LBE5010 Renewable Energies and Energy Planning

Hydroelectric and Wind Power Plants

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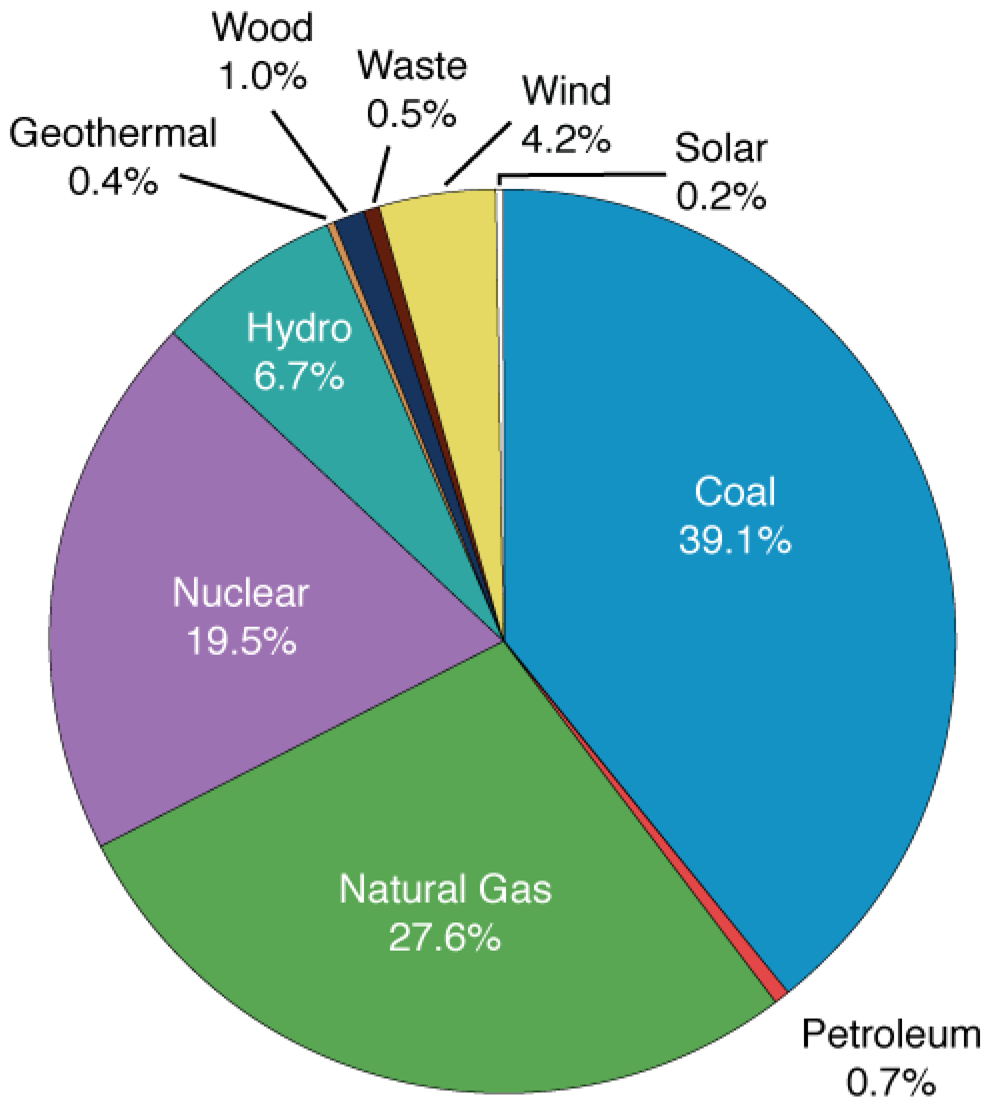
Universidade de São Paulo

