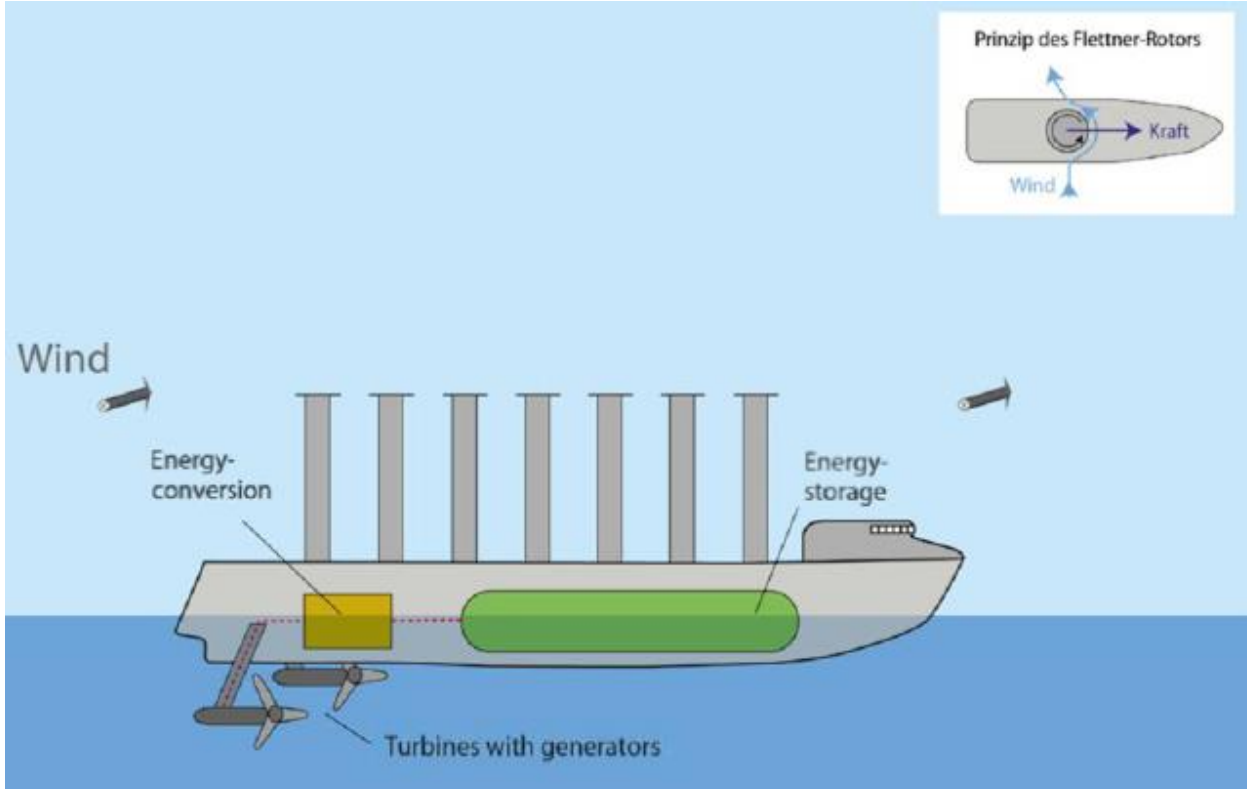
+ Different technologies available for storage, transfer, and conversion back to power
+ Long-term storage
+ Different energy carriers
+ High energy density
- Low efficiency (32-40%)
- Expensive



Source: Sterner, 2009

Think more about power to gas!

- A full range of energy carriers (power, heat, and transport fuel)
- Increasing system flexibility, is it an ultimate solution?
- New concepts: sail energy, wind fuel, power fuel, etc.

