

# Harnessing More Value from Hydropower Reservoirs: Virtual pumped storage + Combined cycle hydropower



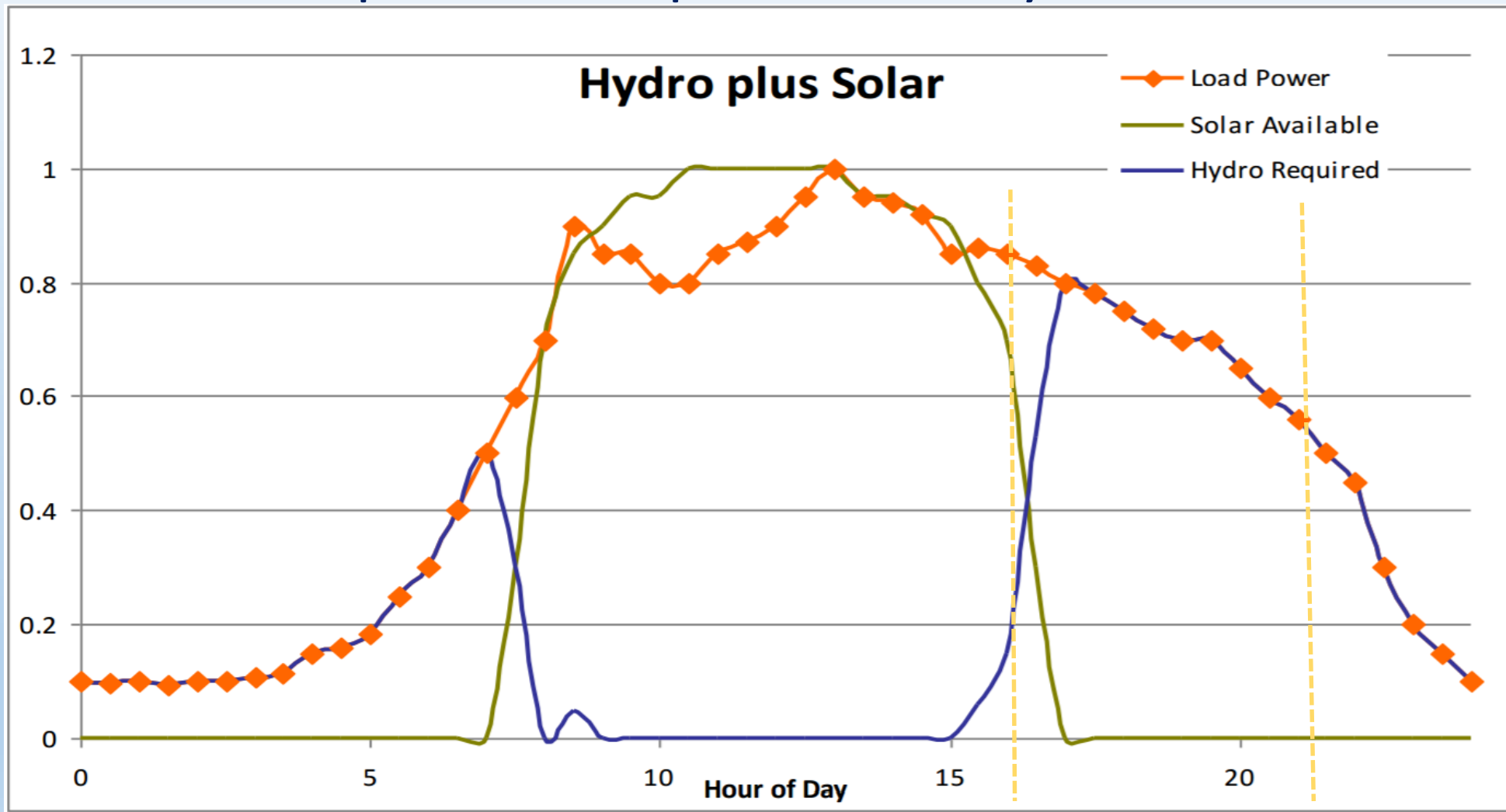
Alto Rabagão dam in Portugal: World's first floating photovoltaic project in which the solar power is integrated with generation from a hydropower plant. Floating Solar PV adds 220 kW to the 68-MW hydro plant

