instituto acende Brasil
O OBSERVATÓRIO
DO SETOR ELÉTRICO BRASILEIRO

MB 11– ELECTRICITY MARKET DESIGN

Hydro Challenges: Externalities, Operational Interdependencies and Systemic Valuation

Informs International

10/JUN/2019

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Agenda

Introduction

Electricity Spot Market Standard Design

Hydropower Generation Features

Coasean Two Settlement System

Hydro Financial Storage Rights

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Motivation

WHY ELECTRICITY MARKETS?

Move from **centralized command and control** to **markets** motivated by need to:

- promote optimization innovation
- adapt to new power supply mix
  - small-scale distributed generation
  - variable (intermittent) renewable generation
- embrace distributed knowledge

OBJECTIVES

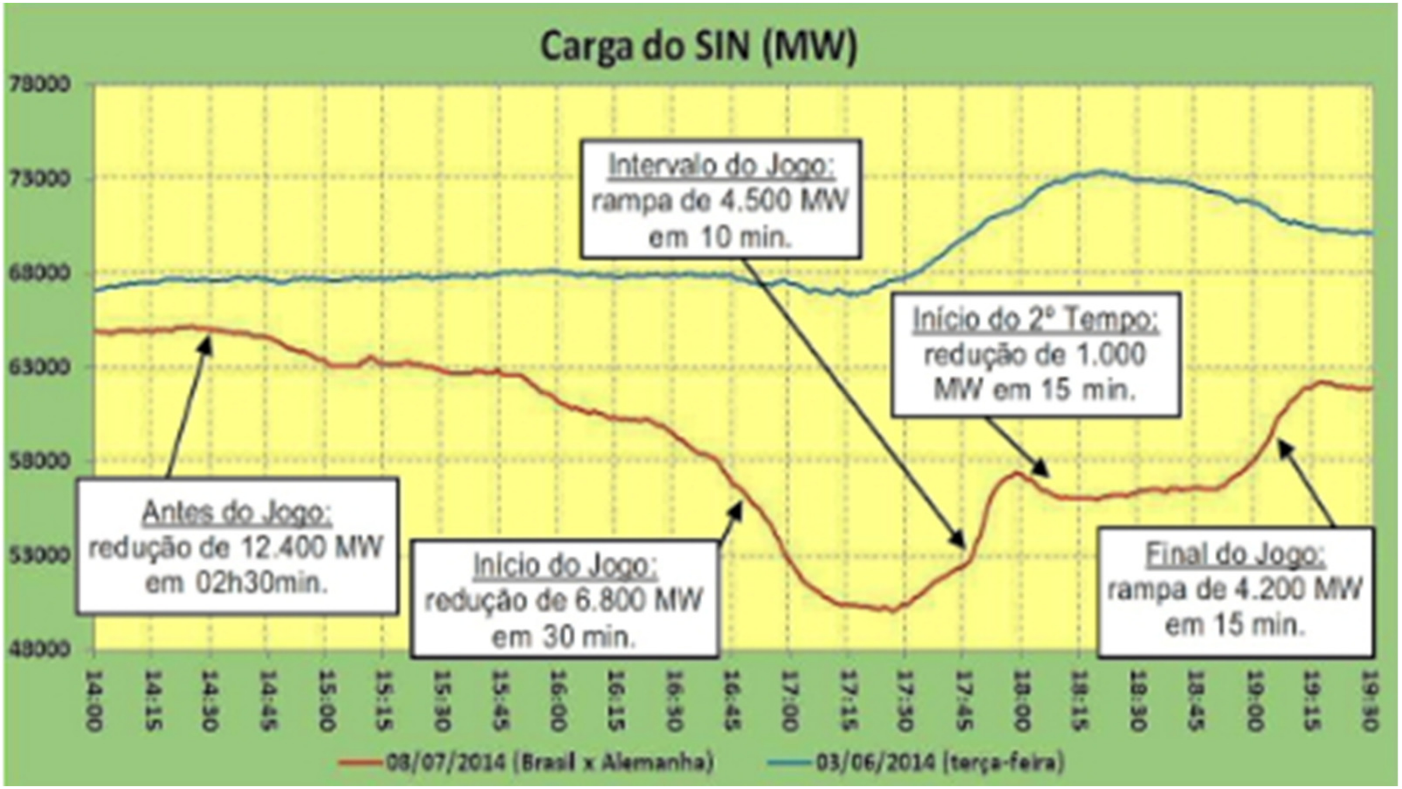
Propose adjustments to electricity market to better incorporate peculiarities of hydropower plants

MARKET EQUILIBRIUM

Due to high cost of electric power storage, **real-time balance** of production and consumption is required

Consumption presents regular patterns, but a stochastic variations, must be dealt by **load-following** supply

