HYDROPOWER

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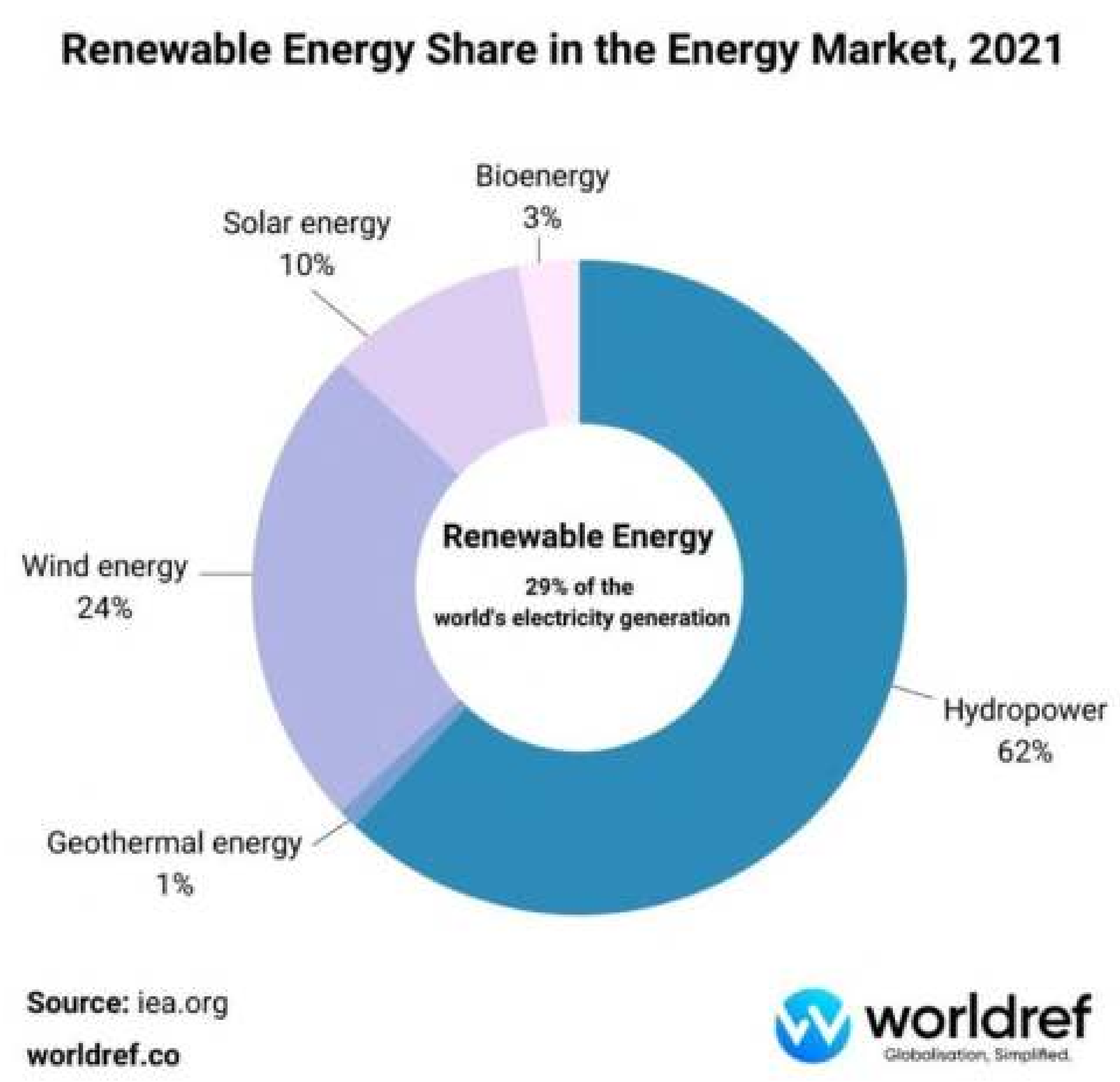
INTRODUCTION

Hydropower is one of the oldest energy sources in human history, originally used thousands of years ago to turn simple watermills. Its evolution accelerated in the late 19th century with the invention of modern water turbines, which transformed hydropower into a reliable source of electricity. In 1882, the first hydroelectric power plant was built in Wisconsin, marking the start of large-scale hydroelectric generation and paving the way for the global expansion of renewable energy

Technical Foundations

Hydropower basics



⚡ How Hydropower Works

Hydropower converts the kinetic energy (motion) and potential energy (elevation) of moving water into mechanical energy, and then into electrical energy using turbines and generators.

🔹 Basic Principle

When water flows from a higher elevation to a lower elevation, it gains speed and kinetic energy.
This energy turns the turbine blades, which are connected to a generator that produces electricity.