# Virtual pumped storage + Combined cycle hydropower

- A. Hybrid Hydro-Solar Energy Systems:** Integration of floating solar PV with hydroelectric power provides valuable synergies, over and above these 2 technologies standalone:
1. Hydropower generation's quick ramping characteristic serves as a **virtual pumped energy storage** to balance variable solar output – water flow can be reduced as solar ramps up, or increased as electric demand ramps up
    - Water can be conserved to cater to evening peak energy demand (ToD) or dry season
    - Quick ramping hydropower – Intermittent solar power can be made dispatchable
    - Storage capacity is a “freebie” since capital cost is for the solar power capacity added
  2. **Reduced environmental impacts** from large hydro
    1. More energy from same flooded area footprint
    2. More energy from same water throughput
  3. **Existing transmission lines and substation** – these can be upgraded if necessary at lower cost than constructing new greenfield infrastructure
- B. Hydrokinetic Turbines:** Added at the outlet of the existing conventional hydropower turbine to capture residual hydrokinetic (flow) energy

# A.1. Virtual Pumped Energy Storage:

## Typical load and production profiles for Hydro+Solar



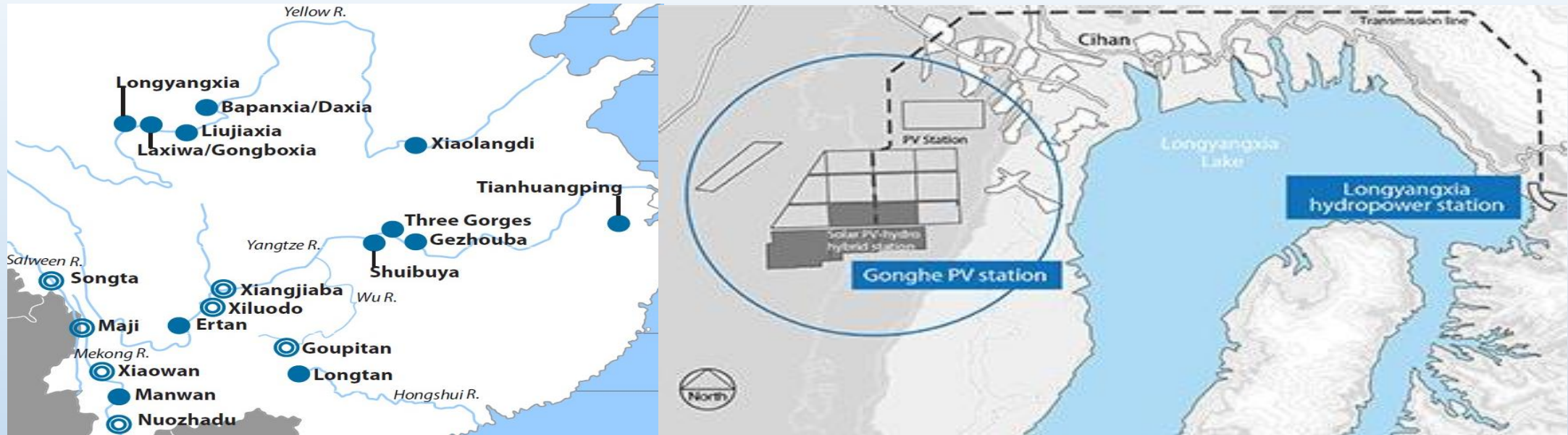
4 – 9 pm: Dropping solar but high demand (peak ToD pricing)