BRAZILIAN LOAD CURVE DURING WORLD CUP GAME



Source: ONS - Operador Nacional Do Sistema De Energia Elétrica

Features of Thermal Power Generation

THERMAL POWER PLANT ECONOMICS

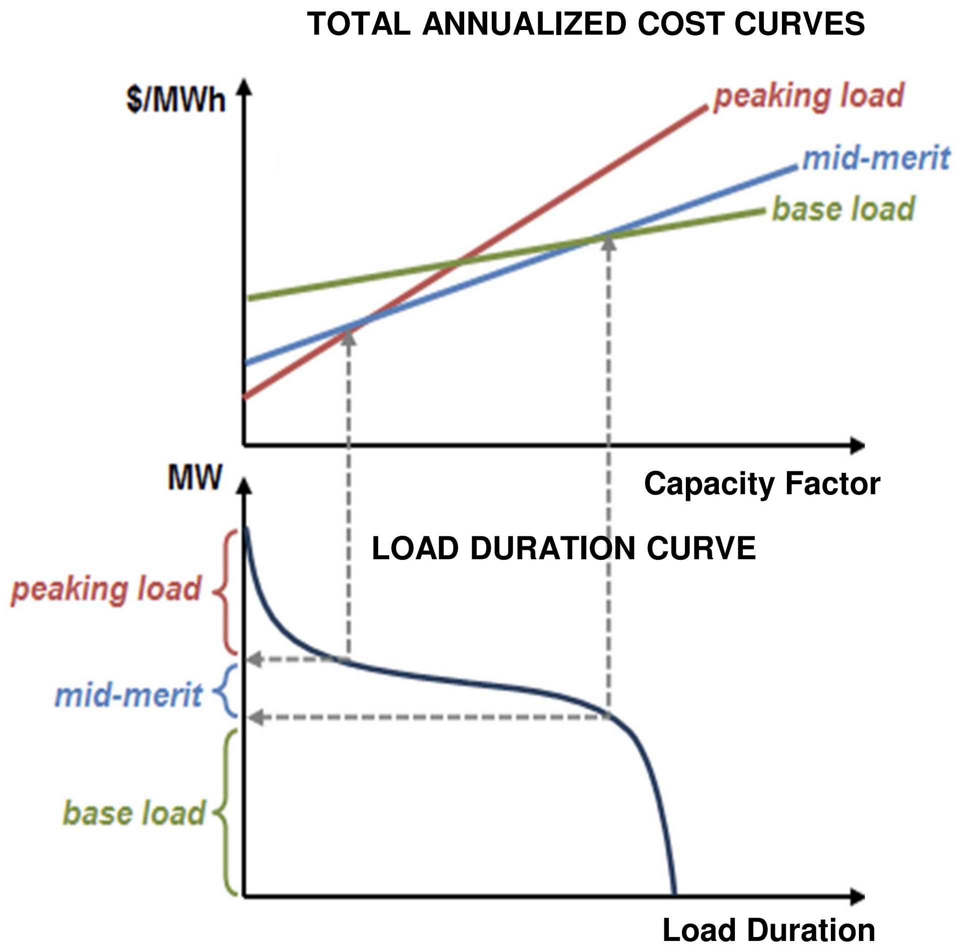
Load is met by power plants with lowest **marginal operating costs**, resorting to higher cost plants to meet infrequent demand

A **mix of thermal** power plants with different combinations of fixed and variable costs are used to meet daily load variation

Thermal power plants are **capacity constrained**

Thermal Power plant operation dynamics is relatively simple:

- ON if price above its variable costs
- OFF if price below variable costs



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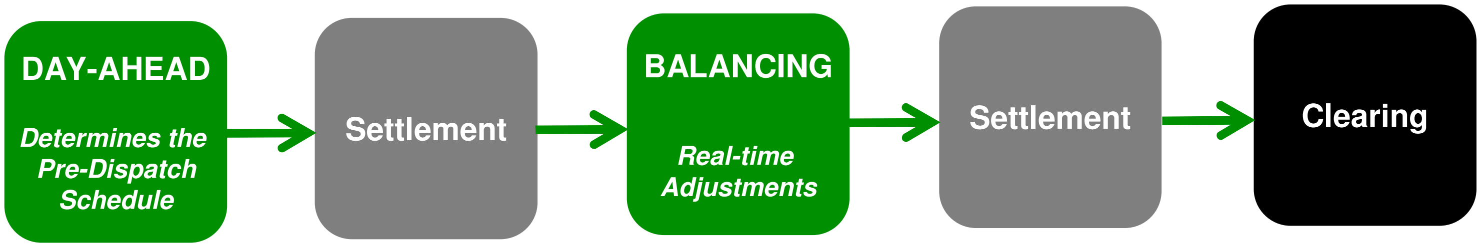
Two Settlement System