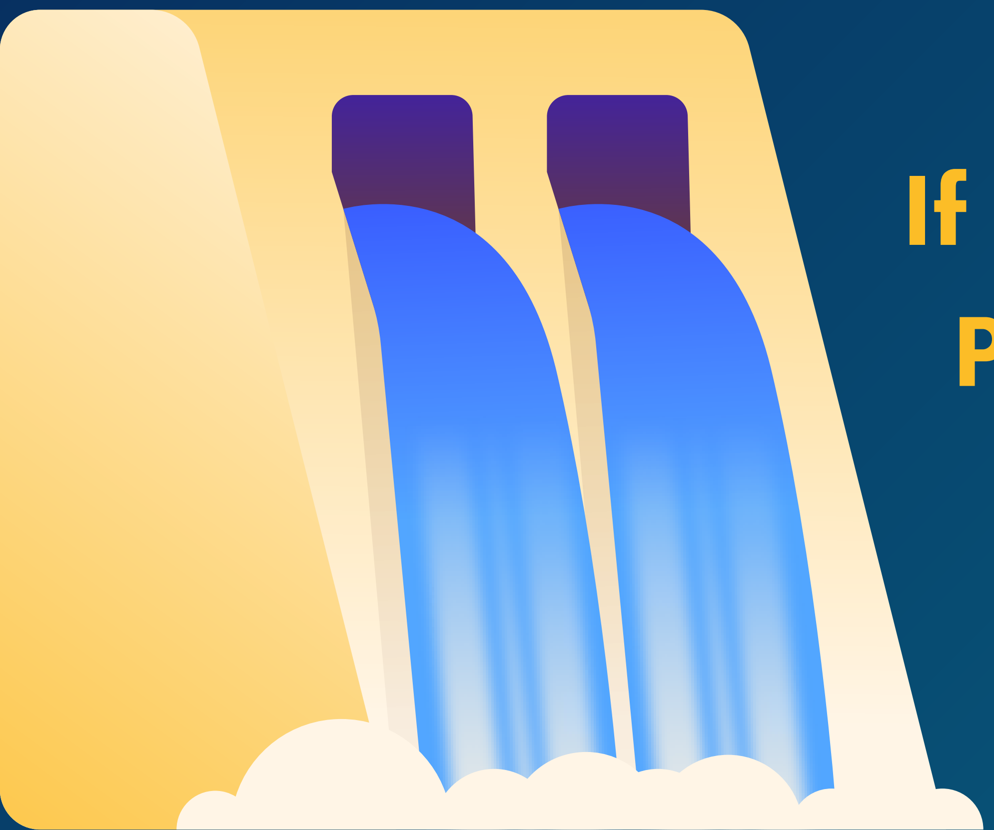
◆ **power output**

The power output of a hydropower plant can be estimated using the formula:

$$P=\eta\times\rho\times g\times Q\times H$$

Where:

- P = electrical power output (Watts)
- η = efficiency of the system (typically 0.7–0.9)
- ρ = density of water (≈ 1000 kg/m^3)
- g = acceleration due to gravity (9.81 m/s^2)
- Q= flow rate of water (m^3/s)
- H = effective head (height difference between water levels, in meters)



⚡Example:

If $H=50m$, $Q=20\ m^3/s$ and $\eta=0.85$\:

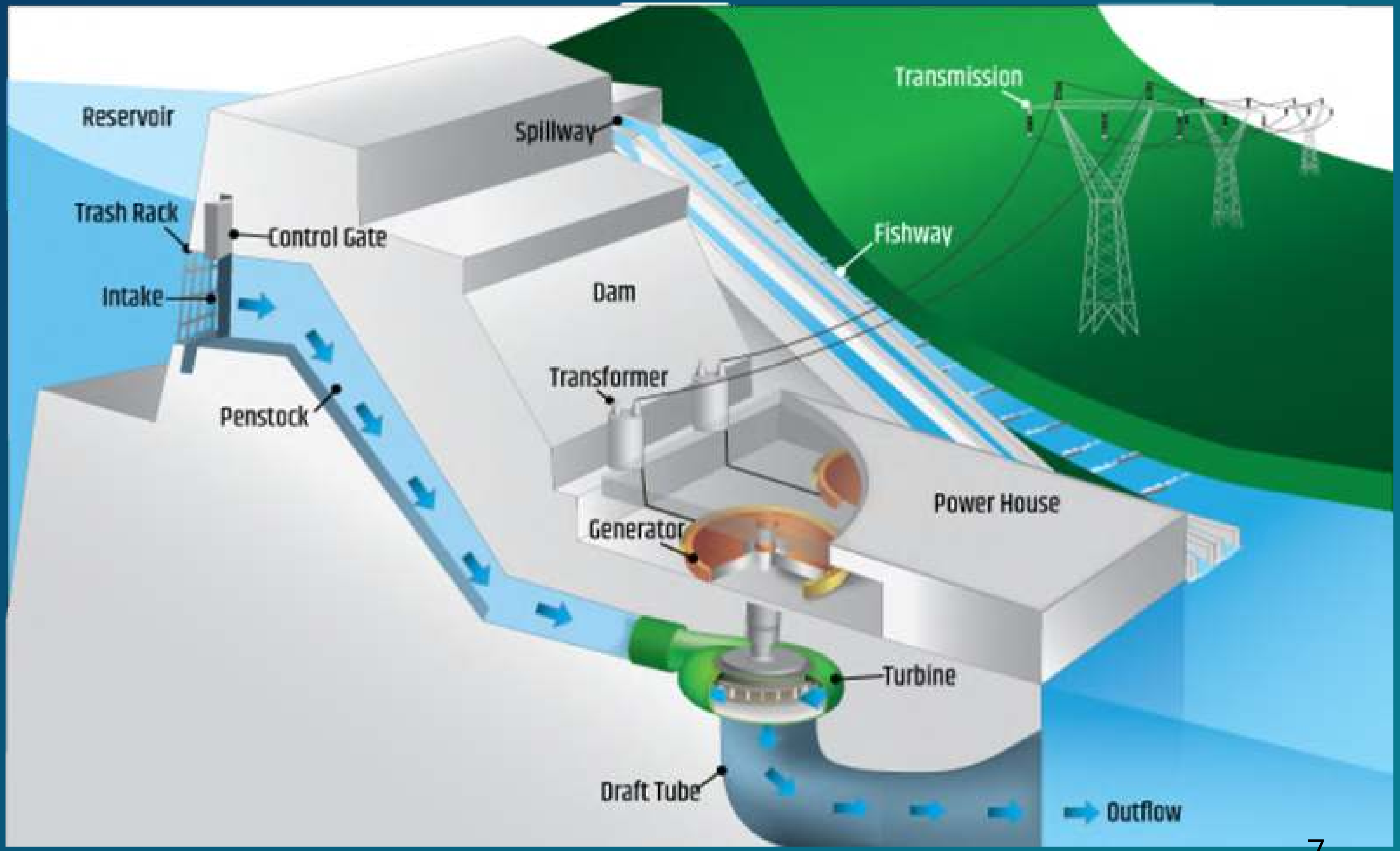
$$P=0.85\times1000\times9.81\times20\times50=8.34MW$$