## A.1. Virtual Pumped Energy Storage:

### Electricity can be stored and time-shifted to higher ToD pricing regime

- Typical hydro designs are based on 50% capacity factor, e.g., 100 MW project produces 1,200 MWh/day
- Solar PV plant capacity factor is typically 20%, i.e., 100 MW PV plant produces 480 MWh/day – 40% of the 100 MW hydro plant's output
- Case of separate operation: Total revenue is \$158,400/day
  - ❖ Hydro plant has a base load PPA to deliver all its output at \$0.10/kWh = \$120,000/day
  - ❖ Intermittent solar supplied to the grid has a PPA price of \$0.08/kWh = \$38,400/day
- Assuming hydro plant owns the solar asset, hydro output can be curtailed during solar hours while delivering the same base load to the grid. The conserved water can then be used to generate extra power between ToD peak pricing 4pm-9pm: Total revenue is: \$192,000/day
  - ❖ Hydro plant has a base load PPA to deliver all its output at \$0.10/kWh = \$120,000/day
  - ❖ Solar power all shifted to supply to grid peak during ToD pricing hours at \$0.15/kWh = \$72,000/day

# Largest Hydro-Solar integration: Longyangxia, China



- ❑ Hybrid: Largest Hydro-Solar integrated generation station in the world, with recently added 850 MW ground mounted Solar PV coupled to existing 1280 MW hydroelectric turbines
- ❑ 850 MW of ground mounted Solar PV is spread over 25 km<sup>2</sup>, built 2013-2015, with 25 year design life
- ❑ Automatic regulation of the output, hydro to balance solar resource variability before dispatch to the grid
- ❑ **Ramp rate is 8 sec for 10 MW. These are circa 1980's turbines and ramp rate on newer ones will be faster. Also continues to supply spinning reserves and ancillary services to the grid.**

Picture source: <http://www.hydropower.org/blog/case-study-solar-pv%E2%80%93hydro-hybrid-system-at-longyangxia-china>

## A.2 Reduced Environment Impacts:

### Adding Large Hydro vs. Adding Floating Solar PV (FPV)

Expanding Large Hydro	Adding FPV to Existing Large Hydro
Creates environmental issues	<b>Less likely to create environmental issues</b>
More water throughput needed	<b>No additional water throughput needed</b>
More Capital intensive (\$2 - 3/ W) Lower O&M cost LCOE 6-10 c/kWh	Less Capital intensive (\$1 - 1.20/ W) Higher O&M cost LCOE 6-10 c/kWh
Large economies of scale but not modular	No appreciable economies of scale but modular/scalable
Must have 40-50 year PPA for 100% of power upfront	Modular buildout as power demand increases. 20-25 year PPA can be accordingly phased as capacity is added
Long construction time before it generates any revenue to service debt	Can deploy quickly and revenue starts to be generated right away
May have to build new greenfield transmission lines	<b>Use existing transmission infrastructure or relatively easily upgrade existing assets</b>

## A.2. More power with minimal environmental impact: Adding FPV to Existing Large Hydropower Reservoir

- ✓ General “err on the side of caution” rule of thumb is 2% of available water surface can be used for FPV with no environmental repercussions
  - Anecdotal data, as well as reservoir modeling studies, suggest negligible effects on fish, boat traffic and other environment at <10% of reservoir area coverage
- ✓ Adding FPV to an existing hydropower reservoir will not displace people or submerge land
- ✓ Floating solar reduces evaporation often a major cause of fresh water loss
- ✓ Large hydro reservoirs on the other hand can have potentially large social and environmental impacts, and require a much longer planning horizon
- ✓ Cooling effects of the reservoir water body improves panel efficiency, which helps reduce the lifecycle carbon footprint of the solar plant equipment

## A.2 More Electricity from the same Water Throughput

**Total energy delivered from the original hydro plant can be enhanced by adding FPV on the reservoir surface**

- Typical hydro designs are based on 50% capacity factor, e.g., 100 MW project produces 438,000 MWh per year (i.e. equivalent to a steady 24/365 output of 50 MW)
- Solar PV plant capacity factor is typically 20%, i.e., 100 MW PV plant produces 175,200 MWh per year – 40% of a 100 MW hydro plant output
- Since annual water flow through a hydropower system is the rate-limiting factor for energy output (MWh), a co-located FPV component will allow additional energy production at the same water throughput
  - ❖ Multiplier effect – Since water is often a scarce resource, it effectively means more electricity is being generated from same amount of water. This can cater to peak demand or make a seasonal system perennial
  - ❖ Pay only for the additional generation capacity – the Virtual Pumped Energy Storage capacity is a “freebie”



