RECENT IMPROVEMENTS IN THE OPTIMIZATION MODELS FOR GENERATION PLANNING AND MARKET PRICING IN BRAZIL

Eletrobras
Cepel

HPSC
2022

Hydropower Scheduling Conference
Programme | Oslo 12-13 September

SINTEF NTNU Statkraft

Andre Luiz Diniz
CEPEL, Brazil

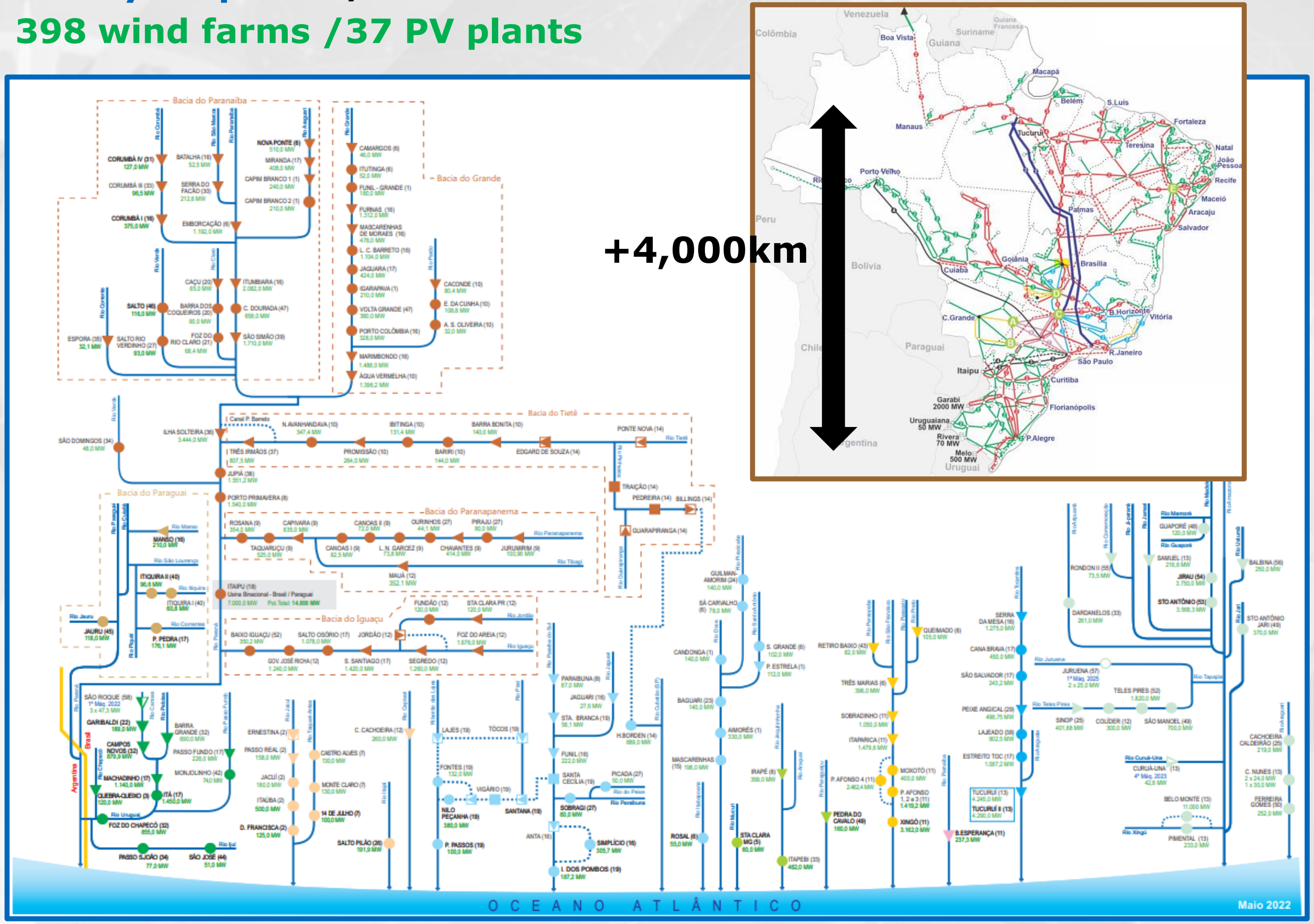
Brazilian Interconnected System Centrally Dispatched by the Brazilian ISO (ONS)

Cepel A pesquisa que constrói o futuro

162 hydro plants /**386 termal units**

398 wind farms /**37 PV plants**

+9,000buses / +13,000 transmission lines



HYDRO (61.6%)

2022	2026
109.058 MW (61,6%)	109.868 MW (55,2%)

THERMAL (13.9%)

	2022	2026
GAS/LNG	15.459 MW (8,7%)	20.820 MW (10,5%)
OIL/DIESEL	4.198 MW (2,4%)	4.241 MW (2,1%)
COAL	3.017 MW (1,7%)	3.017 MW (1,5%)
NUCLEAR	1.990 MW (1,1%)	1.990 MW (1,0%)

WIND/SOLAR (15.4%)

	2022	2026
🌬	22.214 MW (12,5%)	29.505 MW (14,8%)
☀	5.552 MW (3,1%)	12.556 MW (6,3%)

BIOMASS+ OTHERS (8.9%)

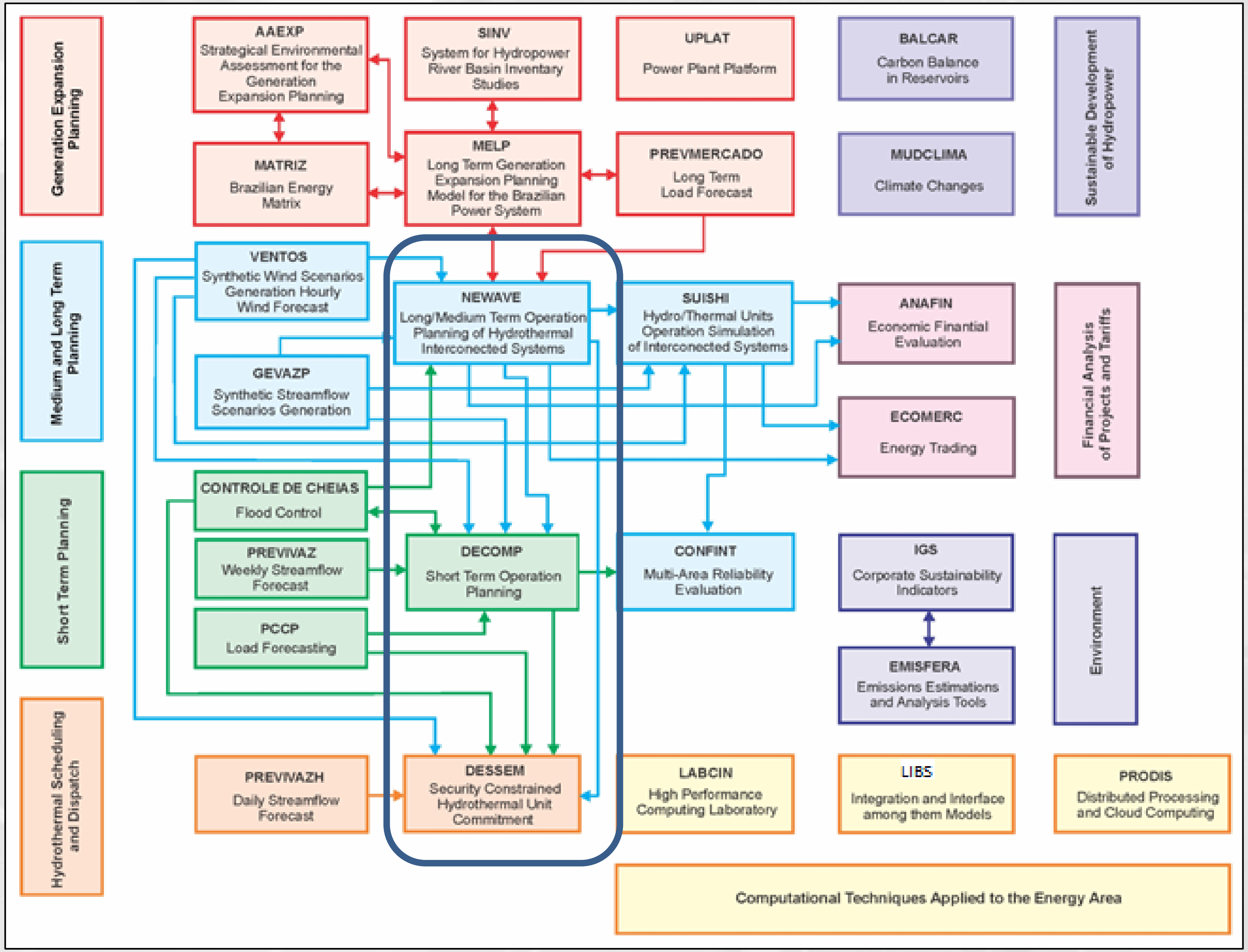
	2022	2026
	14.989 MW (8,5%)	16.264 MW (8,2%)
	645 MW (0,4%)	851 MW (0,4%)