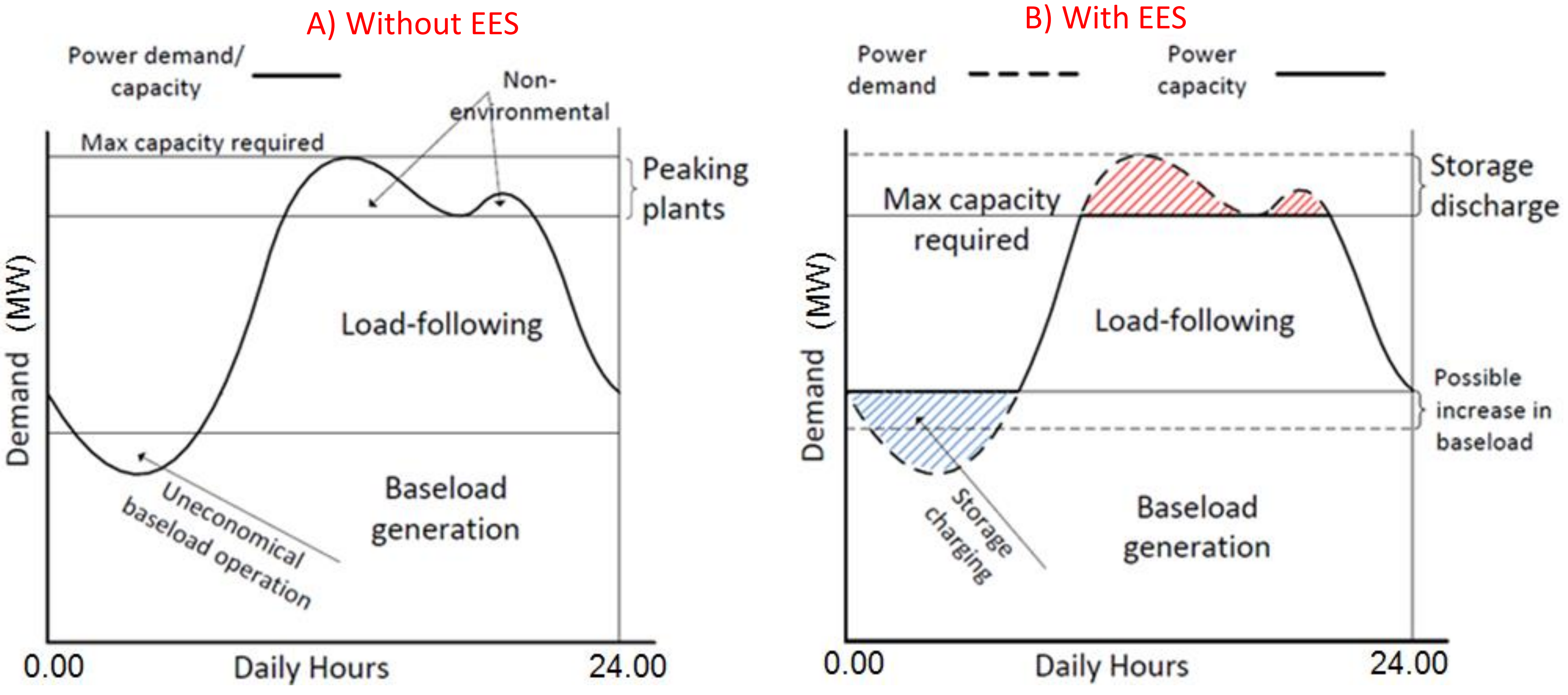


www.segelenergie.de

www.skysails.info

Electricity storage in power systems

- In late1880s, EES were the original solution for night-time load in New York City private area (lead-acid battery)