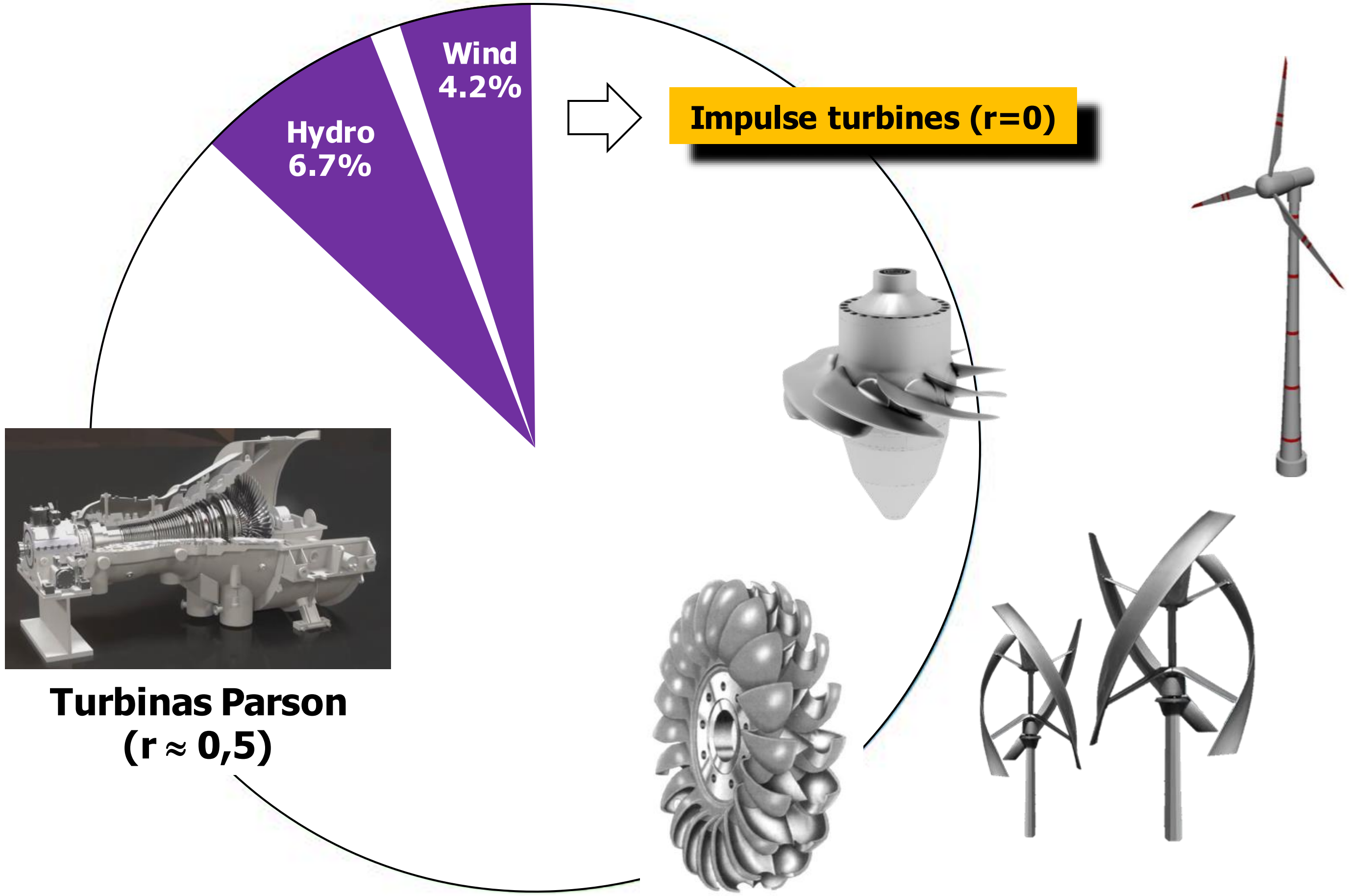
Electricity Generation, 2013



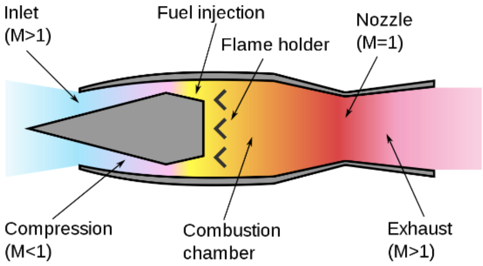
IER INSTITUTE FOR ENERGY RESEARCH

Electricity Generation, 2013

Approximately 11% of all electricity generated in the world comes from impulse turbines