TOTAL	2022	177.122 MW	2026	199.112 MW

source: www.ons.org.br

OPTIMIZATION MODELS FOR ENERGY PLANNING DEVELOPED BY CEPEL

Cepel A pesquisa que constrói o futuro



Generation Expansion Planning

AAEXP Strategical Environmental Assessment for the Generation Expansion Planning

SINV System for Hydropower River Basin Inventary Studies

UPLAT Power Plant Platform

BALCAR Carbon Balance in Reservoirs

Sustainable Development of Hydropower

MATRIZ Brazilian Energy Matrix

MELP Long Term Generation Expansion Planning Model for the Brazilian Power System

PREVMERCADO Long Term Load Forecast

MUDCLIMA Climate Changes

Medium and Long Term Planning

VENTOS Synthetic Wind Scenarios Generation Hourly Wind Forecast

NEWAVE Long/Medium Term Operation Planning of Hydrothermal Interconnected Systems

SUISHI Hydro/Thermal Units Operation Simulation of Interconnected Systems

ANAFIN Economic Finantial Evaluation

Financial Analysis of Projects and Tariffs

GEVAZP Synthetic Streamflow Scenarios Generation

ECOMERC Energy Trading

Short Term Planning

CONTROLE DE CHEIAS Flood Control

PREVIVAZ Weekly Streamflow Forecast

DECOMP Short Term Operation Planning

CONFINT Multi-Area Reliability Evaluation

IGS Corporate Sustainability Indicators

Environment

PCCP Load Forecasting

EMISFERA Emissions Estimations and Analysis Tools

Hydrothermal Scheduling and Dispatch

PREVIVAZH Daily Streamflow Forecast

DESSEM Security Constrained Hydrothermal Unit Commitment

LABCIN High Performance Computing Laboratory

LIBS Integration and Interface among them Models

PRODIS Distributed Processing and Cloud Computing

Computational Techniques Applied to the Energy Area

Developed by CEPEL, collaborating with scientific comunity

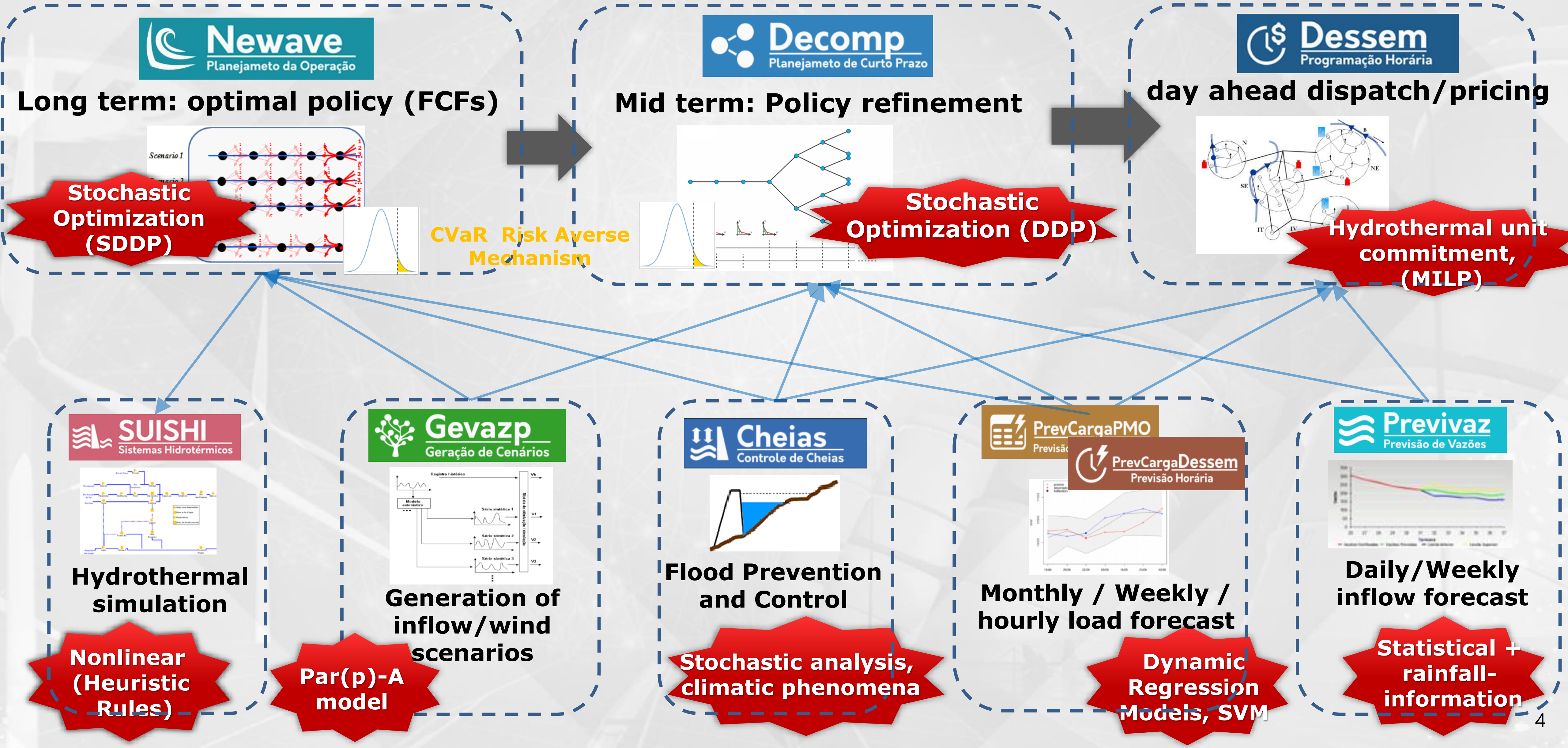
Validated in working groups in by ONS, CCEE, EPE, MME, ANEEL, as well as task forces with most power system utilities

Approved for official use by the regulatory agency

Used by:

- **EPE for system planning**
- **ONS to dispatch the system**
- **CCEE to stablish market prices**

Models for risk-averse energy Planning, Hydrothermal-wind Scheduling and Price Setting



Newave Planejameto da Operação

Long term: optimal policy (FCFs)

Stochastic Optimization (SDDP)

CVaR Risk Averse Mechanism

Decomp Planejamento de Curto Prazo

Mid term: Policy refinement

Stochastic Optimization (DDP)

Dessem Programação Horária

day ahead dispatch/pricing

Hydrothermal unit commitment, (MILP)

SUISHI Sistemas Hidrotérmicos

Hydrothermal simulation

Nonlinear (Heuristic Rules)

Gevazp Geração de Cenários

Generation of inflow/wind scenarios

Par(p)-A model

Cheias Controle de Cheias

Flood Prevention and Control

Stochastic analysis, climatic phenomena

PrevCargaPMO Previsão

PrevCargaDessem Previsão Horária

Monthly / Weekly / hourly load forecast

Dynamic Regression Models, SVM

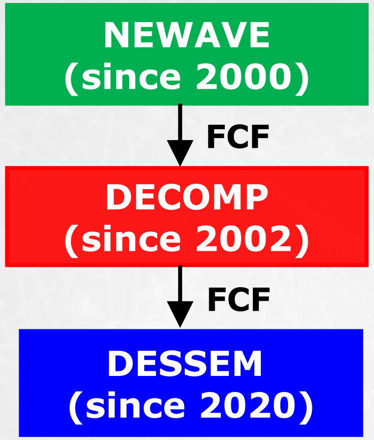
Previvaz Previsão de Vazões

Daily/Weekly inflow forecast

Statistical + rainfall-information

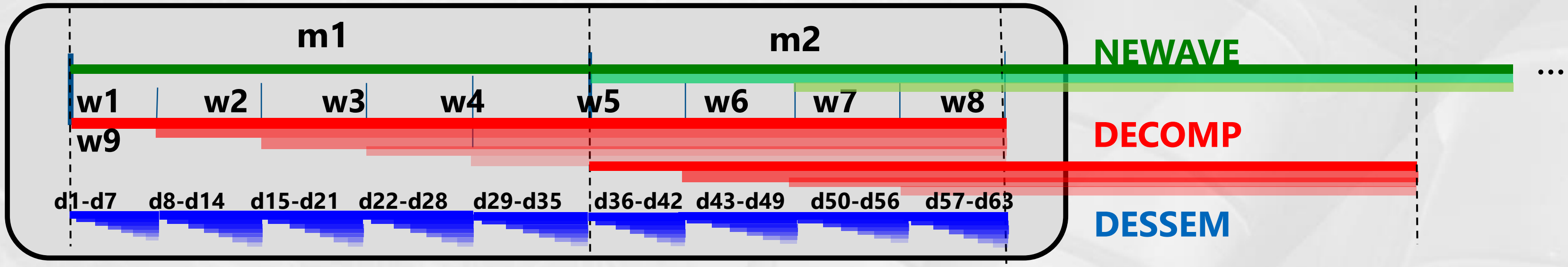
COST MINIMIZATION GENERATION PLLANNING WITH CVAR RISK AVERSE CRITERION - Rolling Horizon Scheme