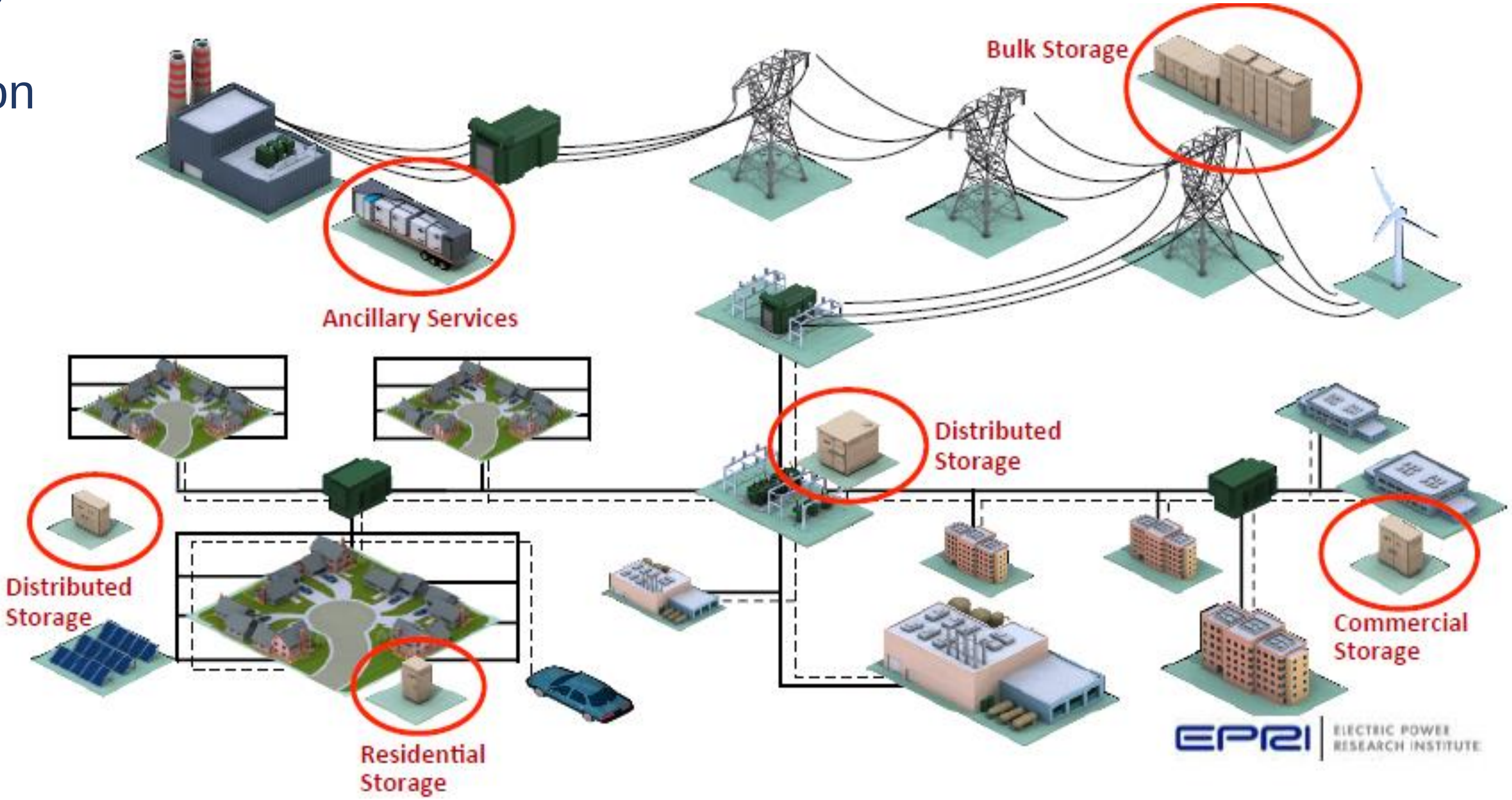
Group exercise: benefits (services) of storage

- Discuss with your group members:

  - **What** are the use cases and benefits of electricity storage?
  - **Who** benefits from storage in that service? (e.g., electricity generator, system operator, end user, etc.)