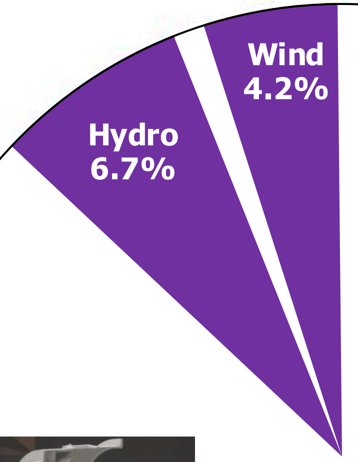


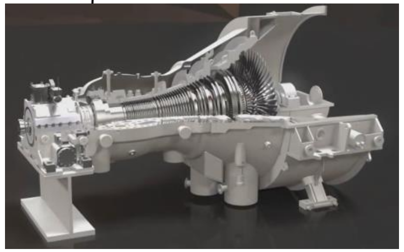
Electricity Generation, 2013



ramjet, scramjet, etc.
(r = 1)

Approximately 11% of all electricity generated in the world comes from impulse turbines





Parson turbines
(r ≈ 0,5)

Impulse turbines (r=0)

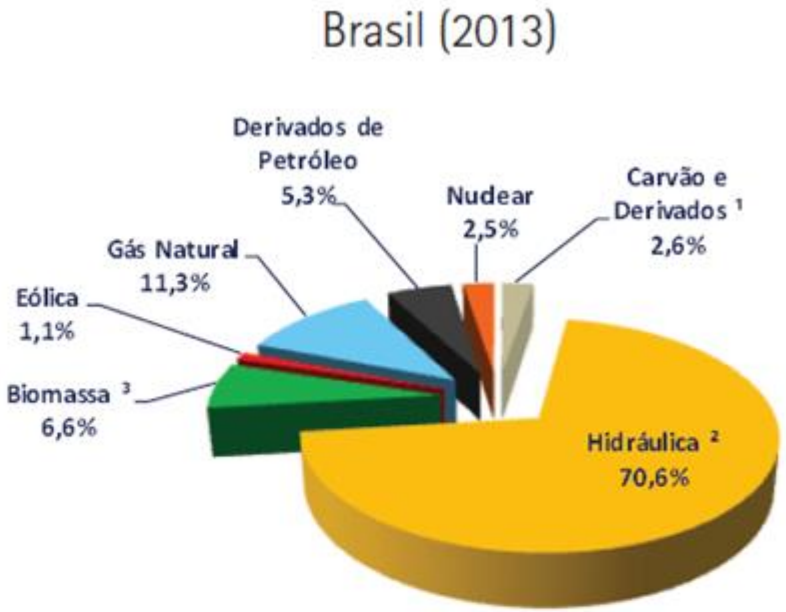
Wind turbines

- ✓ low generation cost (~8 ¢/kWh)
- ✓ virtually unlimited potential
- ✓ complementarity with hydroelectric power plants
- ✓ intermittent

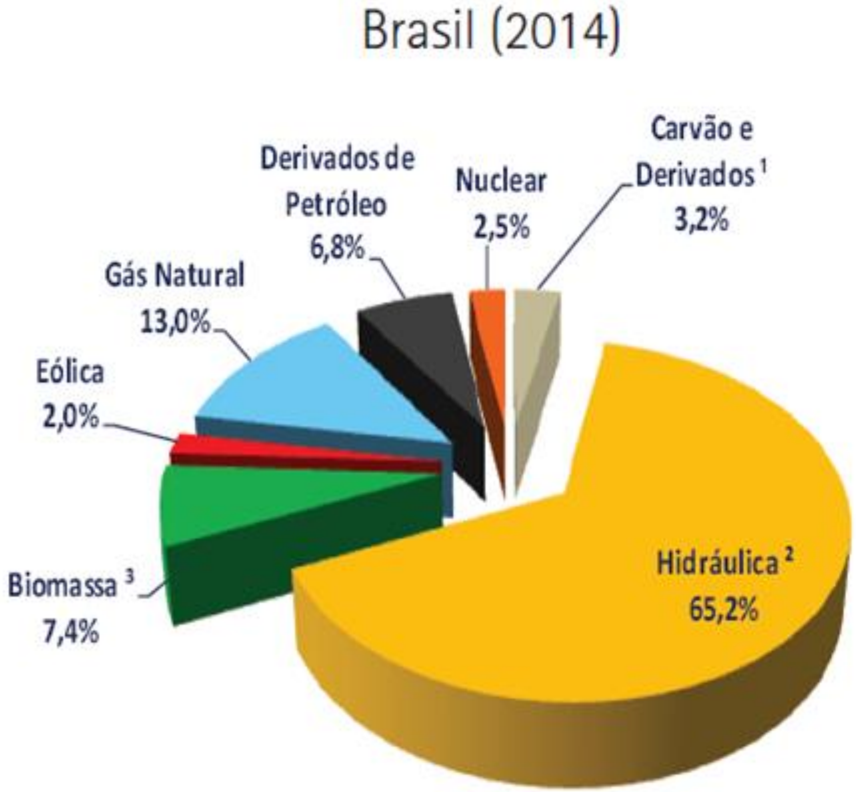
Hydroelectric turbines

- ✓ lowest generation cost (~4 ¢/kWh)
- ✓ 50 – 100 years useful life
- ✓ functionality of the reservoir
- ✓ small growth potential