	Frequency	Horizon	Discretization
long	Monthly	10 years	Monthly
mid	Weekly	2 months	weekly
short	Daily	7 days	up to half-an-hour


NEWAVE (since 2000)
FCF
DECOMP (since 2002)
FCF
DESSEM (since 2020)

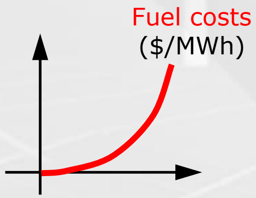
Uncertainty	System Modeling	Solution
Stochastic, CVar	Aggregate reservoirs, tie lines	SDDP
Stochastic, CVar	Individual plants, tie lines,	DDP
Deterministic	unit commitment, DC Power Flow	MILP

Rolling Horizon Scheme

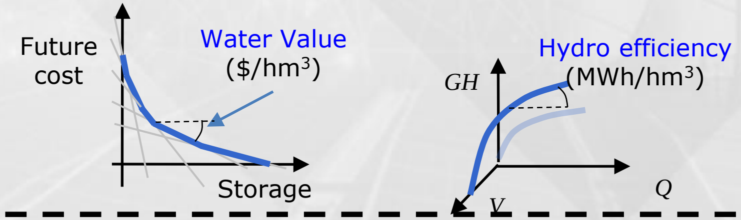


Cost Information

Thermal units



Hydro Plants

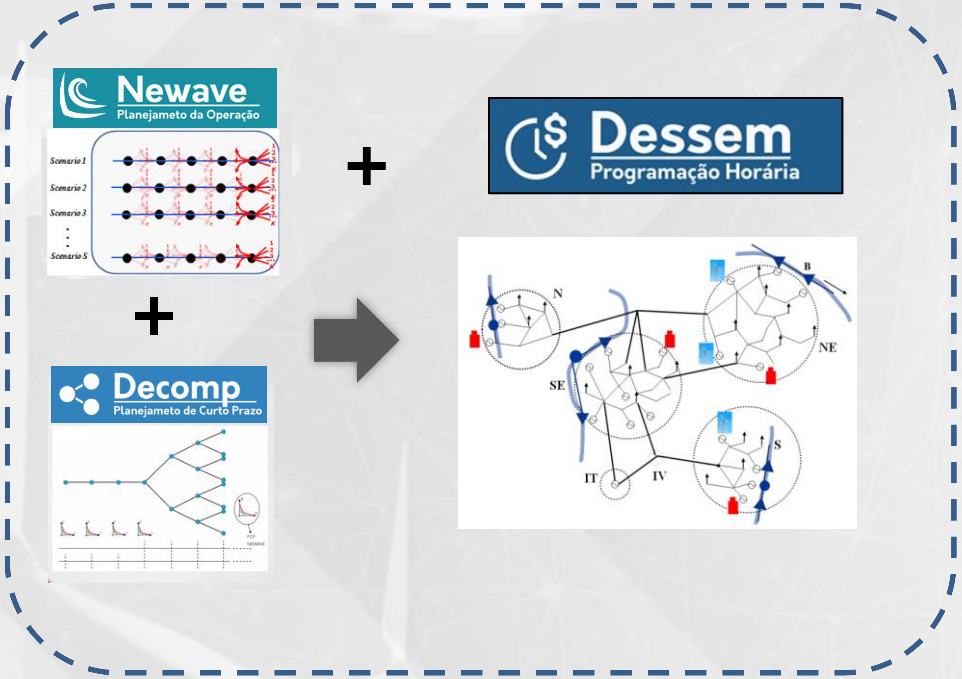


New Renewable generation

- use “free” generation as much as possible
- Generation is curtailed if necessary

DAY-AHEAD SCHEDULING AND HOURLY PRICING IN BRAZIL

Cepel
A pesquisa que constrói o futuro



Official use started on Jan 1st, 2020

ONS
Operador Nacional do Sistema Elétrico

Official use started on Jan 1st, 2021

ccee

Hourly Prices- Sept 11th, 2022 – 7am-8am

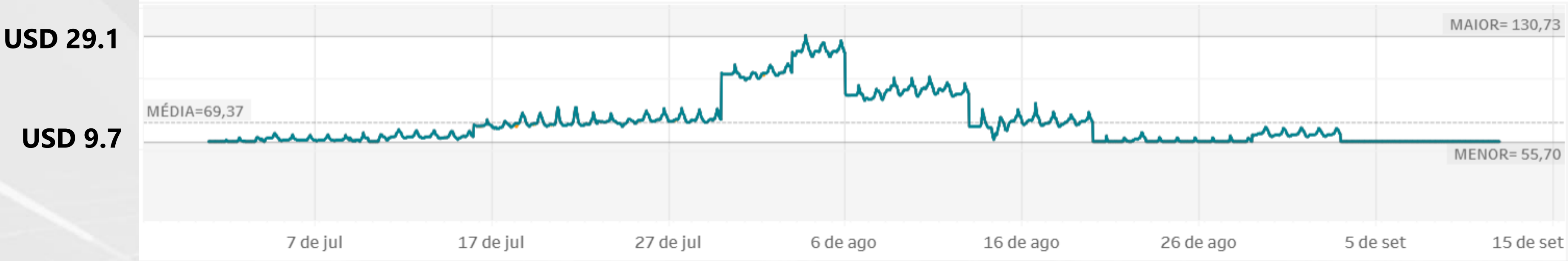
Preço de Liquidação das Diferenças
(Valores em R$/MWh)

	SE/CO - SUDESTE	S - SUL	NE - NORDESTE	N - NORTE
PLD Horário	55,70	55,70	55,70	55,70
Média Diária	55,70	55,70	55,70	55,70