Main Types of Hydropower Plants

1. Impoundment (Reservoir or Dam Hydropower)

Process:

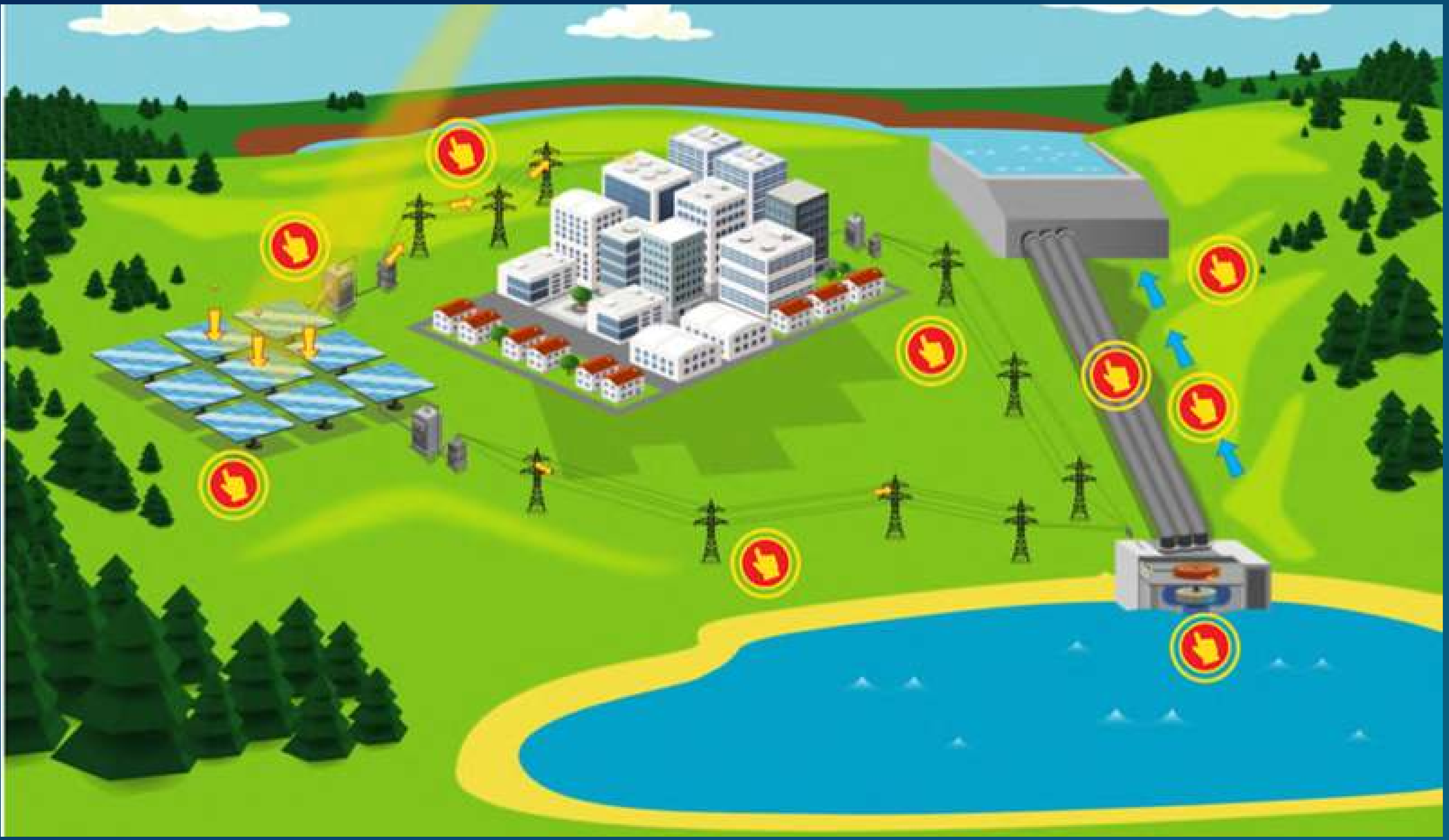
1. Water is stored in a reservoir behind a dam.
2. When released, it flows through penstocks (pipes).
3. The moving water spins turbine blades, activating the generator.