OPERATION OF THERMO POWERPLANTS BETWEEN 2013 – 2014



geração hidráulica² em 2013: 431,3 TWh
geração total² em 2013: 611,2 TWh



geração hidráulica² em 2014: 407,2 TWh
geração total² em 2014: 624,3 TWh

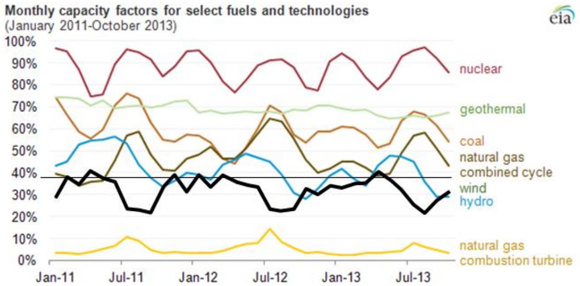
[1] *Inclui gás de coqueria*
[2] *Inclui importação*
[3] *Inclui lenha, bagaço de cana, lixívia e outras recuperações*

WIND ELECTRICITY GENERATION IN BRAZIL

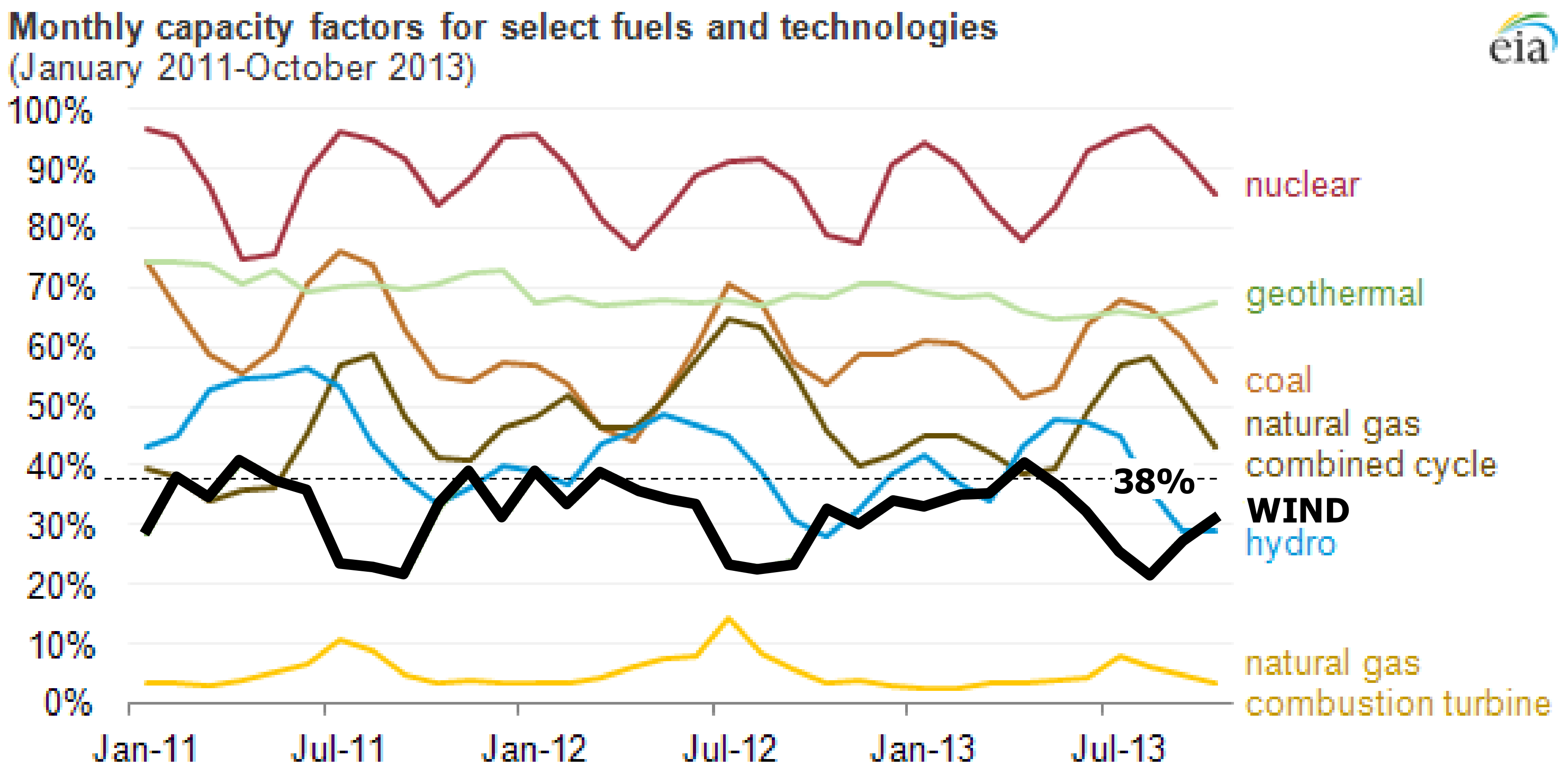
Velocidade média do vento (m/s)
50 m acima do nível da superfície