Hora vigente 7:00 às 7:59 - 11/09/2022 Hoje

10.82 USD

Hourly Prices – last 6 months

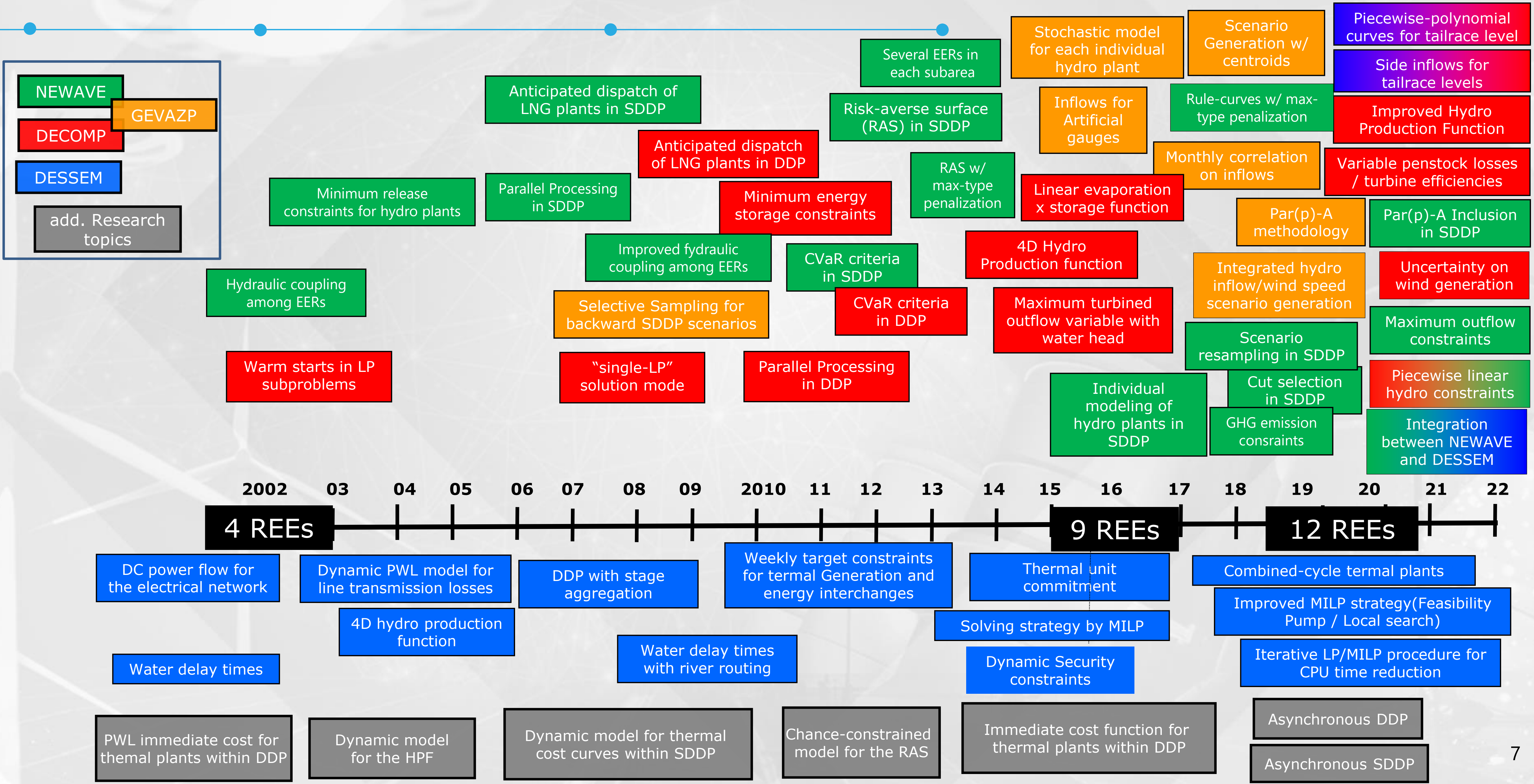


Average: 13.5 USD

Source: CCEE web site (https://www.ccee.org.br/precos/painel-preços)

Features Developed in the last 20 years

A pesquisa que constrói o futuro



🟩 NEWAVE
🟧 GEVAZP
🟥 DECOMP
🟦 DESSEM
⬜ add. Research topics

Hydraulic coupling among EERs

Warm starts in LP subproblems

Minimum release constraints for hydro plants

Anticipated dispatch of LNG plants in SDDP

Parallel Processing in SDDP

Improved fydraulic coupling among EERs

Selective Sampling for backward SDDP scenarios

"single-LP" solution mode

Anticipated dispatch of LNG plants in DDP

Minimum energy storage constraints

Parallel Processing in DDP

Several EERs in each subarea

Risk-averse surface (RAS) in SDDP

RAS w/ max-type penalization

CVaR criteria in SDDP

CVaR criteria in DDP

Stochastic model for each individual hydro plant

Inflows for Artificial gauges

Linear evaporation x storage function

4D Hydro Production function

Maximum turbined outflow variable with water head

Individual modeling of hydro plants in SDDP

Scenario Generation w/ centroids

Rule-curves w/ max-type penalization

Monthly correlation on inflows

Par(p)-A methodology

Integrated hydro inflow/wind speed scenario generation

Scenario resampling in SDDP

Cut selection in SDDP

GHG emission consraints

Piecewise-polynomial curves for tailrace level

Side inflows for tailrace levels

Improved Hydro Production Function

Variable penstock losses / turbine efficiencies

Par(p)-A Inclusion in SDDP

Uncertainty on wind generation

Maximum outflow constraints

Piecewise linear hydro constraints

Integration between NEWAVE and DESSEM

2002 03 04 05 06 07 08 09 2010 11 12 13 14 15 16 17 18 19 20 21 22

4 REEs

9 REEs

12 REEs

DC power flow for the electrical network

Water delay times

Dynamic PWL model for line transmission losses

4D hydro production function

DDP with stage aggregation

Water delay times with river routing

Weekly target constraints for termal Generation and energy interchanges

Thermal unit commitment

Solving strategy by MILP

Dynamic Security constraints

Combined-cycle termal plants

Improved MILP strategy(Feasibility Pump / Local search)

Iterative LP/MILP procedure for CPU time reduction

PWL immediate cost for themal plants within DDP

Dynamic model for the HPF

Dynamic model for thermal cost curves within SDDP

Chance-constrained model for the RAS

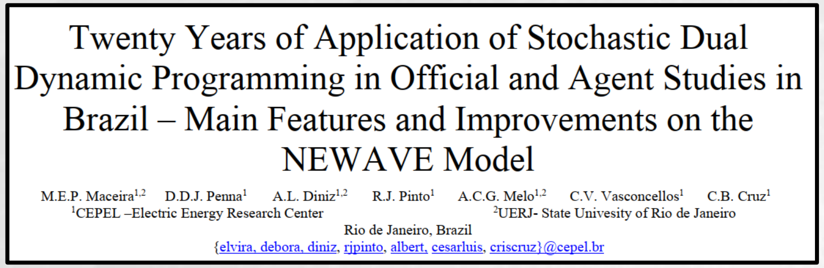
Immediate cost function for thermal plants within DDP

Asynchronous DDP

Asynchronous SDDP

Main References for the Models

Newave
Planejameto da Operação



Twenty Years of Application of Stochastic Dual Dynamic Programming in Official and Agent Studies in Brazil – Main Features and Improvements on the NEWAVE Model

M.E.P. Maceira[1,2] D.D.J. Penna[1] A.L. Diniz[1,2] R.J. Pinto[1] A.C.G. Melo[1,2] C.V. Vasconcellos[1] C.B. Cruz[1]
[1]CEPEL –Electric Energy Research Center [2]UERJ- State Univesity of Rio de Janeiro
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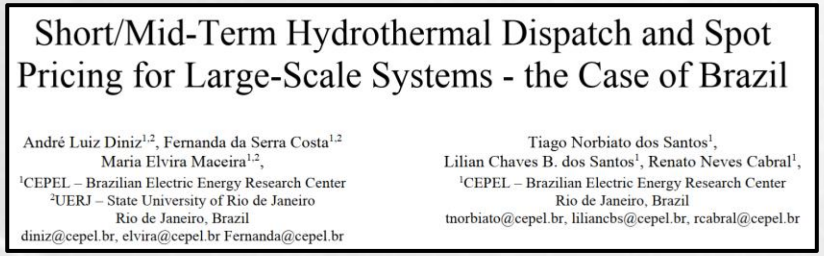
{elvira, debora, diniz, rjpinto, albert, cesarluis, criscruz}@cepel.br

Maceira, Penna et al, PSCC 2018

Decomp
Planejameto de Curto Prazo



Short/Mid-Term Hydrothermal Dispatch and Spot Pricing for Large-Scale Systems - the Case of Brazil

André Luiz Diniz[1,2], Fernanda da Serra Costa[1,2]
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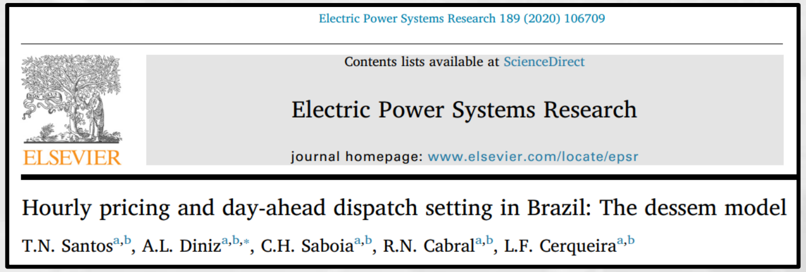
Diniz, Costa et al, PSCC 2018

Dessem
Programação Horária



Electric Power Systems Research 189 (2020) 106709

Contents lists available at ScienceDirect

Electric Power Systems Research

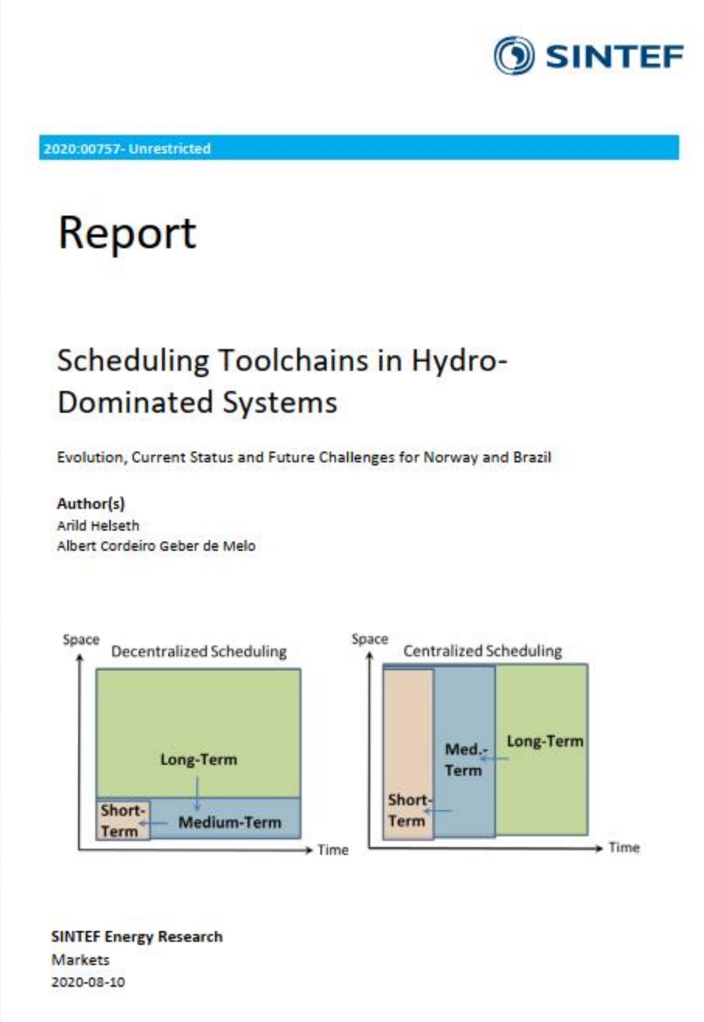
journal homepage: www.elsevier.com/locate/epsr