## A.3 Existing Transmission Infrastructure can be used

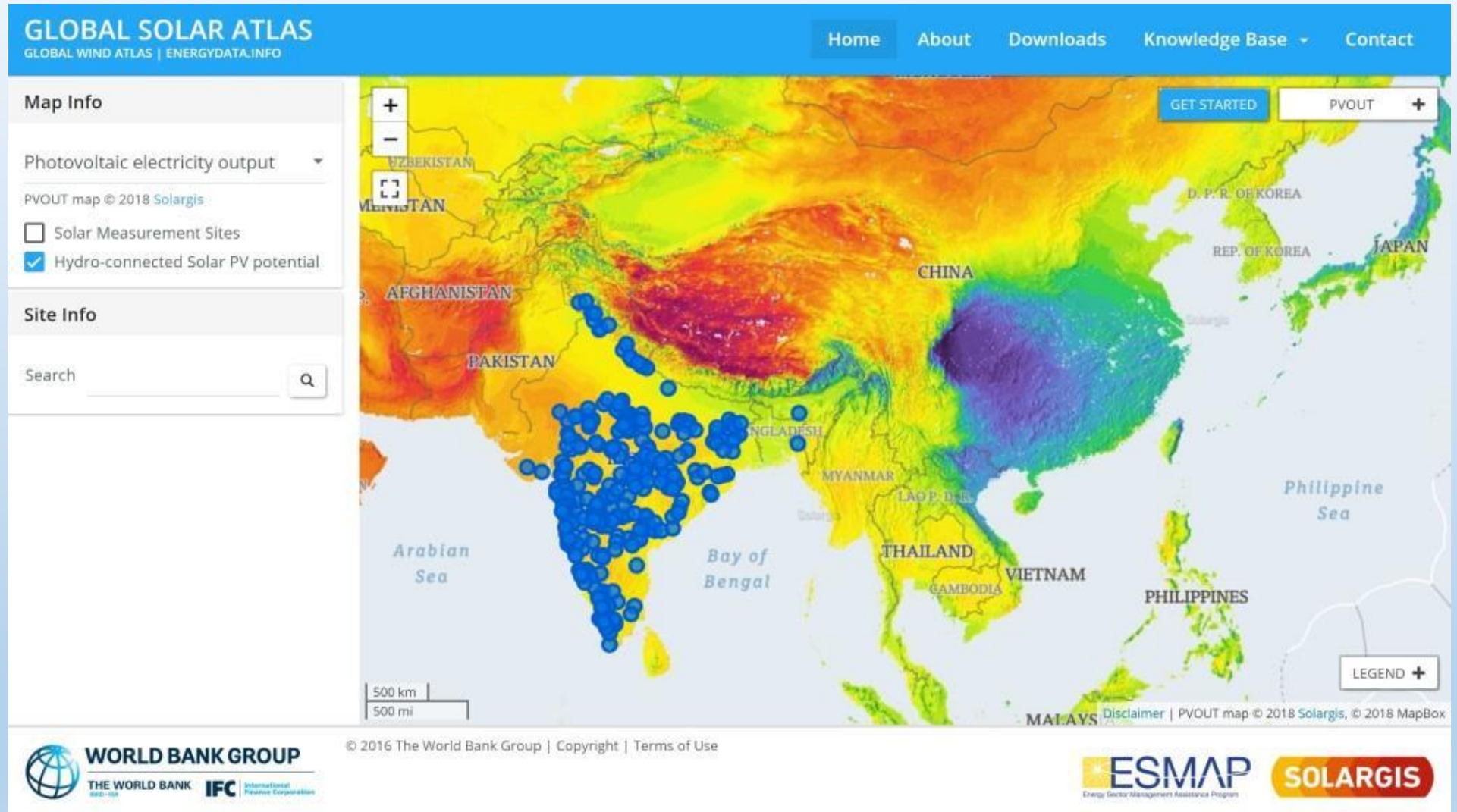
- Typical hydro designs are based on 50% capacity factor, e.g., 100 MW project produces 1,200 MWh/day
- Solar PV plant capacity factor is typically 20%, i.e., 100 MW PV plant produces 480 MWh/day – 40% of the 100 MW hydro plant's output
- In the above scenario, 40% extra energy can theoretically be handled by existing transmission infrastructure in a levelized output regime since it was sized for 100 MW peak
  - ❖ Total daily energy output is  $1200+480= 1680$  MWh/day – the levelized power output that leads to this is  $1680/24= 70$  MW
- Further, in this scenario, theoretically up to 250 MW of FPV can be added without upgrading any transmission infrastructure, leading to the equivalent of a steady 100 MW base load generation
  - ❖ Even if more FPV than this is added (subject to reservoir size limitations), it is much easier to upgrade the infrastructure than build new infrastructure
- The FPV can likely be integrated with a minigrid study rather than a full fledged grid integration study