Applications of electricity storage

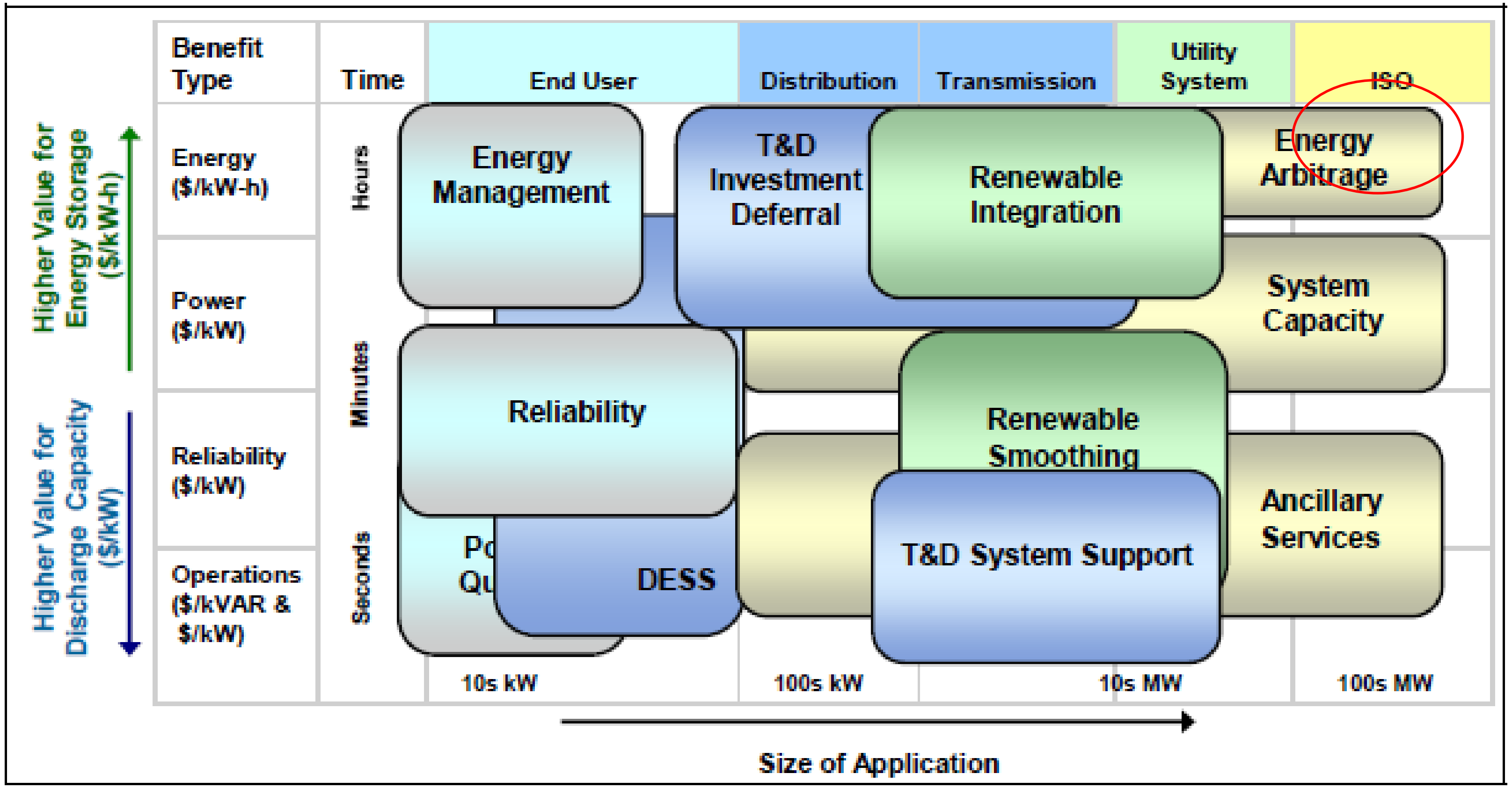
- Wholesale energy services (bulk storage, arbitrage, ancillary services, and frequency regulation)
- Renewable integration
- T&D support
- Distributed EES



18 applications with different requirements

Applications of electricity storage (2)

- Benefits of EES should be first monetized/valued
- Benefits depend on the market design