ELSEVIER

Hourly pricing and day-ahead dispatch setting in Brazil: The dessem model

T.N. Santos[a,b], A.L. Diniz[a,b,*], C.H. Saboia[a,b], R.N. Cabral[a,b], L.F. Cerqueira[a,b]

Santos, Diniz et al, EPSR, 2020



SINTEF

2020:00757- Unrestricted

Report

Scheduling Toolchains in Hydro-Dominated Systems

Evolution, Current Status and Future Challenges for Norway and Brazil

Author(s)
Arild Helseth
Albert Cordeiro Geber de Melo

SINTEF Energy Research
Markets
2020-08-10

Helseth, Melo, Sintef Report, 2020

MOST RECENT DEVELOPLENTS

1) "Max-type" penalization strategy for violation of rule curves: Consideration of a novel penalization strategy for violation of minimum storage level constraints in the SDDP strategy, where a time-linking maximum violation strategy is employed

2) Par(p)-A model: Extension of the autoregressive periodic model to add a term related to average annual inflows for the last year and taking into account this term in the SDDP solving strategy

3) Joint inflow/wind speed uncertainty model to generate scenarios for long/mid-term planning, and modeling of wind farms in SDDP and DDP strategy with the possibility of generation curtailment

4) Latest improvements in the plant-based hydro production function for all models:

- penstock losses variable with turbined outflow and turbine/generator efficiency variable with turbined outflow and water head
- Piecewise polynomial curves for the tailrace level
- Effect of "side inflows" in the tailrace level
- improvements in the hydro production function

5) Direct link between operation planning and short term scheduling to take into account the impact of the hourly uncertainty/variability of renewable generation in long term planning

1) “Max-type” penalization strategy for violation of minimum storage level constraints (rule curves)

Motivation

Traditional Penalization for violation of constraints:

$$Cviol = \Delta_5 \, p_{viol} + \Delta_6 \, p_{viol}$$

- ✓ in the SDDP algorithm, there is a cumulative effect in the computation of water values, since one drop δ of water relieves both violations $(2 * p_{viol})$
- ✓ That causes very high marginal costs

Improved “max-type” penalization

$$Cviol = \max\{\Delta_5, \Delta_6\} \, p_{viol}$$

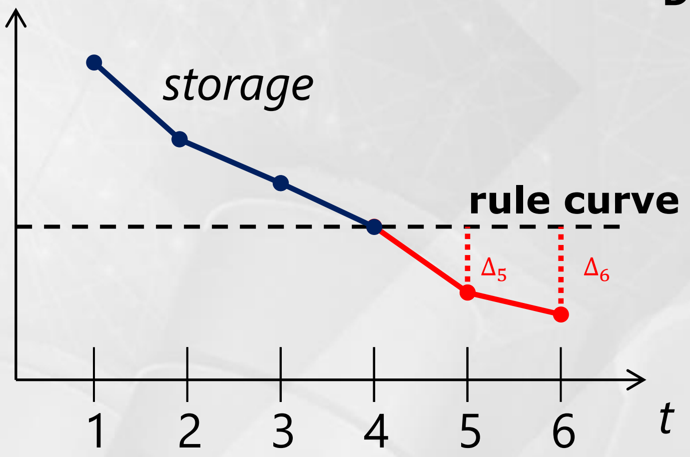
- ✓ Although relieveing both violations, the impact of δ in system costs is only accounted once
- ✓ It allows using intuitve values (most expensive termal cost) when setting the value of p_{viol}

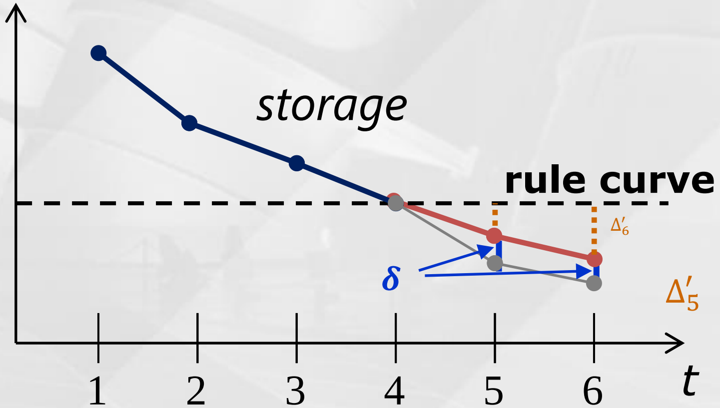
Annals of Operations Research
https://doi.org/10.1007/s10479-019-03419-4

A combined SDDP/Benders decomposition approach with a risk-averse surface concept for reservoir operation in long term power generation planning

Andre Luiz Diniz[1,2] · Maria Elvira P. Maceira[1,2] · Cesar Luis V. Vasconcellos[1] · Debora Dias J. Penna[1]

Diniz, Maceira et al, ANOR, 2020





1) "Max-type" penalization strategy for violation of rule curves:

Implementation in SDDP requires an additional state variable

only in the last seasonal period

additional state variable in the FCF

$$\textbf{Min} \quad (\ldots) \quad + \cancel{p_{viol}\Delta^t} + p_{viol}\boxed{\Delta^t_{MAX}} \quad + \quad \alpha(v^t, \boxed{\Delta^{t-1}_{MAX}})$$

s.t.

$$(\ldots)$$

$$V^t + \Delta^t \geq VMIN_t \quad \Rightarrow$$

minimum level constraint for each t

$$\Delta^t_{MAX} - \Delta^t \geq 0$$

Only in backward pass

$$\boxed{\Delta^t_{MAX} \geq \Delta^{t-1}_{MAX}}$$

$\}$ "max-type" constraints for each t

2) PAR(p)-A Model: Extended Par(p) model including average annual inflows

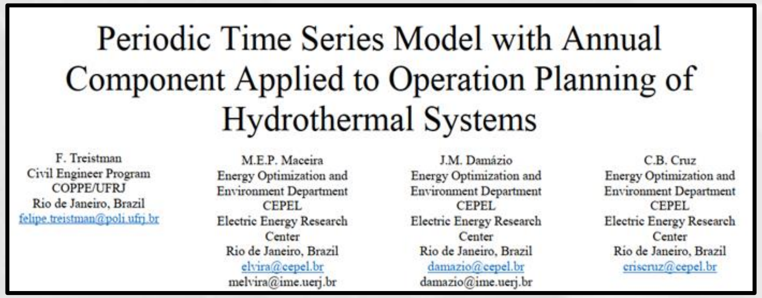
Cepel
A pesquisa que constrói o futuro

Gevazp
Geração de Cenários

Newave
Planejameto da Operação

Motivation

- Par(p) methodology has a low order of magnitude ($p = 1$ or 2) for most plants, which makes it difficult to represent the annual correlation
  - ✓ recent history “looses its memory” after some months (6-12)
- Some river basins (specially in the Northeast region) had been experiencing very negative inflows (below average) for many consecutive years



Periodic Time Series Model with Annual Component Applied to Operation Planning of Hydrothermal Systems

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Treistman, Maceira et al, PMAPS 2020

- In order to address this issue, we **add an additional regression term ψ related to average inflows for the last year** in the Par(p) model, in order to better represent recente critical hydrological conditions

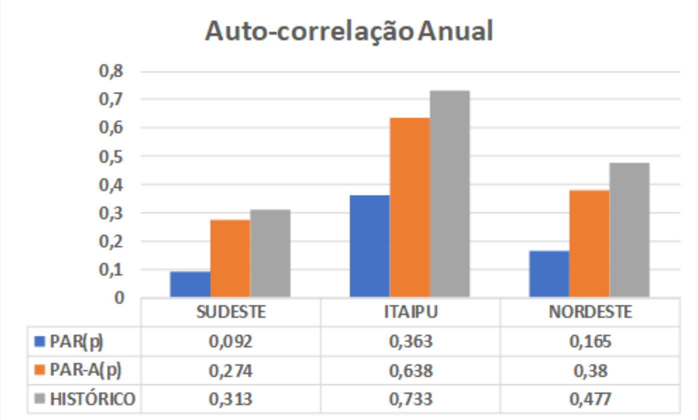
$$\boxed{I_{t,i} = \sum_{j=1}^{p_m} (\phi_{t,j,i}) I_{t-j,i} + \boldsymbol{\psi_{t,i} I_{A,t}} + \varepsilon_{t,i}}$$