# Combining Hydropower and FPV – Limitations

Notwithstanding the benefits accruing from virtual pumped storage, environmental advantages, and adequacy of existing transmission infrastructure, there are some limits to bear in mind

1. Transmission line and transformer maximum rated capacities
2. Upper “safe limit” of percentage of reservoir area occupied by FPV
3. Reservoir level must remain within FPV anchoring and mooring limits
4. Hydropower operation range may put limits on full dispatchability
  - Tail water minimum flow requirements (e.g. environmental mitigation or irrigation releases)
  - Dam level regulations limitations to avoid erosion to reservoir banks
5. Hydropower turbine response time (depending on turbine type)
  - PV generator ramp rates caused by rapid local weather phenomena such as moving clouds may affect quality of supply and exceed regulatory requirements

- Globalsolaratlas.info is currently only populated for India, Bangladesh, West Africa
- ADB identified via desktop analysis, several potential sites in some of its other member countries

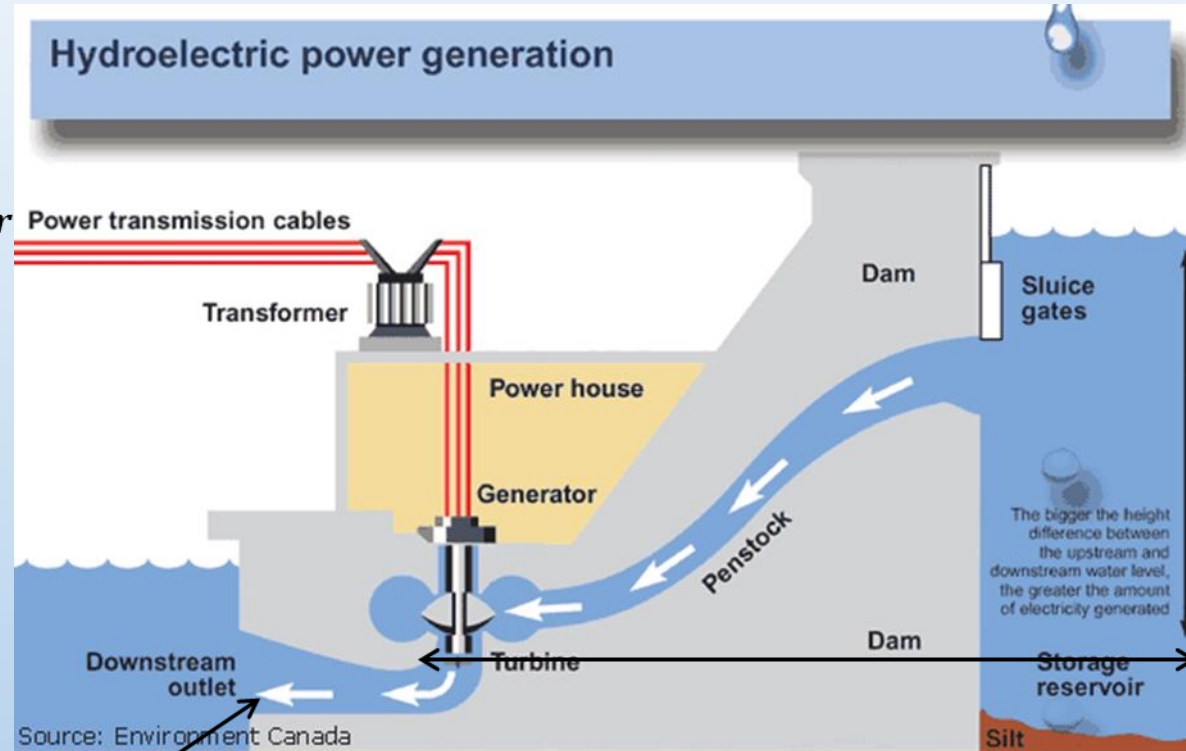


# B. Combined-cycle hydroelectric power system

**Hydrostatic Power**  
 $= \eta \rho Q g h$

**Hydrokinetic Power**  
 $= \frac{1}{2} \eta \rho A V^3$

Where, Power in watts;  $\eta$  is the dimensionless efficiency of turbine;  $\rho$  is the density of water in kg per cubic meter;  $Q$  is the flow in cubic metres per second;  $g$  is the acceleration due to gravity;  $h$  is the height difference between intake and outlet;  $A$  is the area of the rotor blades,  $V$  is the fluid velocity in meters per second.



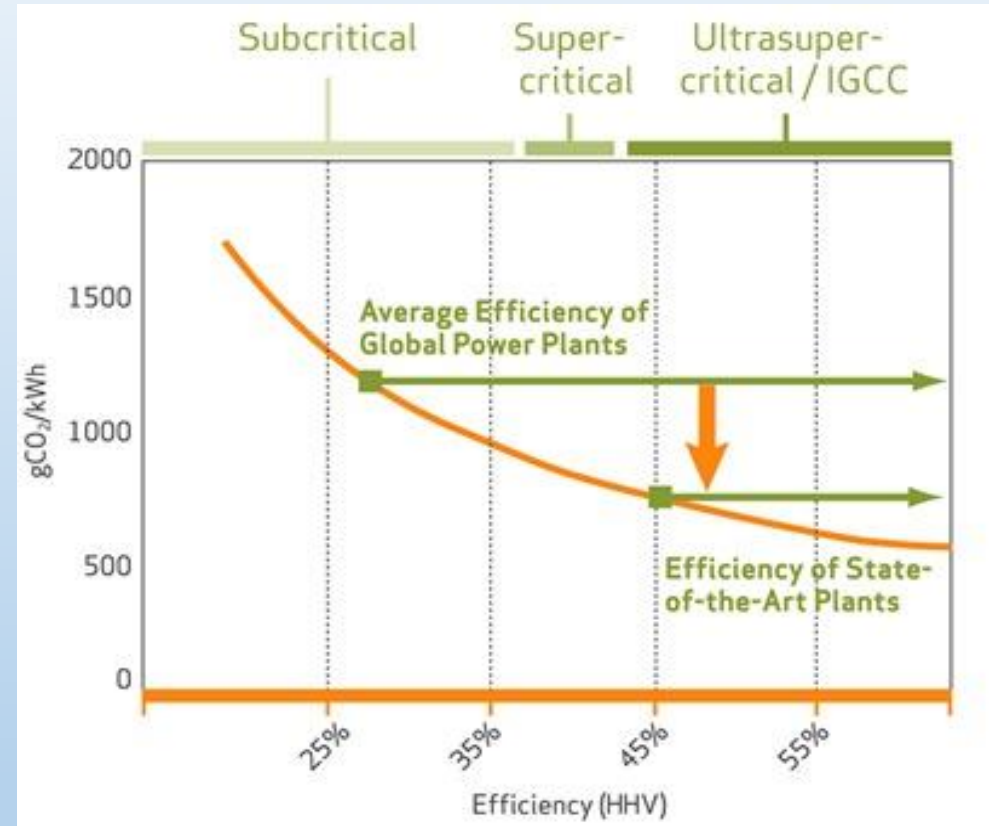
**Turbine Outflow**  
**Potential Hydrokinetic power**