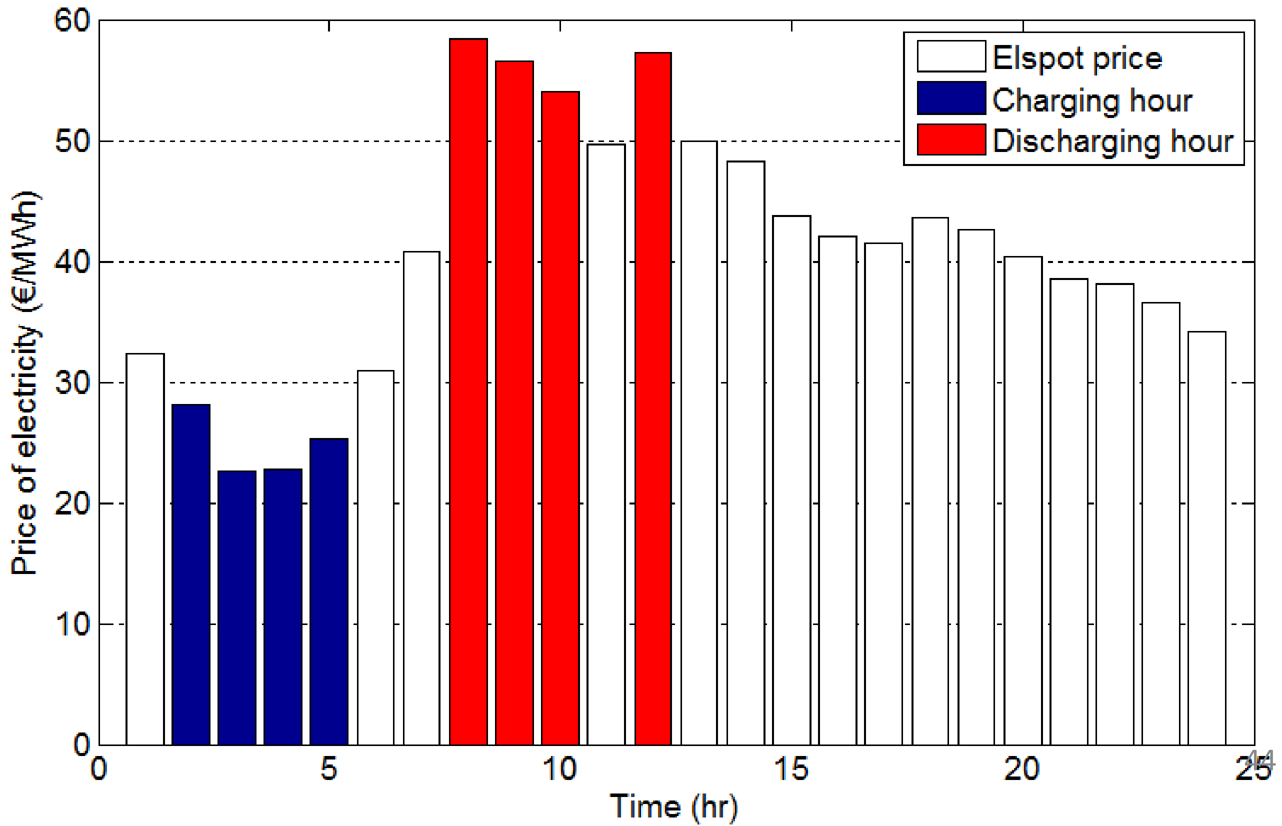


Source: Electric Power Research Institute (EPRI)