, where $\boldsymbol{I_{A,t}} = \sum_{j=1}^{12} I_{t-j,i}$

- Implementation in the SDDP solving procedure leads to the inclusion of additional state variables for the problem related to past inflows from ($t = p + 1$) to ($t = 12$) for each plant

2) PAR(p)-A Model: Assessment of scenarios

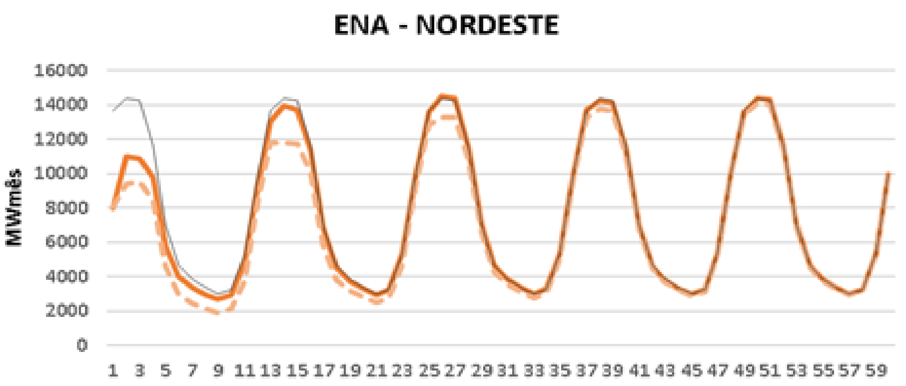
- Better representation of annual correlation

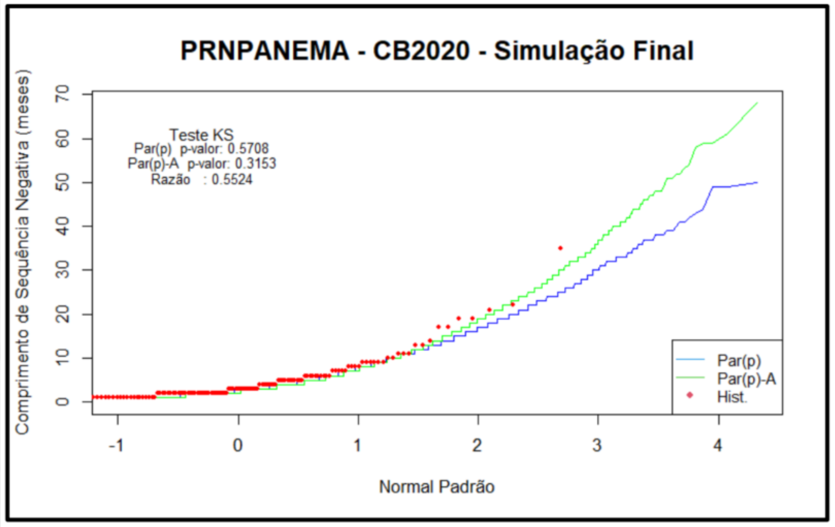


	SUDESTE	ITAIPU	NORDESTE
■ PAR(p)	0,092	0,363	0,165
■ PAR-A(p)	0,274	0,638	0,38
■ HISTÓRICO	0,313	0,733	0,477

- Thorough statistical tests showed that the Par(p)-A methodology yielded
  - ✓ Better adherence to historical autocorrelation structure and negative sequences
  - ✓ the same good ahderence of the Par(p) model in average, standard deviation and distribution of Monthly inflows, as well s spatial correlation

- Scenarios generated with Par(p)-A methodology have a better persistence of negative inflows

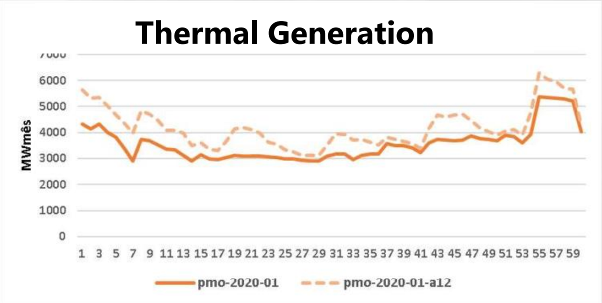




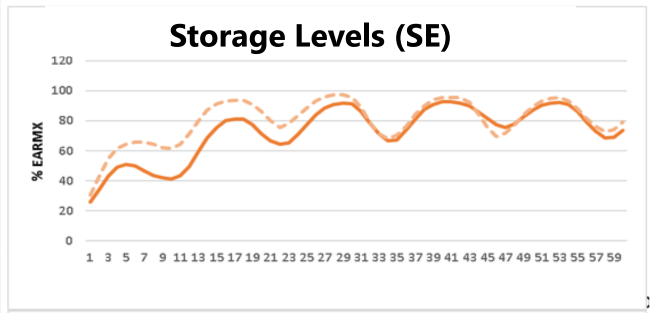
Test for negative sequences of inflows

2) PAR(p)-A Model: Results of the NEWAVE model

higher thermal generation


Thermal Generation

higher storage levels in the reservoirs

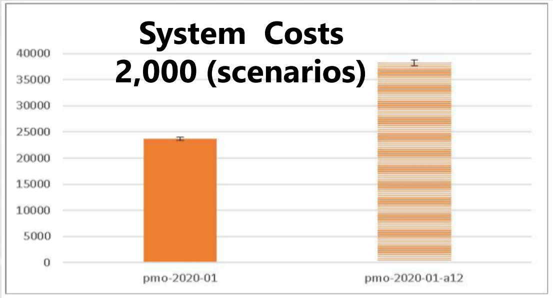

Storage Levels (SE)

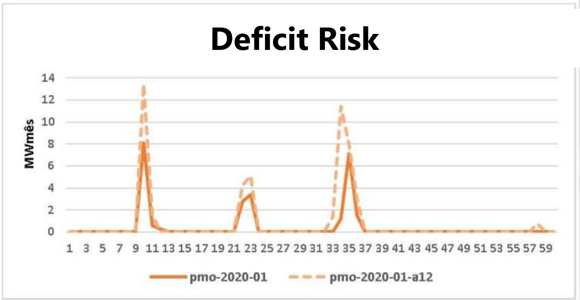
\- - - - Par(p)-A

—— Par(p)

reduction of the déficit


Marginal Costs (SE)


System Costs 2,000 (scenarios)


Deficit Risk

- Despite the increase in the number of state variables (past inflows), the CPU time per iteration did not increase significantly, but convergence takes longer

PAR(p)-A methodology yields a more risk-averse policy in the presence of critical scenarios

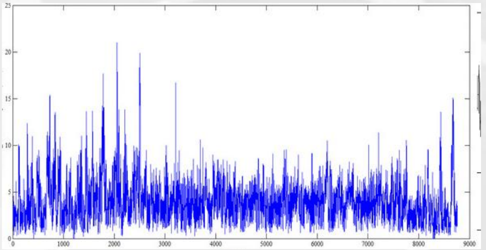
3) Joint inflow/wind speed uncertainty model

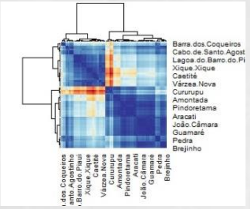
Wind Uncertainty Modeling in Long-Term Operation Planning of Hydro-Dominated Systems

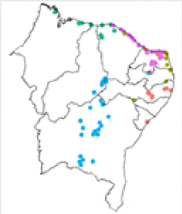
M. E. P. Maceira ; A. C. G. Melo ; J. F. M. Pessanha ; C. B. Cruz ; V. A. Almeida ; T. C. Justino

Maceira, Melo et al, PMAPS 2022

Historical / reanalysis data of hourly wind speed / generation

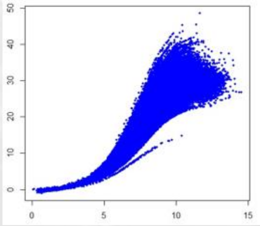




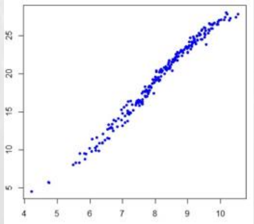


Aggregation of wind farms based on spatial correlation data

Computation of monthly Power x speed Production Curves



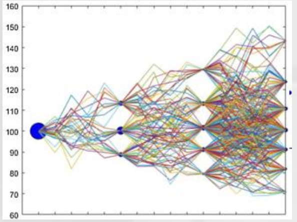
Hourly curve



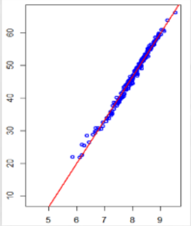
Monthly curve

- **Par(p)-Par(P)-A model for inflows**
- **Weibull distribution for wind speed**
- **Spatial correlation of wind and inflows**