## Hydrokinetic Power Generation Scheme

- As seen in the equation, the hydrokinetic power that can be extracted is proportional to the cube of the velocity of flow, the cross-sectional area of turbine, and the density of the water.
- Density for water is 1000kg/m<sup>3</sup> which is about 817 times that of wind's 1.223 kg/m<sup>3</sup>,

# Combined-cycle Gas Turbine Principle

- It first burns coal partially in oxygen in a gasification chamber to produce a “synthetic” gas (pressurized hydrogen and carbon monoxide).
- The plant combusts the syngas in air in a gas turbine—a modified jet engine— to make electricity (After removing sulphur compounds and other impurities).
- The heat in the exhaust gases leaving the gas turbine turns water into steam, which is piped into a steam turbine to generate additional power.



Efficiencies of different coal technologies

Source: IEA “Focus on Clean Coal” (2006)

Note: 1% increase in efficiency – 2-3% decrease in emissions

# Advantages of Adding a Hydrokinetic device at a dam exit



**Hydrokinetic turbines (HKT)** are powered by moving water and are different from traditional **hydropower turbines** in that they are placed directly in the flow of water. They generate power only from **kinetic energy of moving water**

Their advantages include:

- ✓ Maximize the power extraction from river energy – extract the residual energy from dam exit water flow, thus acting as “enhancer” to dam capacity
  - ❖ Enhanced power extraction effect is a few percent
- ✓ Dispatchable (as it is acts as a “enhancer” to hydro turbine generation)
- ✓ Provide added clean energy with minimal civil engineering work required
- ✓ Unidirectional operation, less flow variation, predictable power generation
- ✓ Cost range per kW is slightly above to conventional hydropower (\$2-5/W)
- ✓ Ease of connection to grid due to collocation with hydropower plant

# Hydrokinetic Turbine Technology Availability

HKT devices are still at an relatively early stage of development. However, most of components (blades, generator, power converter, etc.) needed for designing a HKT system are readily available (Khan, Iqbal, and Quaicoe 2008).

Device Developer	Device Name	Type	Development Status
<b>AeroHydro Research and Technology</b>	Unknown	Oscillatory	Laboratory
<b>Free Flow Power</b>	FFP Turbine Generator	Horizontal Axis	Experimental
<b>Free Flow 69</b>	Osprey	Vertical Axis	Experimental
<b>Lucid Energy</b>	Gorlov Helical Turbine	Vertical Axis	Technology Demonstration
<b>Hydro Green Energy</b>	Krouse Turbine	Horizontal Axis	Experimental
<b>New Energy Corporation</b>	EnCurrent Turbine	Vertical Axis	Commercial Demonstration
<b>Ocean Renewable Power Corp</b>	OCCGen	Crossflow Axis	Technology Demonstration
<b>UEK</b>	Underwater Electric Kite	Horizontal Axis	Commercial Demonstration
<b>Verdant Power</b>	Free Flow Turbine	Horizontal Axis	Commercial Demonstration
<b>Vortex Hydro</b>	VIVACI	Vertical Axis	Laboratory
<b>Hydrovolts</b>	Flipwing	Paddlewheel	Technology Demonstration
<b>Energiin</b>	?	?	Laboratory

# Potential Scale of Generation from these Technologies

- Potential for significant generation capacity addition from these technologies
- 1200 GW of installed hydropower worldwide (less than half the identified technical potential)
  - 5% additional from hydrokinetic devices is 60 GW
- 260,000 km<sup>2</sup> surface area of hydropower reservoirs worldwide
  - 1% of surface area covered by FPV at 100 MW/km<sup>2</sup> is 260 GW
- Hydropower reservoirs form only a small fraction of the locations where these technologies can be used



# THANK YOU

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