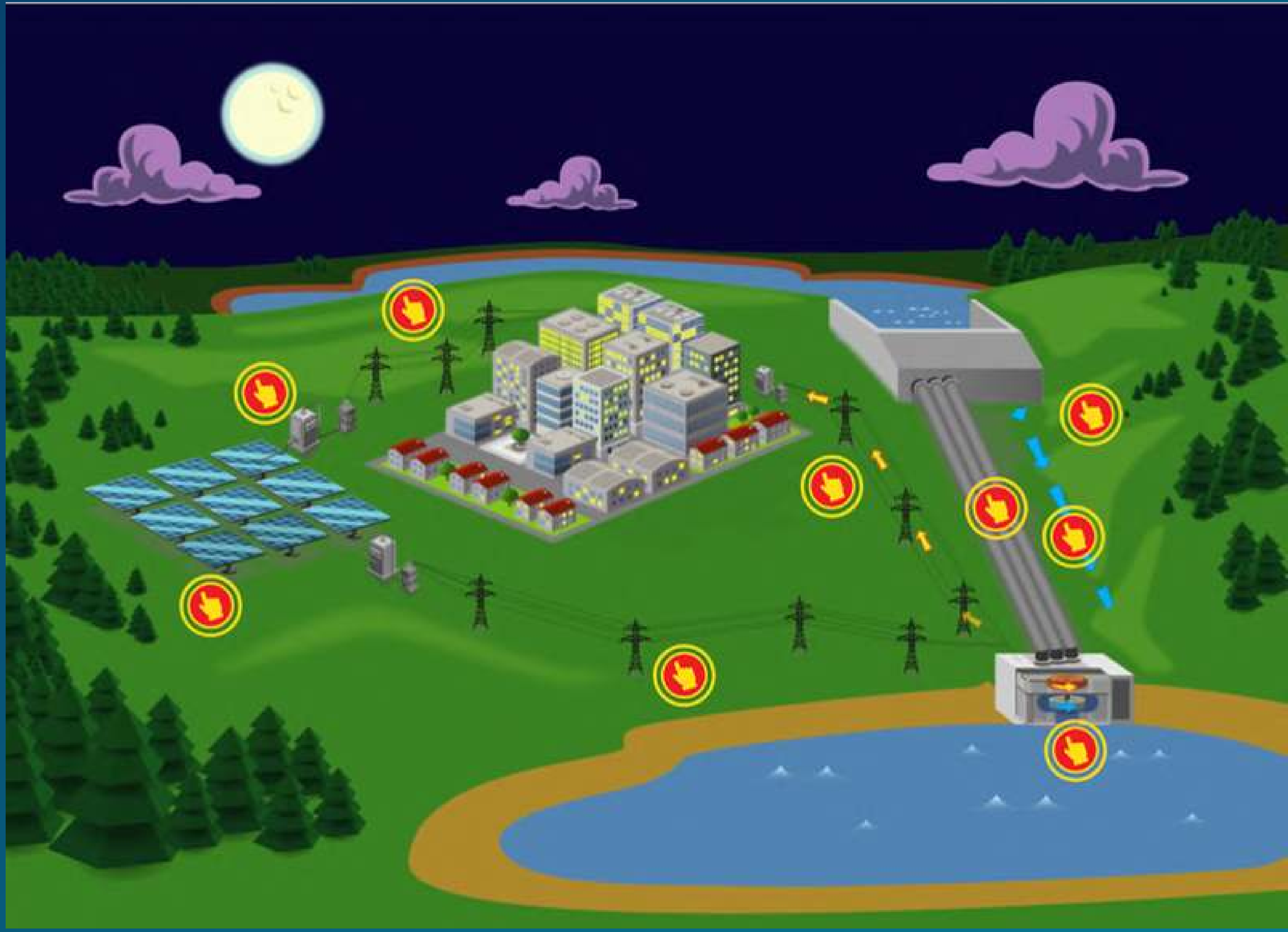


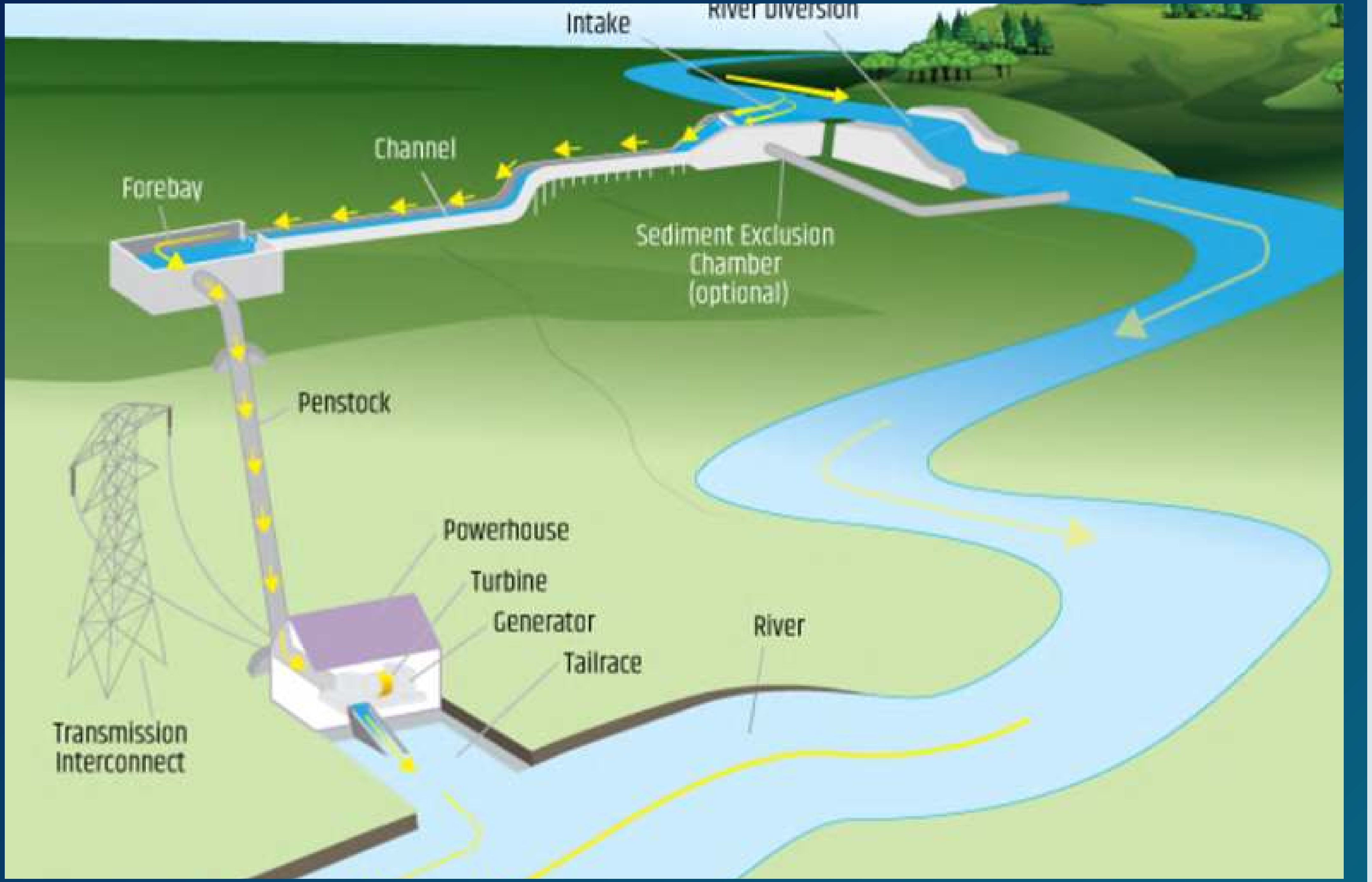
2. Pumped-Storage Hydropower (PHS)