DAY-AHEAD MARKET

Daily auction for supply of the next 24 hours

Power producers **submit bids** in the form of price and quantity duplets for each time interval of the following day

Bids are ordered from lowest to highest cost (**merit order**)

System is simulated to take into consideration **transmission constraints**, which are circumvented by substitution for the least cost alternative, given rise to different **locational marginal pricing** (all suppliers at particular node and time remunerated at same price)

Accepted bids for each time interval of the following day are <u>financially binding commitments</u> that make up the **Pre-Dispatch** schedule for the following day

BALANCING MARKET

Next a second auction is held to **acquire flexibility**, bids for additional supply (or reduced demand from consumers) or for reduction of supply of power plants committed in the Pre-Dispatch

Any **deviation** from Pre-Dispatch schedule is settled at the current **Balancing Market price**

Incentive Structure

DAY-AHEAD MARKET

Day-ahead commitment enables planning least-cost supply, considering transmission restrictions, unit commitment problems…

Rewards firm-predictable supply

BALANCING MARKET

Provides flexibility to deal with contingencies, intermittent supply, unpredicted demand fluctuations

Rewards flexibility

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Hydropower Economics

HYDROPOWER ECONOMICS

Hydropower plants are **energy constrained** (availability of hydro inflows)

Capacity is a second order constraint since installed capacity is generally larger than the amount of “**firm energy**” that can be expected to be reliably supplied by hydropower plant

No cost of fuel, thus marginal cost is determined from system **opportunity costs**

Reservoirs enable **intertemporal arbitrage** possible, so opportunity costs take into consideration not only current alternatives but also future generation alternatives

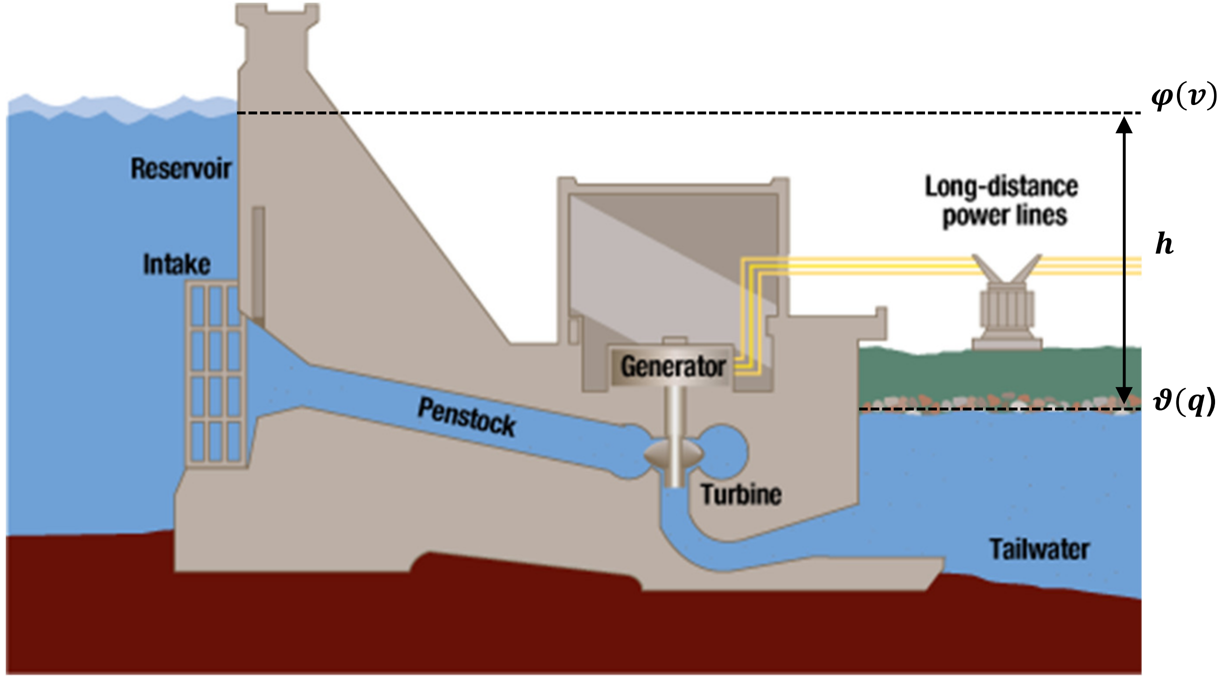
Future opportunity costs are generally computed using Dynamic Programming (such as Stochastic Dual Dynamic Programming)

Hydropower Production Characteristics

HYDROPOWER PRODUCTION FUNCTION

$$p(v,q) = \rho \cdot g \cdot \epsilon(v,q) \cdot h[\varphi(v) - \vartheta(q) - \varsigma(q)]$$