Energy Arbitrage

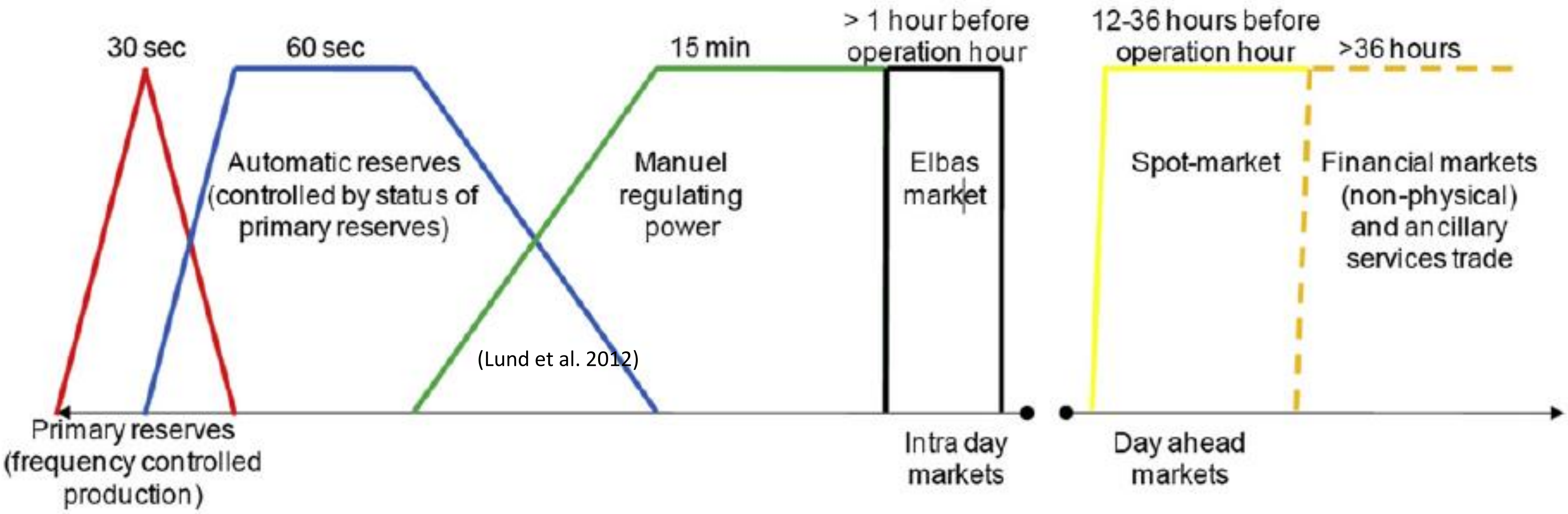
- Charging in low power prices to sell at peak times ➔ power price difference must be higher than marginal costs of EES
- Daily charge/discharge cycles or longer periods (from weekends to weekdays)
- Knowledge or estimation of day-ahead power prices

➔ What is the impact of EES on power prices? (self-competition)



Role of storage in balancing markets

- Balancing market are growing as a result of higher RE integration
- In balancing market, EES can make revenues both in charging (down-regulation) and discharging (up-regulation)
- Some EES technologies are able to charge/discharge simultaneously