This type stores energy like a giant battery.
Process:

- During low electricity demand, water is pumped upward from a lower reservoir to an upper one.
- During peak demand, water is released back down to generate power.







3. Diversion (Run-of-River Systems)

These systems use the natural flow of a river without a large dam.

Process:

- Part of the river water is diverted through a canal or penstock.
- It drives turbines and then returns to the river.

4. Floating Hydropower

Floating systems use turbines placed on water surfaces (rivers, tidal currents, ocean streams).

Mechanism:

- Turbines capture the kinetic energy of moving water without needing elevation.
- Often used in rural or remote areas where building a dam isn’t feasible.

Scale of Hydropower Systems

Large Hydropower
> 30 MW
National grids, industrial cities

Small Hydropower
100 kW – 10 MW
Small towns, villages

Micro Hydropower
< 100 kW
Single homes, farms, local communities

Innovations in Hydropower Technology

- Micro-Hydro Systems
- Wave and Tidal Technology
- Dam and Reservoir Development

Economic Aspects

Investment and construction cost

Hydropower is a capital-intensive technology with long lead times.

- High upfront capital expendure
- Drivers
  civil works: dams, tunnels; site geology and infrastructure access
- From $1,000 to over $5,000 per kilowatt

O&M (Operation & Maintenance) Costs and Lifespan

Operation and Maintenance

Annual O&M costs are often quoted as a percentage of the investment cost per kW per year, with typical values ranging from 1% to 4%.

Lifespan

These are typically 40 years or more for electro-mechanical equipment and over 50 years for penstocks and tailraces. Civil components, which represent about 45% of the installed cost, tend to have even longer economic life, commonly between 50 and 100 years