$p(\cdot)$ power output
v volume of water in hydro reservoir
q water flow through hydro turbine
ρ density of the water
g gravity acceleration constant
$\epsilon(\cdot)$ turbine-generator efficiency
$h(\cdot)$ head
$\varphi(\cdot)$ upper hydraulic head
$\vartheta(\cdot)$ lower hydraulic head
$\varsigma(\cdot)$ penstock losses



Long-term Hydropower Generation Planning

LONG-TERM HYDROPOWER PRODUCTION FUNCTION

$$\boldsymbol{p}(\boldsymbol{v}, q) = \boldsymbol{\rho} \cdot \boldsymbol{g} \cdot \boldsymbol{\epsilon}(\boldsymbol{v}, q) \cdot \boldsymbol{h}[\boldsymbol{\varphi}(\boldsymbol{v}) - \vartheta(q) - \varsigma(q)]$$

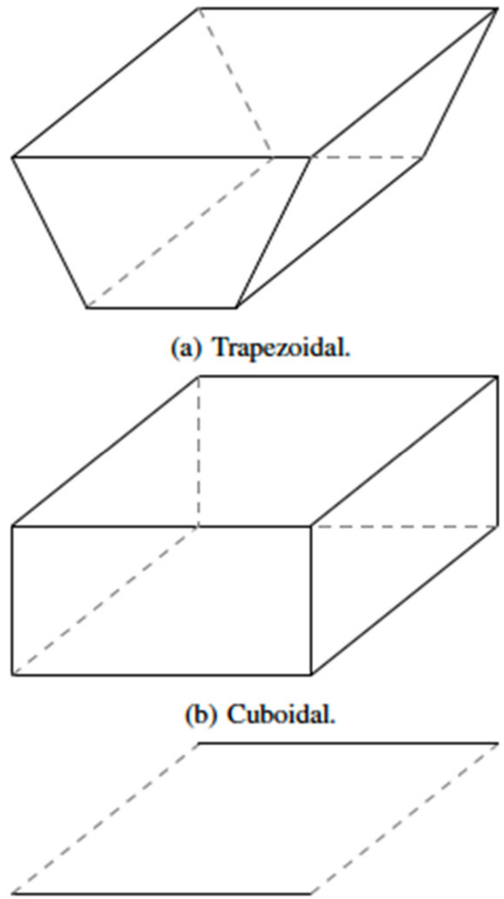
In long-term planning, the upper hydraulic head, $\boldsymbol{\varphi}(\boldsymbol{v})$, is the most relevant feature, which varies as a function of the stored water in the hydro reservoir

The relation between volume, $\boldsymbol{v}$,of the upper hydraulic head, $\boldsymbol{\varphi}(\boldsymbol{v})$, depends on the geometry of the hydro reservoir.

Often the upper hydraulic head is assumed constant, which implies the hydro reservoir would be equivalent to a two-dimensional **plane** that extends infinitely horizontally to accommodate hydro inflows.

If the reservoir takes the form of a **cuboid**, the volume-to-height function is linear.

Most reservoirs are best represented by a **trapezoid**, in which case the volume-to-height function becomes nonlinear, but concave: $\partial\boldsymbol{\varphi}/\partial\boldsymbol{v} > \mathbf{0}$ and $\partial^2\boldsymbol{\varphi}/\partial\boldsymbol{v}^2 < \mathbf{0}$



(a) Trapezoidal.

(b) Cuboidal.

(c) Planar.

Short-term Hydropower Planning

SHORT-TERM HYDROPOWER PRODUCTION FUNCTION

$$\boldsymbol{p}(v,\boldsymbol{q}) = \boldsymbol{\rho} \cdot \boldsymbol{g} \cdot \boldsymbol{\epsilon}(v,\boldsymbol{q}) \cdot \boldsymbol{h}[\varphi(v) - \boldsymbol{\vartheta}(\boldsymbol{q}) - \boldsymbol{\varsigma}(\boldsymbol{q})]$$

In short-term operation, one can consider that **reservoir levels do not change significantly** (except for small reservoirs).

In this scenario the **intensity of dispatch in particular hours** is what is what most impacts hydropower productivity.