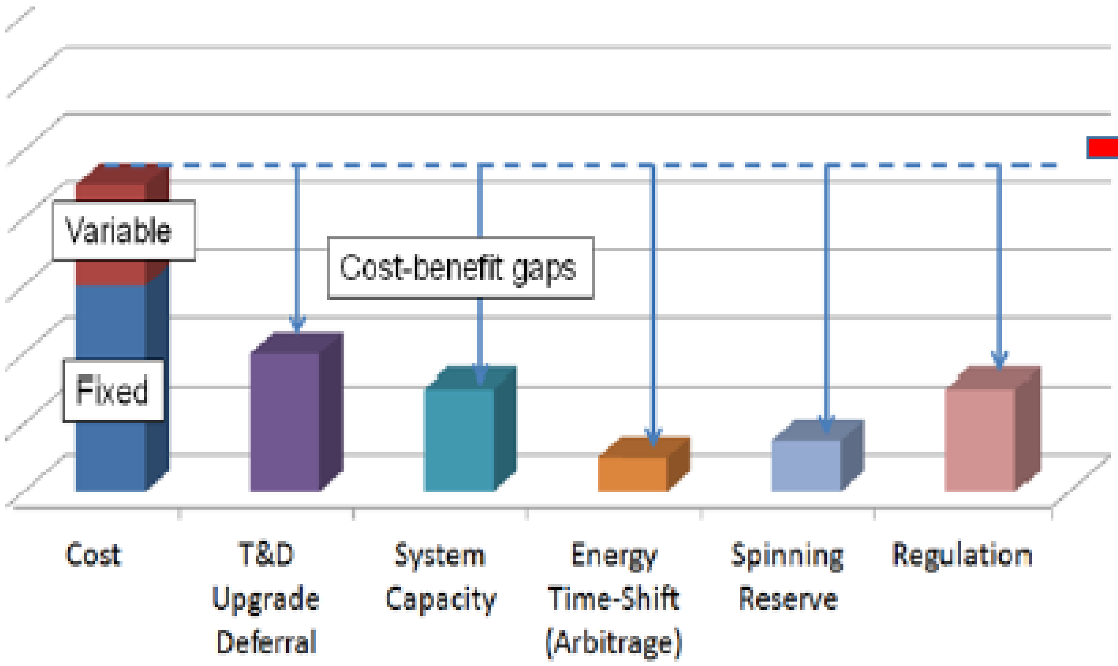


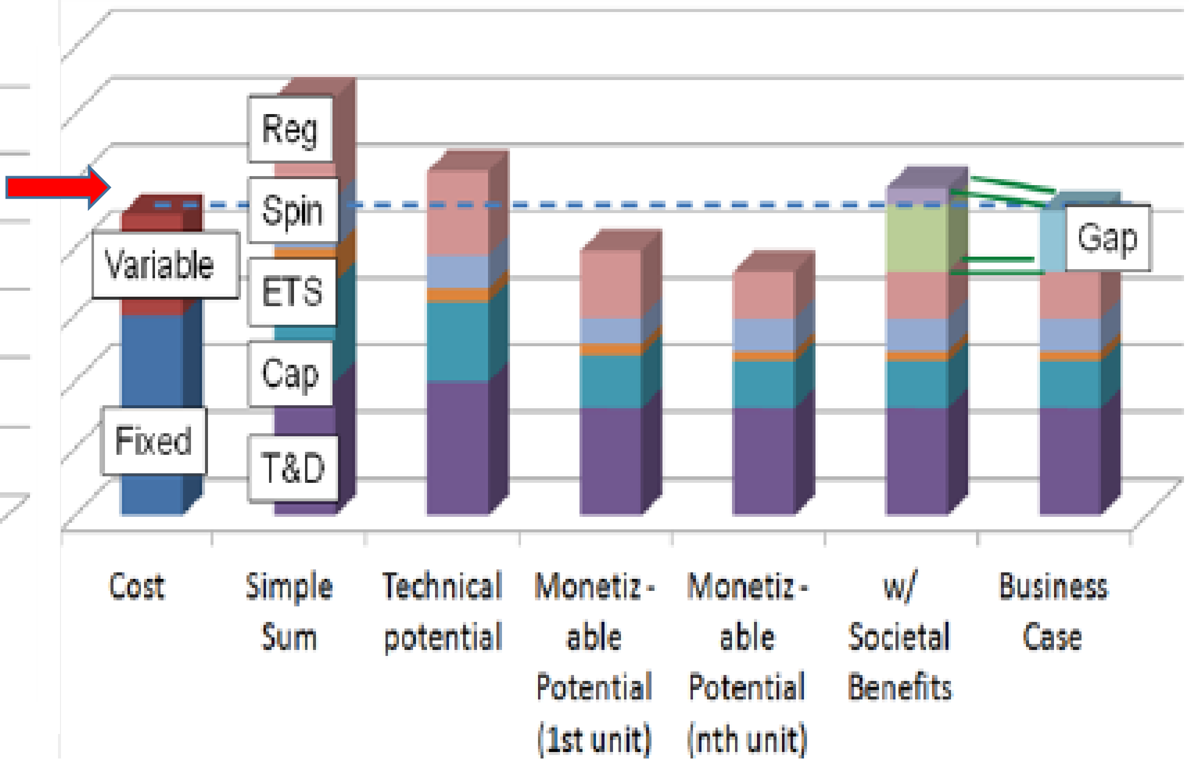
(Lund et al. 2012)