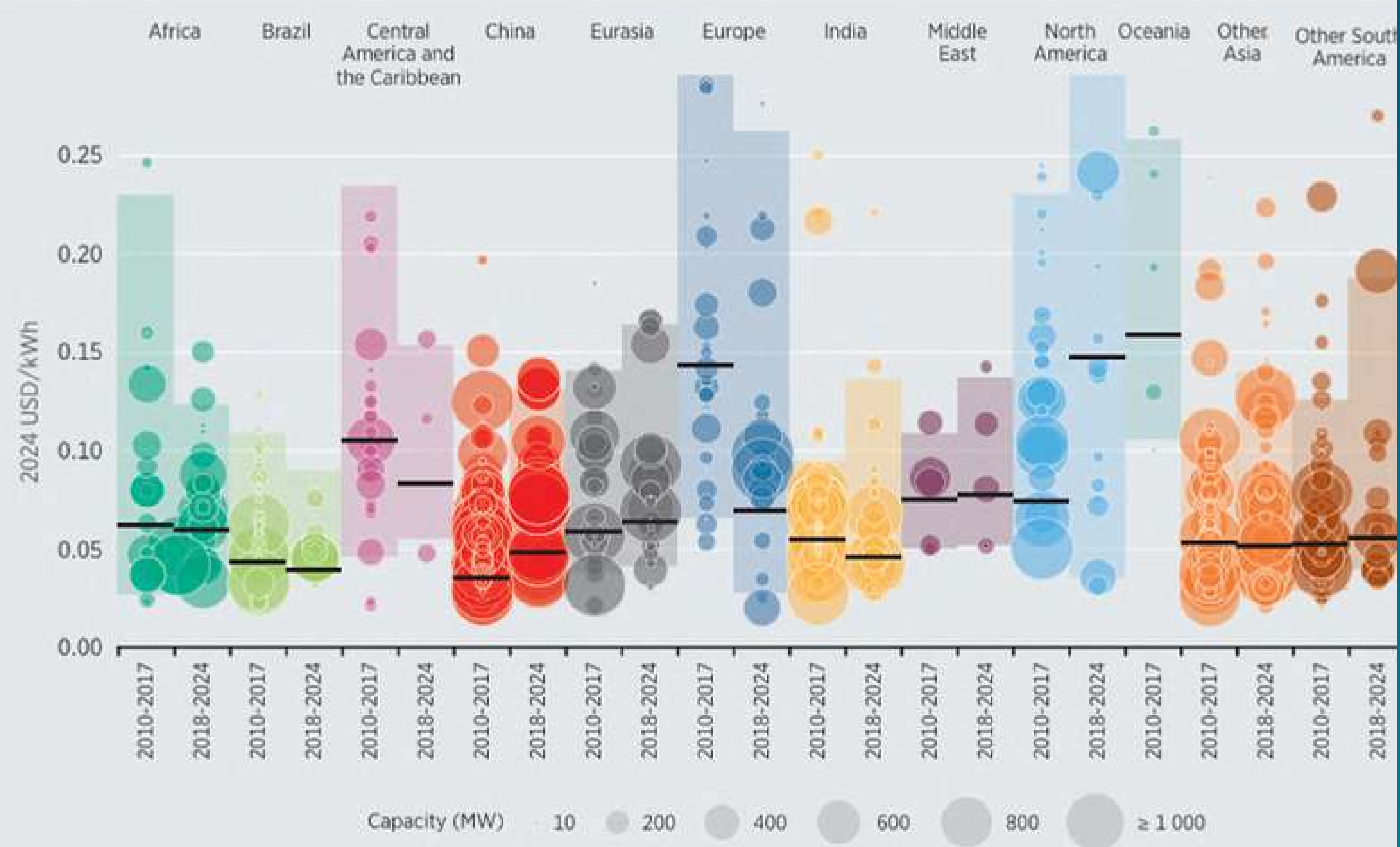
Table 6.6 Hydropower O&M costs by category from a sample of 25 projects

Project component	Share of total O&M costs (%)		
	Minimum	Weighted average	Maximum
Operational costs	20	**46**	61
Salary	13	**35**	74
Other	5	**15**	28
Material	3	**4**	4

Cost Competitiveness (LCOE)

The weighted average regional LCOE of hydropower projects, large and small, in the IRENA renewable costs database reflects the variation in site-specific and country-specific project installed costs and capacity factors.

Figure 6.8 Large hydropower project LCOE and weighted averages by country/region, 2010–2024



Main financing models for hydropower plants

Model	Funding Source	Ownership	Risk Bearing	Example
Public Financing	Government	Public	State	Three Gorges Dam (China)
Private (IPP)	Private Investors	Private	Developer	Nam Theun 2 (Laos)
PPP (BOT/BOOT)	Public + Private	Mixed	Shared	Tarbela 4 (Pakistan)
Multilateral	IFIs	Public or Mixed	Shared	AfDB/World Bank projects
Green Bonds	Capital Markets	Public/Private	Market investors	EDF, Statkraft
Blended Finance	Mixed (Donor + Private)	Mixed	Shared	SEFA/AfDB Hydro

Economic Benefits

Job creation

Local infrastructure

Electricity price stability

Political & Environmental Aspects

Political Aspects

National Sovereignty vs. Transboundary Conflict

A nation's sovereign right to build hydropower often clashes directly with its downstream neighbor's existential need for water security, transforming energy projects into sources of diplomatic tension and potential conflict.

Corruption and "Big Engineering" Lobbies

The massive budgets for large dams foster a powerful "hydropower lobby" of construction firms and political elites, whose influence can push projects forward for vested interests rather than public good, often leading to major corruption scandals

Domestic Politics: Displacement and Social Equity

Large hydropower projects often force the displacement of local and indigenous communities, sparking domestic conflict as governments prioritize national energy goals over local social equity and land rights.

Environmental Impacts

Ecosystem Fragmentation and Habitat Destruction

Dams act as massive barriers across rivers, disrupting the natural flow regime and fragmenting aquatic ecosystems.

Sediment Trapping and River Morphology

Dams trap sediments (silt, sand, gravel) that would normally flow downstream

Water Quality Changes

The creation of a reservoir fundamentally alters the physical and chemical properties of the river.

Water in a reservoir can become stratified, with cold, oxygen-poor water settling at the bottom (hypolimnion).

Hydropower, International Regulations & Climate Goals

Helsinki Rules (1966)