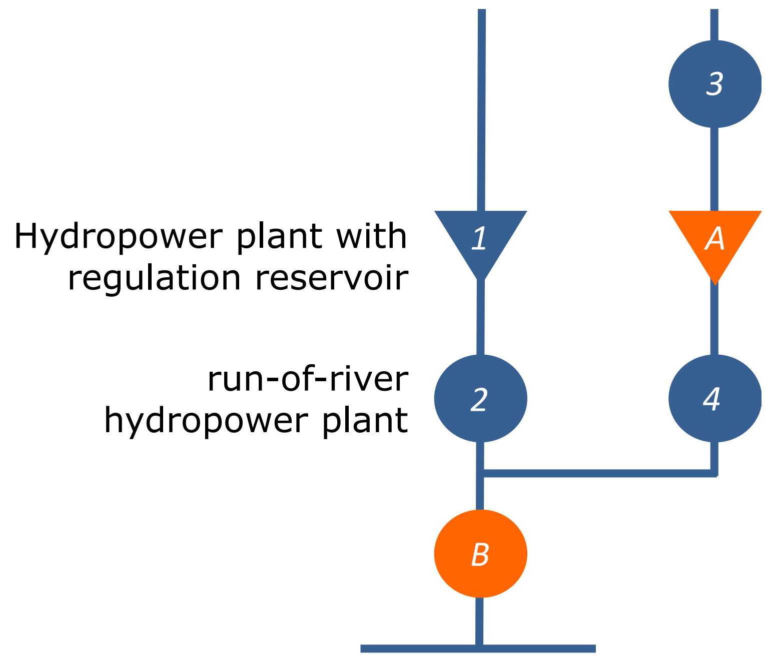
Externalities and Operational Interdependencies

TOPOLOGY OF HYDROPOWER SYSTEMS

Hydro inflows depend on:

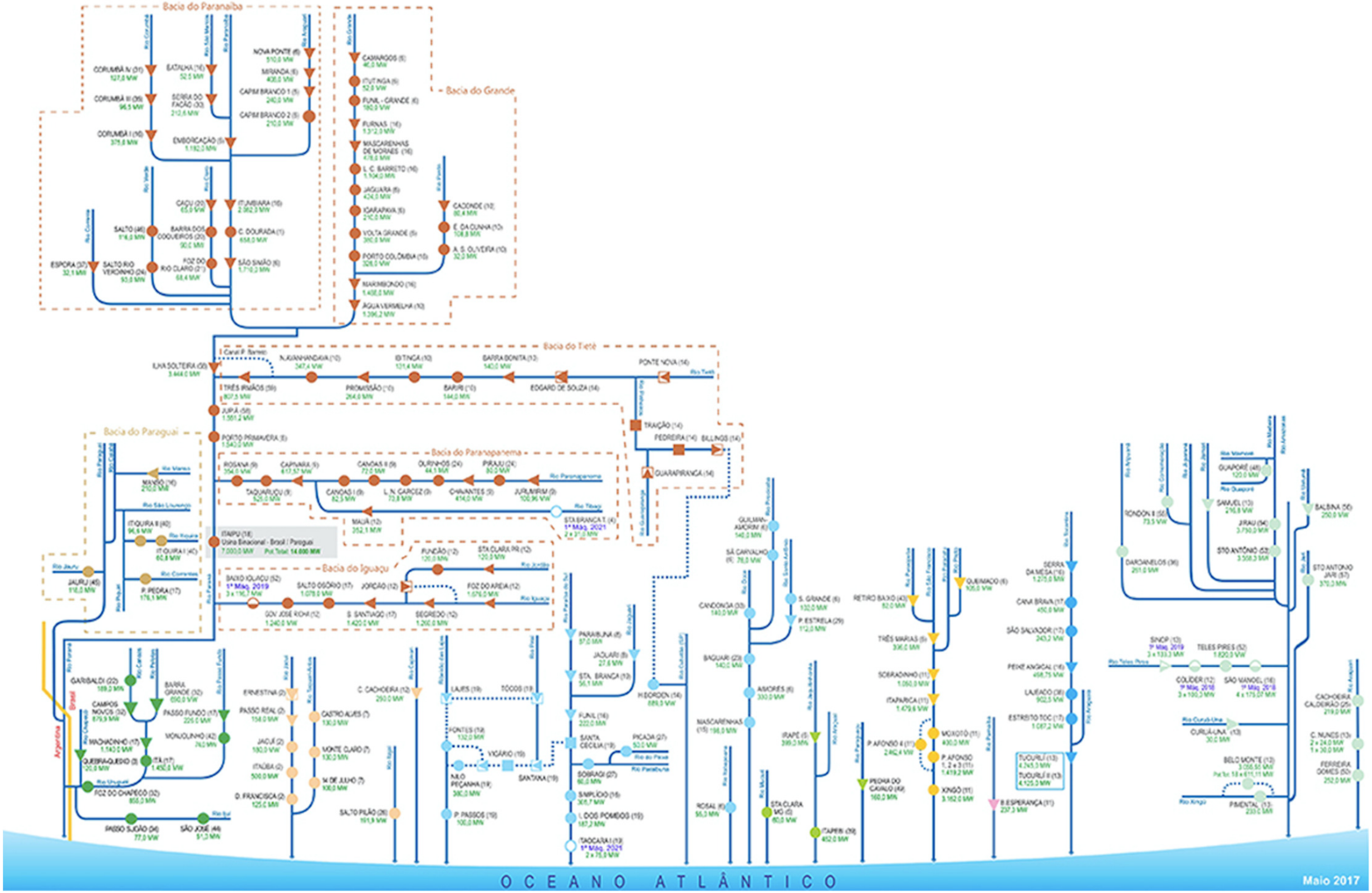
- **rainfall** and
- **upstream reservoirs operation**