Classes de energia	Mata	Campo Aberto	Zona Costeira	Morro	Montanha
4	> 6,0	> 7,0	> 8,0	> 9,0	> 11,0
3	4,5 - 6,0	6,0 - 7,0	6,0 - 7,0	7,5 - 9,0	8,5 - 11,0
2	3,0 - 4,5	4,5 - 6,0	4,5 - 6,0	6,0 - 7,5	7,0 - 8,5
1	< 3,0	< 4,5	< 4,5	< 6,0	< 7,0

Total generation in 2014:	71,26 GW
Technical potential:	143 GW(1)
Operating (2014):	9,91 GW(2)
Hired (2035):	9,93 GW(2)
Average FAC (2014):	38%(2)

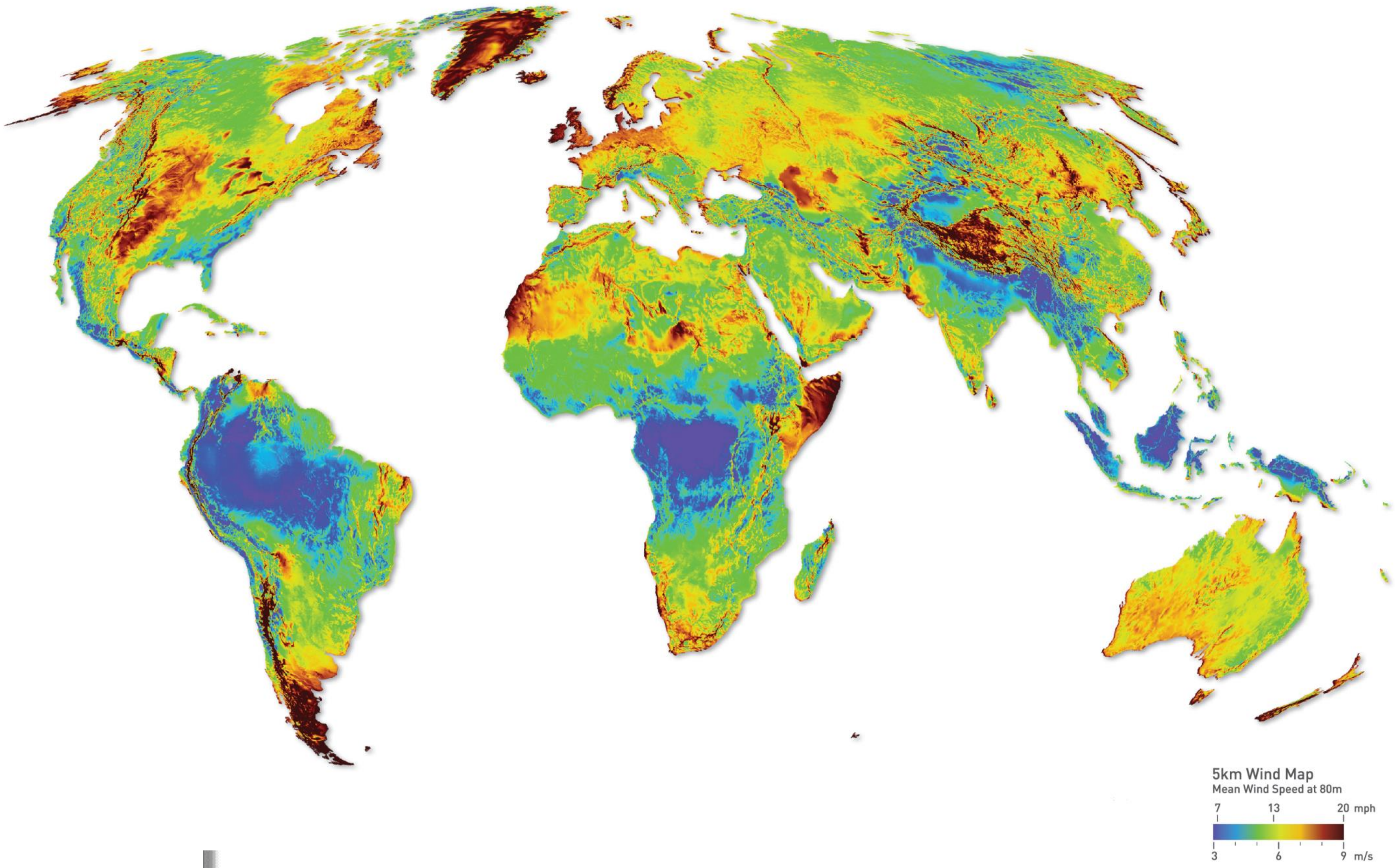


(1) Atlas do Potencial Eólico Brasileiro
(2) Assoc. Brasileira de Energia Eólica


Monthly capacity factors for select fuels and technologies
(January 2011-October 2013)
eia
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Jan-11
Jul-11
Jan-12
Jul-12
Jan-13
Jul-13
nuclear
geothermal
coal
natural gas combined cycle
38%
WIND
hydro
natural gas combustion turbine