Joint generation of inflows / wind speed scenarios



Linear regression for production curves

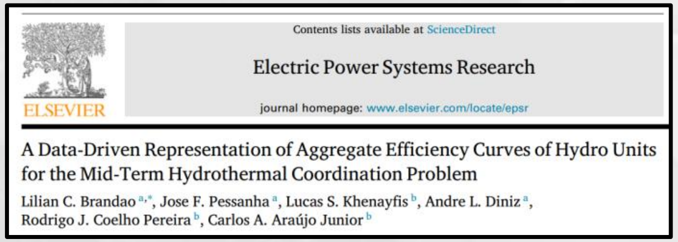


Wind farms formulation in the optimization model with power curtailment

$$\sum_{c=1}^{NPMC} GW_{t,u,c} \leq b^{W}_{t,u} + a^{W}_{t,u} \, V_{t,u}$$

4) New improvements in the 4-D model for the Hydro Production Function (HPF)

A) Data-driven model for the plant-based HPF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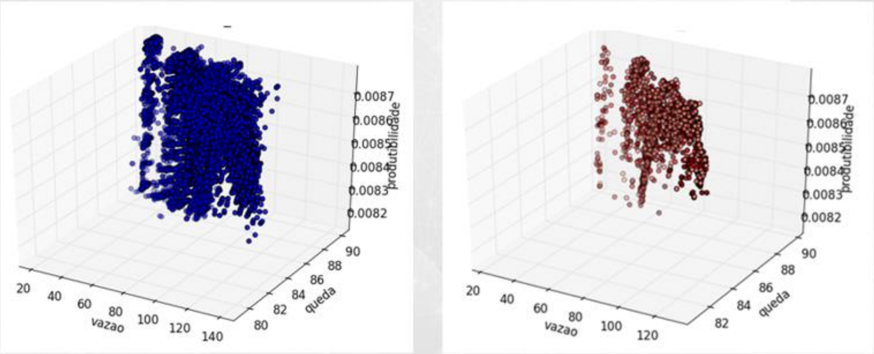
A Data-Driven Representation of Aggregate Efficiency Curves of Hydro Units for the Mid-Term Hydrothermal Coordination Problem

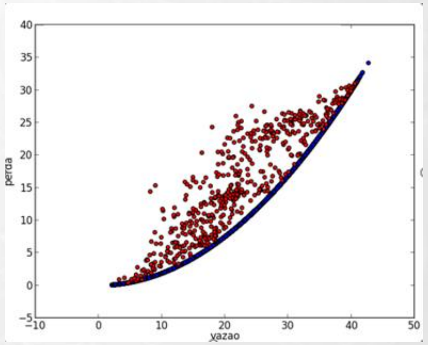
Lilian C. Brandao [a,*], Jose F. Pessanha [a], Lucas S. Khenayfis [b], Andre L. Diniz [a], Rodrigo J. Coelho Pereira [b], Carlos A. Araújo Junior [b]

Brandão,Pessanha et al, EPSR 2022

Turbine—generator efficiency as a nonlinear function of discarge and net head



Penstock losses as a nonlinear function of discharge



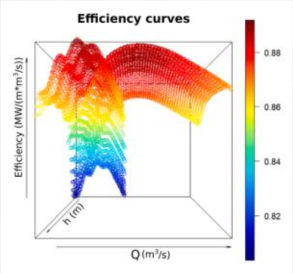
- ✓ Handling of historical data to match the time discretization of the models

Hourly data

weekly data

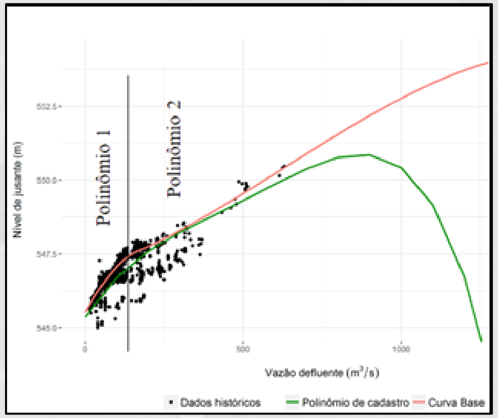
- ✓ Fitting of Generalized aditive models (GAM)

$$f_j(x_j) = \delta_{j,1} + x_j\delta_{j,2} + \sum_{k=1}^{q_j-2} R_j(x_j, x_{jk}^*)\delta_{j,k+2}$$



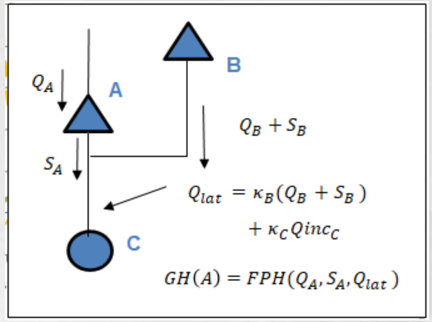
4) New improvements in the 4-D model for the Hydro Production Function (HPF)

B) Use of piecewise polynomial curves for the tailrace level, as a function of total release of the plant



Source: ONS

C) Inclusion of the effect of "side inflows" in the tailrace level for some plants

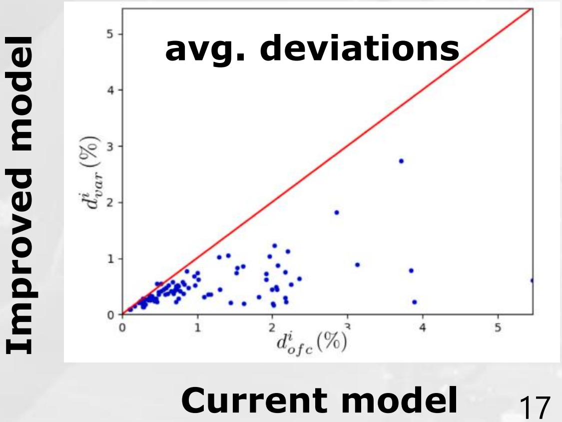


- ✓ Generalization of the model with a term for any non-turbined release

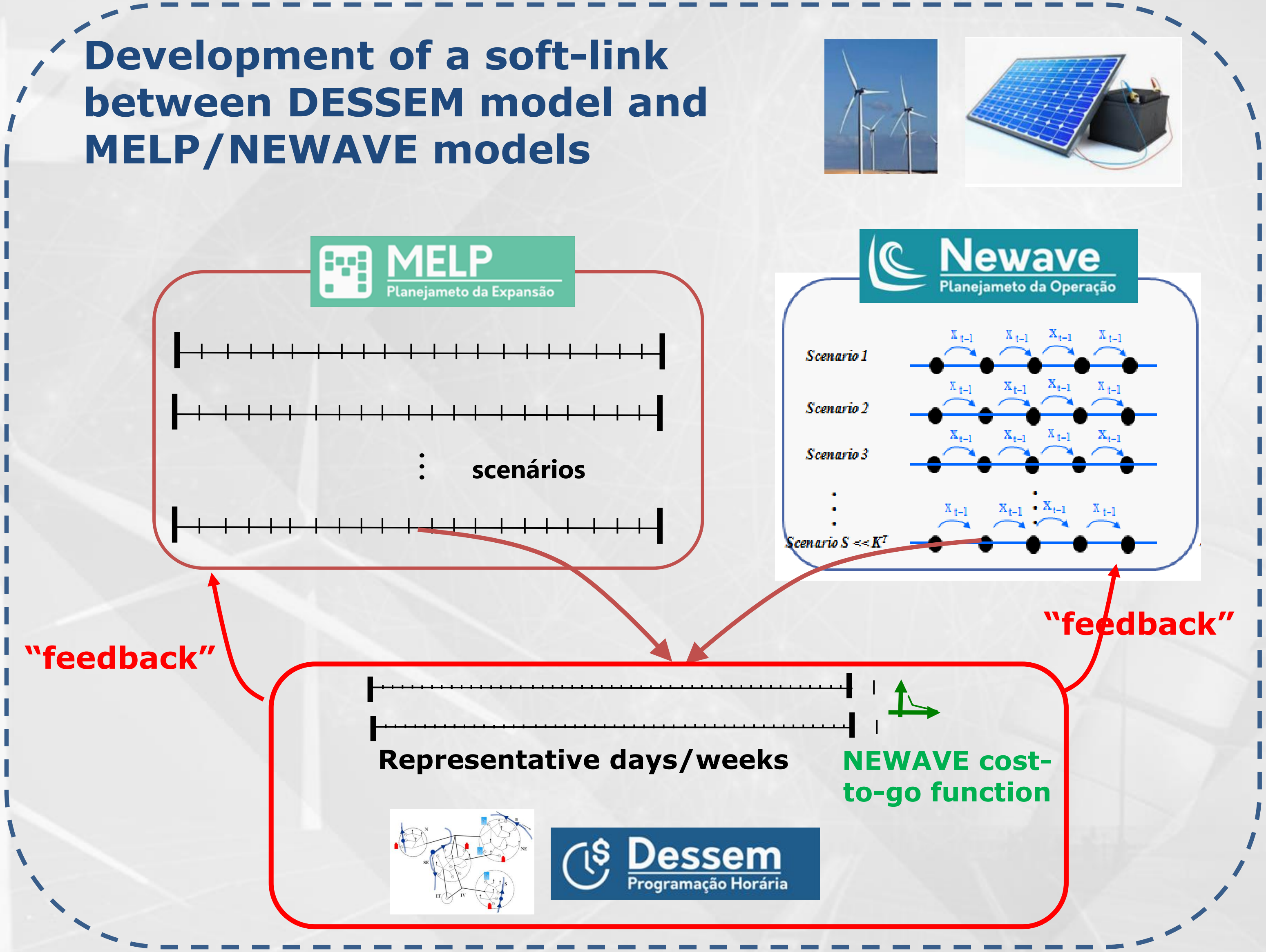
D) Improvements in the convex-hull computation