When hydropower plants are owned by another player, an **asymmetry** arises between **operational control** and **financial interests**, which can lead to distorted operation



HYDROPOWER GENERATION FEATURES

Externalities and Operational Interdependencies



Problems

PROBLEM #1: EXTERNALITIES AND OPERATIONAL INTERDEPECIES

Hydropower generators bid's conditional on bid of upstream hydropower generator

Day-ahead auction may lead to regret

PROBLEM #2: HINDERED INTERTEMPORAL ARBITRAGE

Day-ahead market requires simultaneously bidding for all intervals of the following day, which **precludes intertemporal arbitrage** of opportunity costs of different time intervals

Day-ahead bid based dispatch may be **inconsistent with long-term arbitrage**

Hydropower **productivity conditional on past** (reservoir level) **and present** (lower hydraulic head) **operation**

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Solution for Externalities and Interdependencies

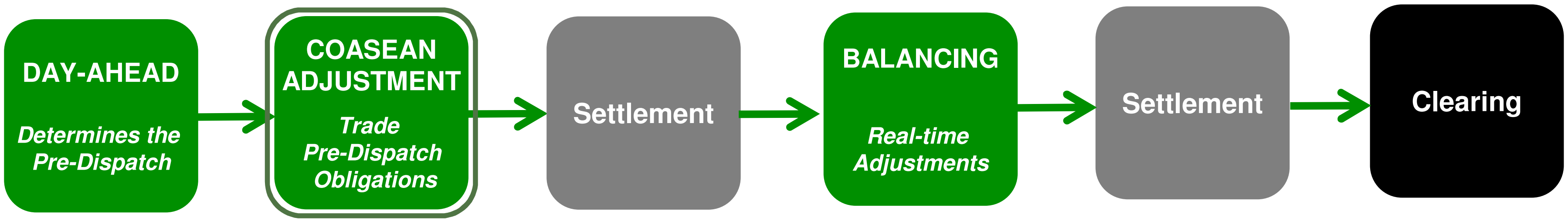
COASEAN ADJUSTMENT

Introduce an additional step in the two settlement system, in which participants are able to trade the Pre-Dispatch obligations

The bilateral trades made during the Coasean Adjustment phase can take two forms:

- **non-enforceable**: commitments that may be traded again, passing the obligation to yet another player
- **enforceable:** commitments that must be fulfilled by the player that acquires the responsibility

This intermediary phase enables Pareto Optimality



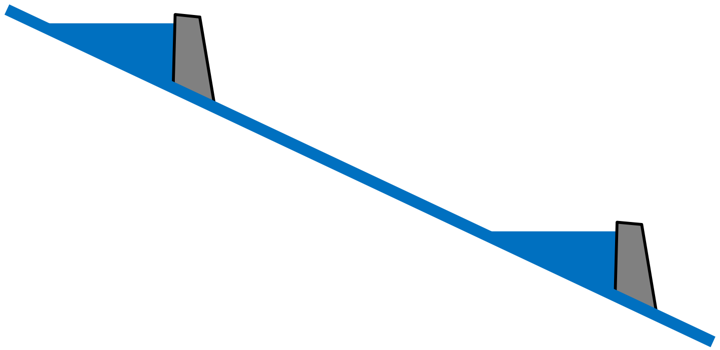
COASEAN THEOREM

If trade in an externality is possible and there are sufficiently low transaction costs, bargaining will lead to a Pareto efficient outcome regardless of the initial allocation of property.

Example

Consider:

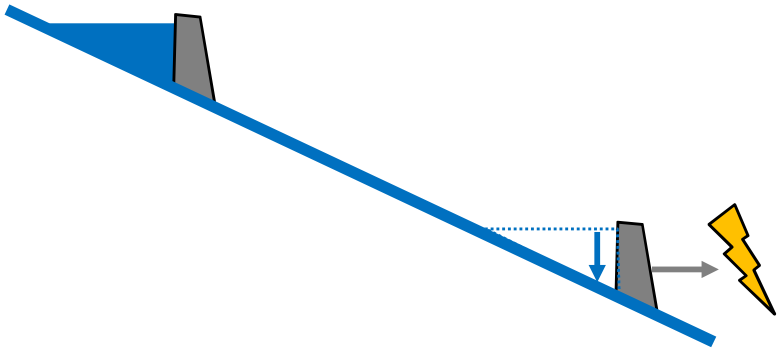
- Two identical hydro power plants on the same river
- At end of wet season the hydro reservoirs are full, each with **1** unit of water
- No hydro inflows occur during dry season
- Each hydro power plant can produce **1** unit of energy with water stored in reservoir
- But if reservoir level maintained at full capacity, the same amount of water can produce **1+ε**