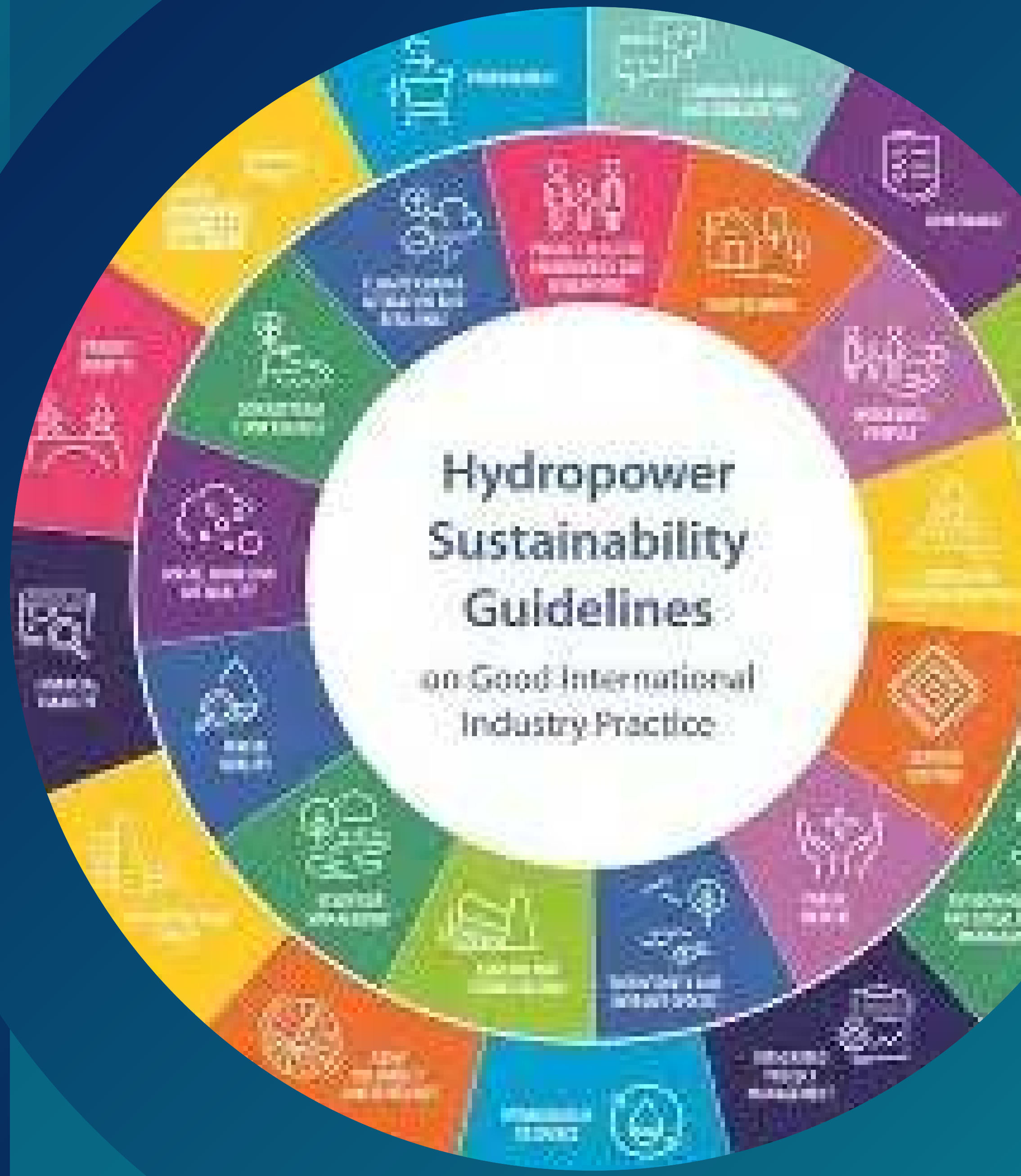
Established the principle of equitable and reasonable use of shared watercourses.
It ensures that countries sharing rivers cooperate and prevent significant harm to others.

UN Watercourses Convention (1997)

Provides a global legal framework for the non-navigational uses of international rivers.
It promotes prior notification, fair water sharing, and environmental protection.

Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Helsinki Convention, 1992)

Encourages joint management and monitoring of shared water resources.
Aims to prevent conflicts, pollution, and ecological degradation in transboundary waters.



Case Studies

China – The Three Gorges Dam

- Produces about 90 TWh/year, supplying electricity to millions.
- Major goals: flood control, navigation improvement, and power generation.
- advanced turbine design, massive grid integration.
- Impacts: displaced over 1.2 million people; major ecosystem changes.
- Large-scale hydro can ensure energy security but needs strict social and environmental safeguards.

Location: Yangtze River
Capacity: ~22,500 MW (world's largest hydropower plant)

Brazil – Itaipu Dam

- Provides around 10% of Brazil's electricity and 90% of Paraguay's.
- A model of binational cooperation (shared governance and revenue).
- Environmental actions: reforestation, wildlife protection zones.
- Regional cooperation can turn hydropower into a tool for both development and diplomacy.

Location: Paraná River (border of Brazil and Paraguay)
Capacity: ~14,000 MW

Ethiopia – Grand Ethiopian Renaissance Dam

- Key for Ethiopia's industrialization and electrification.
- Dispute with downstream countries (Egypt, Sudan) over water rights.
- Domestic benefits: expected to double electricity supply.
- Transboundary water management is critical for regional peace and sustainability.

Location: Blue Nile River

Capacity: ~6,450 MW (largest in Africa, under completion)

Africa – Small, Micro, and Emerging Innovative Hydropower

Morroco

- Micro-hydro in the Atlas Mountains powering isolated villages.
- Often built as hybrid systems with solar panels to ensure continuous supply.
- Supports water pumping, irrigation, and small local industries.

Kenya

- Several community-managed plants (0.5–5 MW) in the central highlands.
- Boostsagro-processing (tea,coffee), refrigeration, and rural SMEs.
- Recognized for strong community ownership and sustainability models.

Rwanda

- Over 20 micro-hydro sites implemented since 2010.
- Provides stable electricity to health centers, schools, and small businesses.
- Strong government–NGO partnerships (e.g., with GIZ, Energy4Impact).

Tanzania

- Micro-hydro powering mini-grids in mountainous areas.
- Used for productive uses: grain mills, sawmills, welding workshops.