Global Mean Wind Speed at 80m

3TIER by Vaisala



Global Mean Wind Speed at 80m

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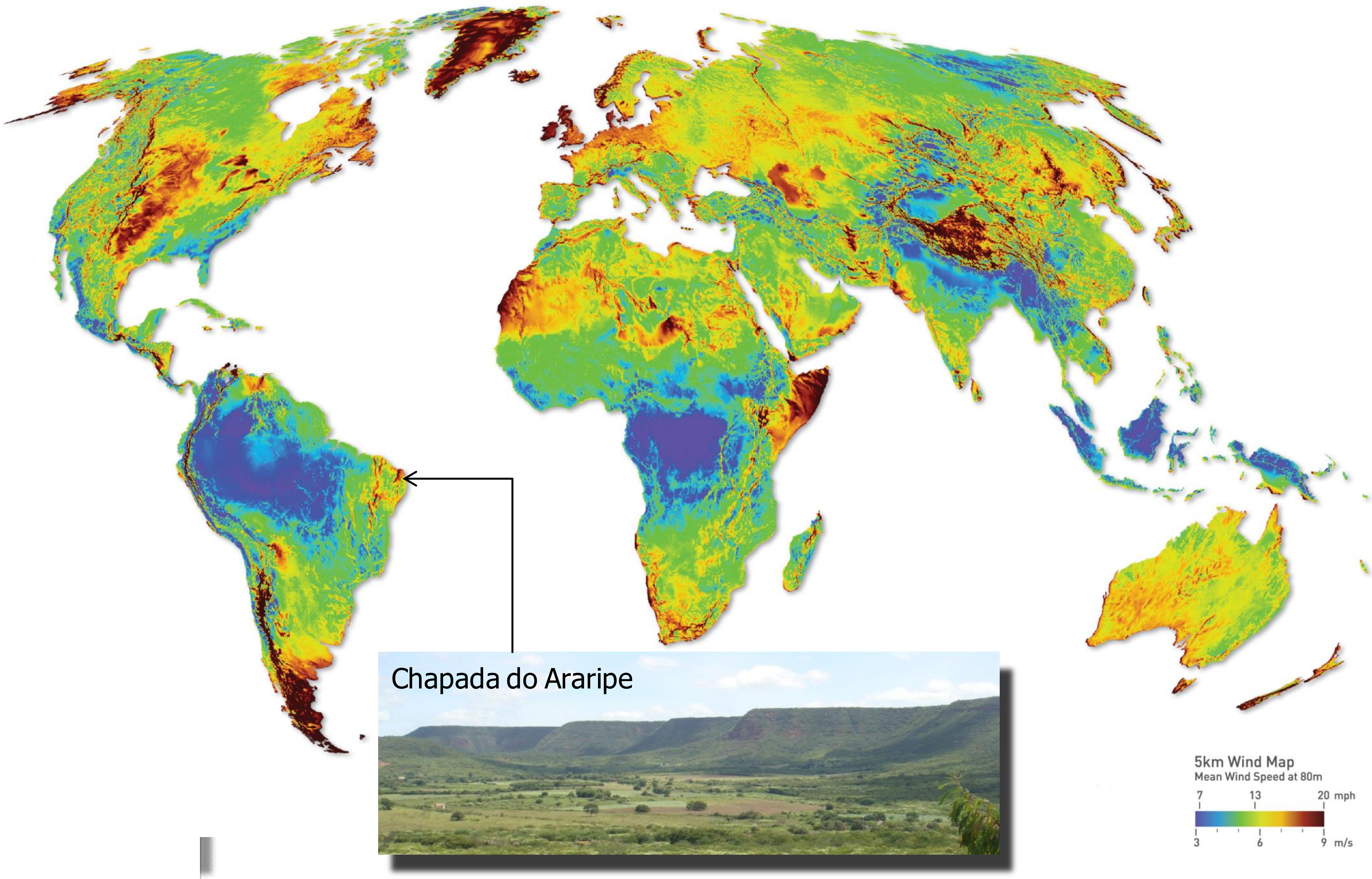
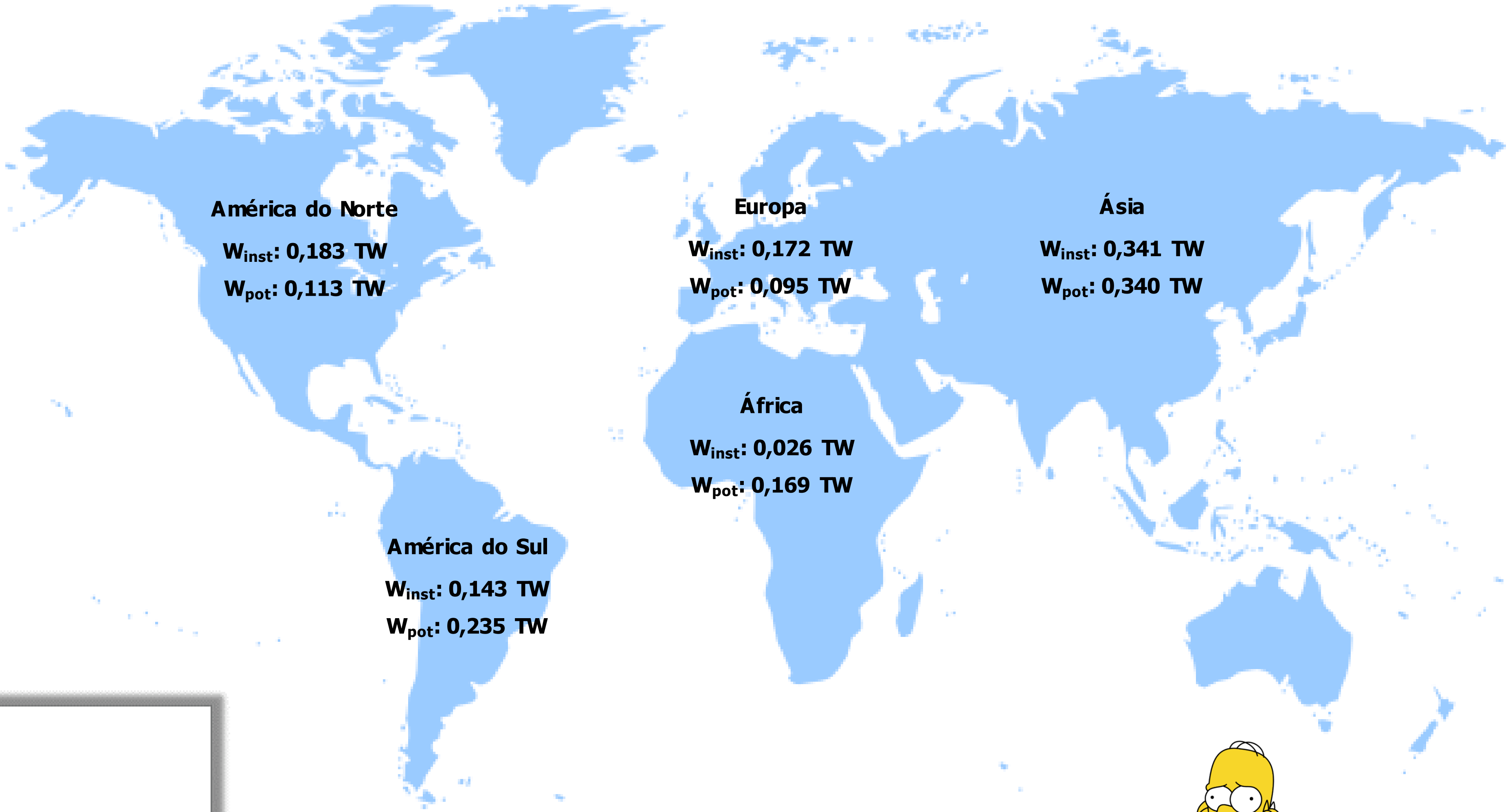