Example

Case 1: Prioritize Preservation of Upstream Storage

Start producing energy from the downstream hydropower plant



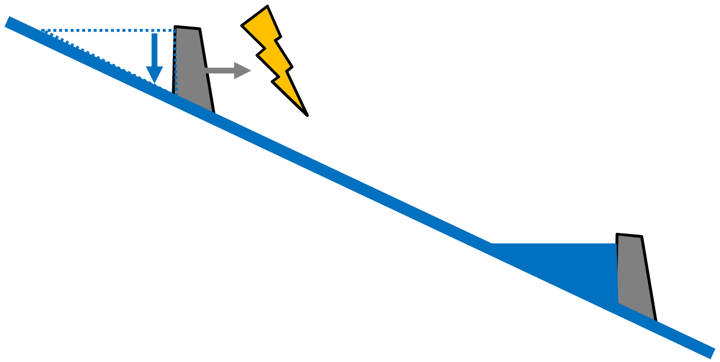
Total Production:

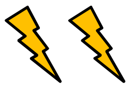
Example

Case 1: Prioritize Preservation of Upstream Storage

Start producing energy from the downstream hydropower plant

...when the downstream reservoir is emptied, the upstream hydropower plant starts to generate



Total Production: 

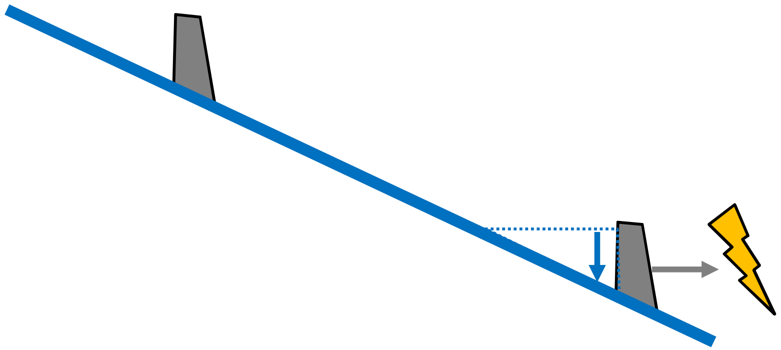
Example

Case 1: Prioritize Preservation of Upstream Storage

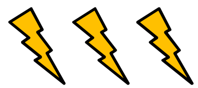
Start producing energy from the downstream hydropower plant…

...when the downstream reservoir is emptied, the upstream hydropower plant starts to generate

...then with the hydro inflows arriving from the upstream reservoir, the downstream hydropower plant can generate one more unit of energy



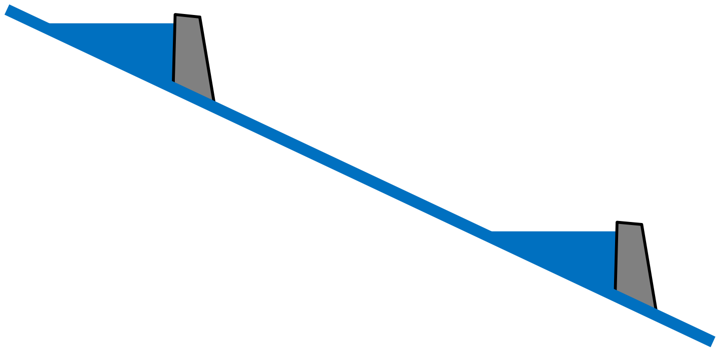
Total Production:



Example

Case 2: Prioritize Preservation of Downstream Storage

Again start with both reservoirs full at end of wet season



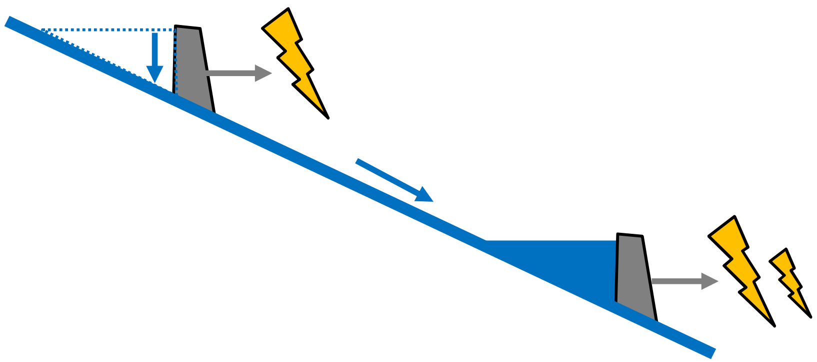
Example

Case 2: Prioritize Preservation of Downstream Storage

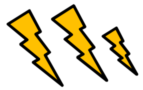
Again start with both reservoirs full at end of wet season