Benefits	Main Challenges
Low-cost electrification for remote regions	Maintenance and need for local technical training
Minimal environmental footprint	Seasonal water variability due to droughts
High community involvement and job creation	Difficulties in securing initial financing
Improved education, healthcare, and local businesses thanks to reliable power	Integration with national grids

Future Outlook & Challenges

The Digital Transformation of Hydropower

Modernization and Digitalization of Hydropower

Smart Monitoring : AI ---> efficiency, maintenance

Data-Driven Decisions : Include Data into decision makings

Building a Smart, Flexible Energy System

Integration with Other Renewables

Hydro + Solar/Wind

Hydropower complements variable renewables, because it can produce energy when they can't, helping balance the grid and store energy.

Pumped-Storage Hydropower (PHS)

It acts like a giant battery: stores extra solar/wind energy by pumping water uphill and releases it to generate electricity when demand increases.

Smart Grids

Smart grids manage energy flows intelligently so electricity from hydropower and renewables moves efficiently and reliably across the network.

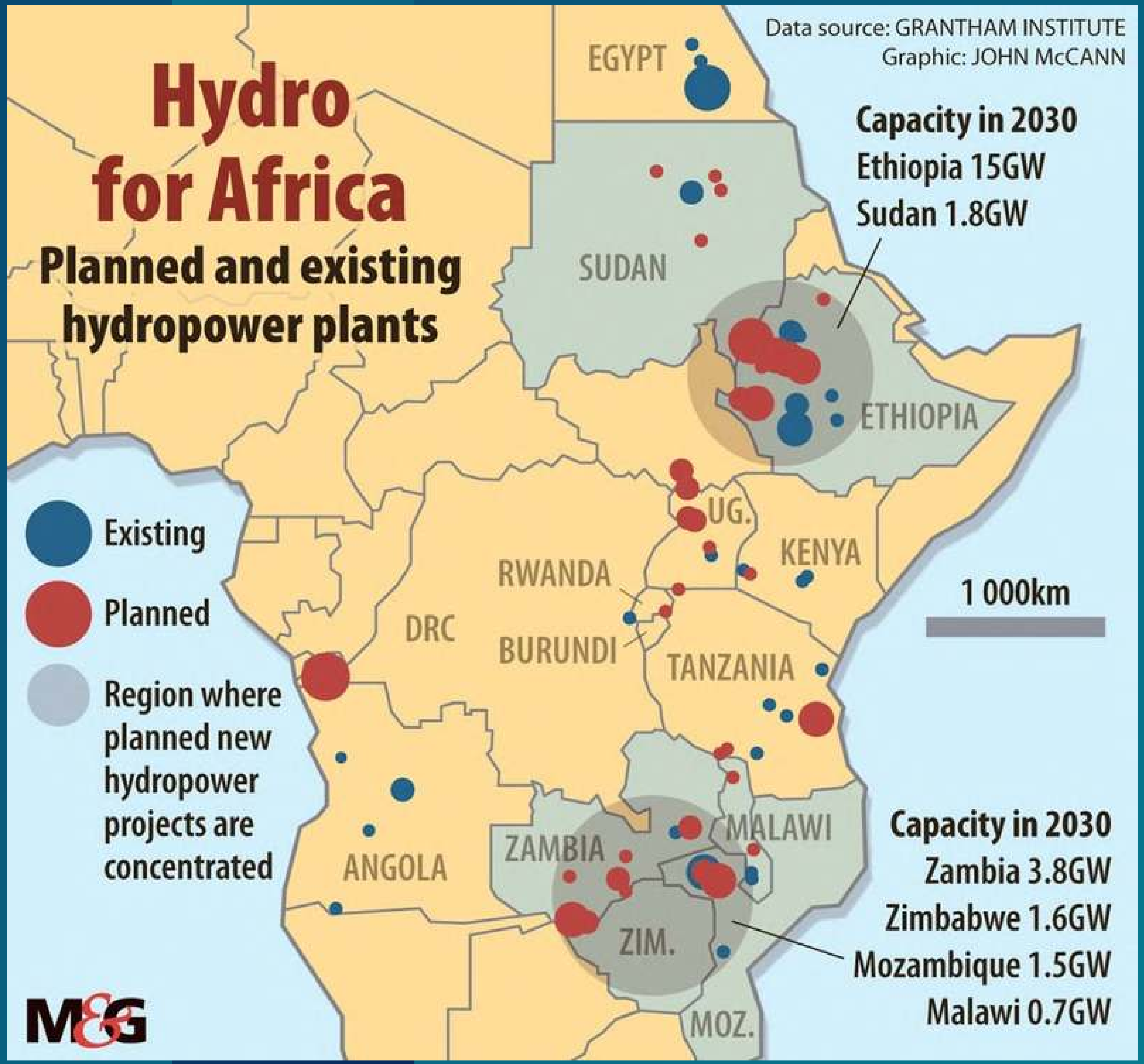
Untapped Potential in Africa

Expanding Access and Opportunity

Africa: Less than 10% of its technical hydropower potential is developed. Projects in Ethiopia, Zambia, Sudan... show growing regional interest.

Rural Electrification: Small and micro-hydro projects can transform access in remote communities.

Sustainability Focus: Future development must balance energy access with ecosystem protection and social equity.



Future Challenges and Pathways Forward

Financing Innovation

Green bonds and public-private partnerships (PPP) to fund modernization and climate-resilient projects.

Resilience

Climate change affects rainfall and increases extreme weather. Future hydropower systems must be designed to handle floods and unpredictable water flow.

Global Coal

Hydropower plays a major role in global decarbonization strategies. Because it’s stable and renewable, many countries see it as a key pillar of achieving a carbon-neutral energy system by 2050.

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