Aggregation of benefits of storage

- EES potential for several applications ➔ aggregation of benefits

Goal: Making business model



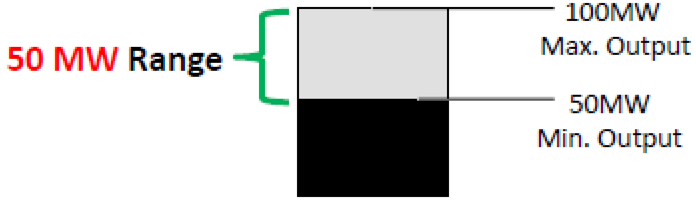


Source: Electric Power Research Institute (EPRI)

Gas turbine vs. electricity storage

1. Application in power regulation

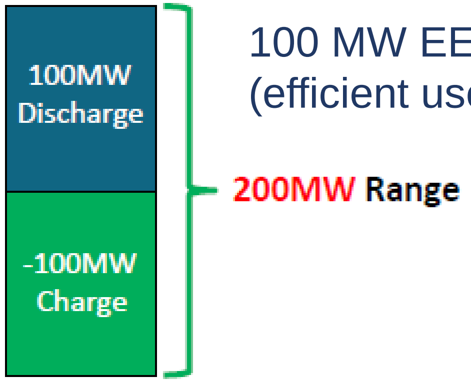
100 MW gas turbine



10 minute ramp
- 50 MW flexible range
- 20-30% useable hours/year
- Emissions

Source:EPRI

100 MW EES
(efficient use)



+ Second time ramp
++ 200 MW flexible range
+ 95% useable hours
+ Reduction of emissions
+ Fast project implementation

2. Application for peaking plants (CF=5%):

LCOE for gas turbine 360, and for lead-acid battery 280-320 €/MWh

➔ It's not always correct to compare the costs in €/kW or €/MWh (what criterion so!?)

Challenges and limitations of energy storage

- Today, lack of information regarding economy of EES is a barrier
- No free markets in some services that EES is a good candidate
- Regulatory supports should be defined by cost-benefit analysis
- Other system-level impacts of EES should be evaluated (RES integration)
- Effect of high penetration of EES in energy markets (self-competition)
- Scheduling, forecasting, and allocation in aggregation of the benefits
- Toxicity, material intensity, and environmental impacts of EES

Final notes

- EES is not a panacea ➔ comparison with alternatives required
- More commercialization is needed to evaluate costs/benefits in practice
- Economic features of EES should be clarified for defining business models (ownership structure) and regulatory incentives
- Other alternatives and their impact on the development of EES ➔ for example, "smoothing effect" of renewables in large-scale integration
- Impact of EU-level power markets with high capability of power exchange
- System-level impacts of EES and study of its socio-environmental benefits

Further reading

- Our world in data (very useful visuals): https://ourworldindata.org/renewable-energy
- Database of EES projects worldwide: http://www.energystorageexchange.org/projects
- DOE energy storage handbook: http://www.sandia.gov/ess/publications/SAND2013-5131.pdf
- Gravity-based EES by rail vehicles (see the video): http://www.aresnorthamerica.com/
- Mountain Gravity Energy Storage: https://doi.org/10.1016/j.energy.2019.116419

Further reading: policy and economics

- Some articles related to policy, regulation, and market-economics of energy storage:

- Sani SB, Celvakumaran P, Ramachandaramurthy VK, Walker S, Alrazi B, Ying YJ, et al. Energy storage system policies: Way forward and opportunities for emerging economies. J Energy Storage 2020;32:101902. https://doi.org/10.1016/j.est.2020.101902.

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- When I showed the slide related to (Vanadium- Redox) flow batteries, some of you looked a little skeptic. See how politicians think about it: https://www.youtube.com/watch?v=iBgENqVLJLs

- Thank you for your attention!

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