...but this time emptying the upstream reservoir first

Both hydropower plants generate simultaneously, but the downstream hydropower plant produces only with the hydro inflows arriving from the upstream hydropower plant, so as to keep its reservoir storage level unchanged



Total Production:



Example

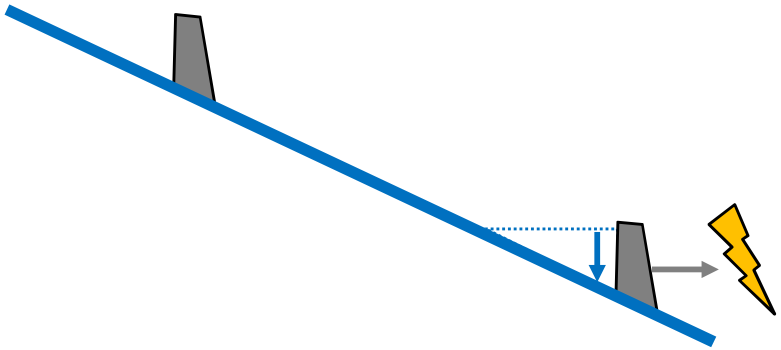
Case 2: Prioritize Preservation of Downstream Storage

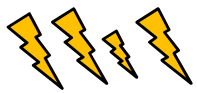
Again start with both reservoirs full at end of wet season

...but this time emptying the upstream reservoir first.

Both hydropower plants generate simultaneously, but the downstream hydropower plant produces only with the hydro inflows arriving from the upstream hydropower plant, so as to keep its reservoir storage level unchanged

...only emptying the downstream reservoir when there is no more storage in the upstream reservoir.



Total Production: 

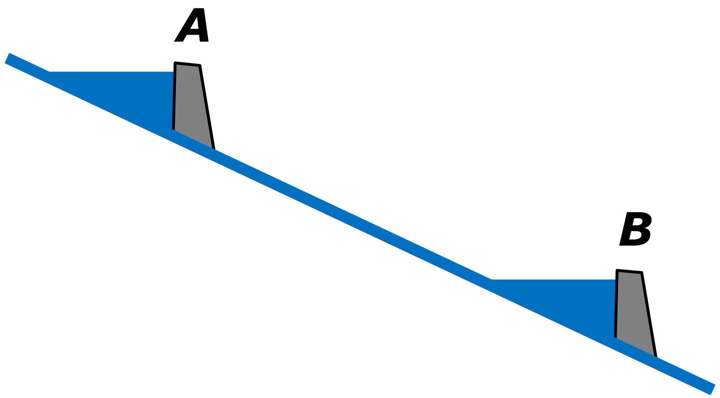
Enables production of more energy with the same hydro inflows

Example

COASEAN ADJUSTMENT

In case submitted bids result in suboptimal dispatch, players have incentives to **restore Pareto Optimality**, by sharing the benefits with other player than can contribute to improved dispatch (or at least mitigate costs)

If the bids submitted by players in the day-ahead market result in **Plant *B*** (downstream) entering the Pre-Dispatch Schedule, but **Plant *A*** (upstream) does not enter, in the Coasean Adjustment Phase, ***B*** may offer to share part of ***ε*** with ***A*** to take on part of its obligations so as to **restore optimal operation**.



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PROPOSED SOLUTION FOR PROBLEM #2: FINANCIAL STORAGE RIGHTS

Solution for Hindered Intertemporal Arbitrage

HYDRO FINANCIAL STORAGE RIGHTS (HFSR)

HFSRs allow System Operator to **reallocate energy offered in different time intervals** so as to minimize system costs, respecting total energy supplied, and the hydropower plant's production and short-term productivity constraints

Hydropower generator could then **couple** flat **supply bid** together with **HFSR**

HFSRs could be offered for a premium in a separate auction or hydropower producers could reap the benefits of the savings provided by their modulation services

HOUR

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

QUANTITY OFFERED BY HYDROPOWER GENERATOR

PRE-DISPATCH PRICES

20	20	20	20	20	20	20	25	25	25	25	25	25	35	35	50	50	70	35	25	25	20	20	20

HYDROPOWER GENERATOR'S DISPATCH AFTER APPLICATION OF HFSR

PRE-DISPATCH PRICES

20	20	20	20	20	20	20	25	25	25	25	25	25	25	25	30	30	30	25	25	25	20	20	20

Take-aways from HFSR

HFSRs offered in conjunction with flat-quantity-supply bid allows:

- ensures optimal modulation of hydropower generators, considering detailed production function
- frees hydropower producers from speculative bidding based on expectations of how other players are going to bid
- allows hydropower producers to set bid prices solely on long-term optimization

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