- ✓ Elimination of very similar cuts
- ✓ Use of a more efficient algorithm
- ✓ Improvement in the computation of the secant term related to spillage

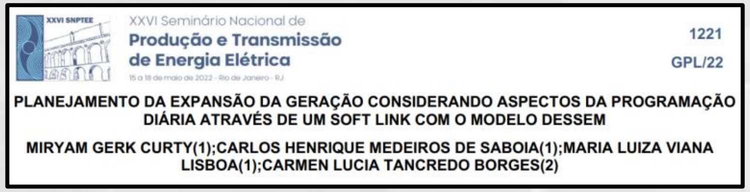
Reduction in the average deviations from the real HPF curve as compared to the original model of (Diniz, Maceira,2008)



5) Direct link between operation planning and short term scheduling



Development of a soft-link between DESSEM model and MELP/NEWAVE models



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PLANEJAMENTO DA EXPANSÃO DA GERAÇÃO CONSIDERANDO ASPECTOS DA PROGRAMAÇÃO DIÁRIA ATRAVÉS DE UM SOFT LINK COM O MODELO DESSEM

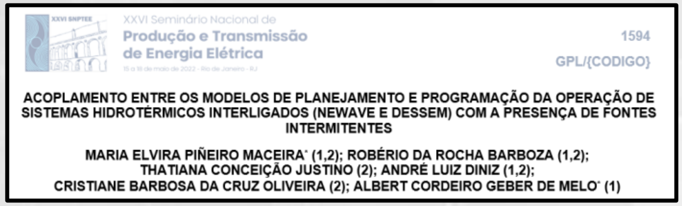
MIRYAM GERK CURTY(1);CARLOS HENRIQUE MEDEIROS DE SABOIA(1);MARIA LUIZA VIANA LISBOA(1);CARMEN LUCIA TANCREDO BORGES(2)

Curty, Saboia et al SNPTEE, 2022

- Evaluation of the operation policy under a very small time granularity
- Assessment of the impact of the high variability and uncertainty of new renewable sources on a daily basis in operation planning studies
- Assessment of the benefits of the inclusion of storage devices

5) Direct link between operation planning and short term scheduling

A pesquisa que constrói o futuro



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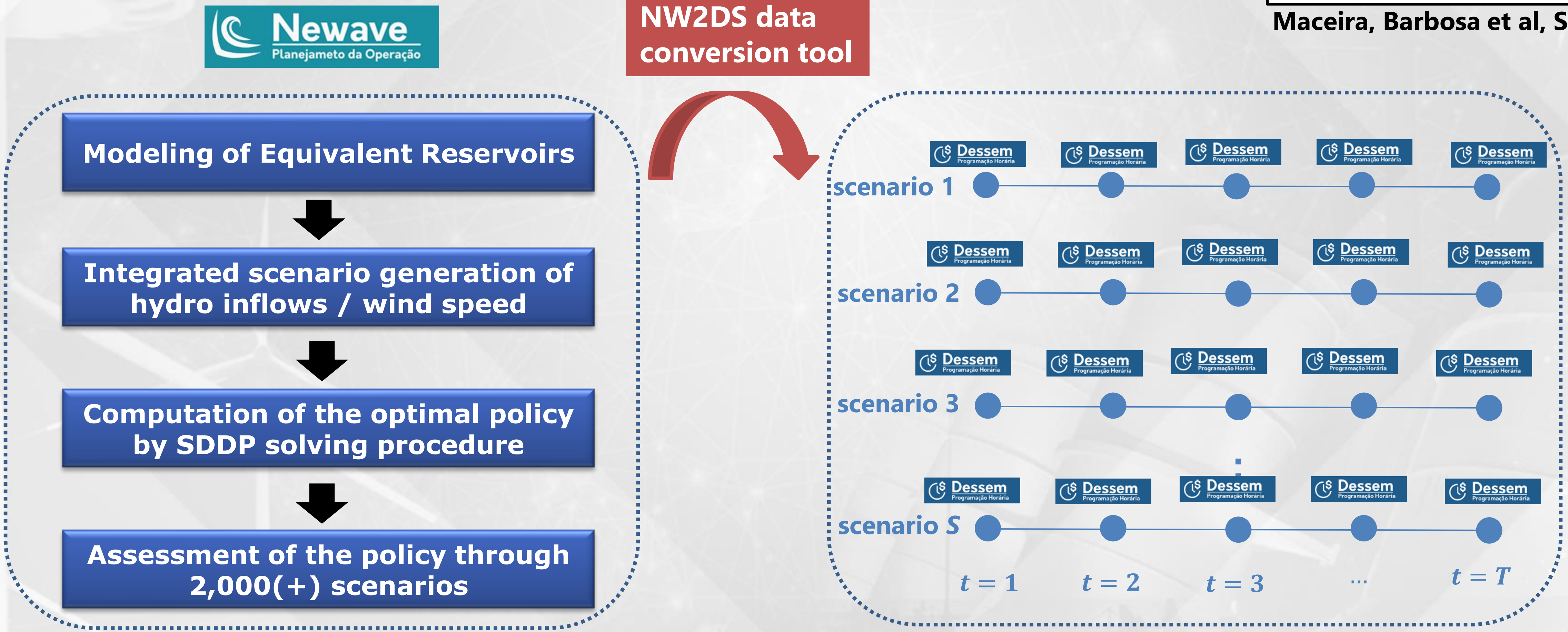
ACOPLAMENTO ENTRE OS MODELOS DE PLANEJAMENTO E PROGRAMAÇÃO DA OPERAÇÃO DE SISTEMAS HIDROTÉRMICOS INTERLIGADOS (NEWAVE E DESSEM) COM A PRESENÇA DE FONTES INTERMITENTES

MARIA ELVIRA PIÑEIRO MACEIRA' (1,2); ROBÉRIO DA ROCHA BARBOZA (1,2);
THATIANA CONCEIÇÃO JUSTINO (2); ANDRÉ LUIZ DINIZ (1,2);
CRISTIANE BARBOSA DA CRUZ OLIVEIRA (2); ALBERT CORDEIRO GEBER DE MELO' (1)

Maceira, Barbosa et al, SNPTEE, 2022

NW2DC tool for integration between NEWAVE and DESSEM



NW2DS data conversion tool

Modeling of Equivalent Reservoirs

Integrated scenario generation of hydro inflows / wind speed

Computation of the optimal policy by SDDP solving procedure

Assessment of the policy through 2,000(+) scenarios

Hourly simulation

FUTURE DEVELOPMENTS (2022-2024)

Newave Planejameto da Operação

- Piecewise linear model for min/max outflow constraints as a function of initial storage levels in the reservoirs
- Improvement in the consideration of "end-effect": derivation of the limiting FCF of the infinite horizon problem instead of extending the planning horizon)
- Individual representation of hydro plants and inclusion of all constraints of the DECOMP model in the entire planning horizon

Gevazp Geração de Cenários

- Possible incoporation of climate-change effects in the scenario generation model

Decomp Planejameto de Curto Prazo

- Conditional electrical/hydraulic constraints
- Representation of the DC electrical network and consideration of scenarios for the 1st month
- More detailed time discretization in the 1st week (improved coupling with DESSEM model)

Dessem Programação Horária

- Modeling of hydro unit commitment constraints
- MILP model for dynamic security constraints (currently addressed with convex approximations or heuristic iterative processes)
- Modeling of more detailed demand response constraints ("block load" shift)

All of this would never be possible without those people!!

Tusen Takk !!

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dessem,gevap@cepel.br

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