WORLD HYDROELECTRIC POTENTIAL

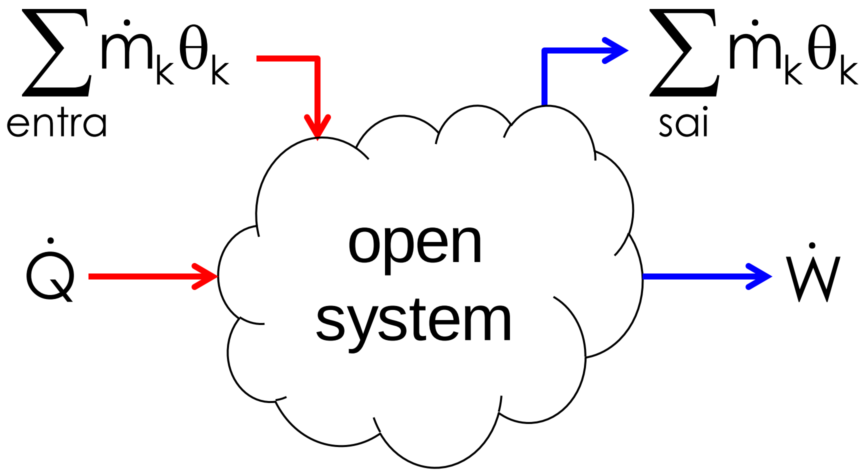


$$\dot{W}_{cons,2012} = 2{,}21\,\text{TW}$$

FLUX MACHINES:

theoretical analysis

Energy inventory in the control volume... 1ª Law of Thermodynamics

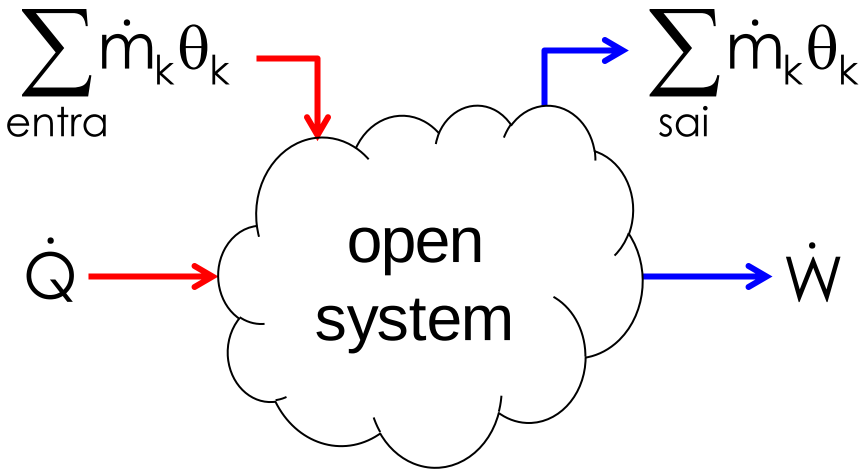


$$\frac{dE_{VC}}{dt} = \dot{Q} - \dot{W} - \left[\sum_{sai} \dot{m}_k \cdot \left(h_k + gz_k + V_k^2/2 \right) - \sum_{entra} \dot{m}_k \cdot \left(h_k + gz_k + V_k^2/2 \right) \right]$$

h_k: thermal energy

$gz_k + V_k^2/2$: mechanical energy

Energy inventory in the control volume... 1ª Law of Thermodynamics

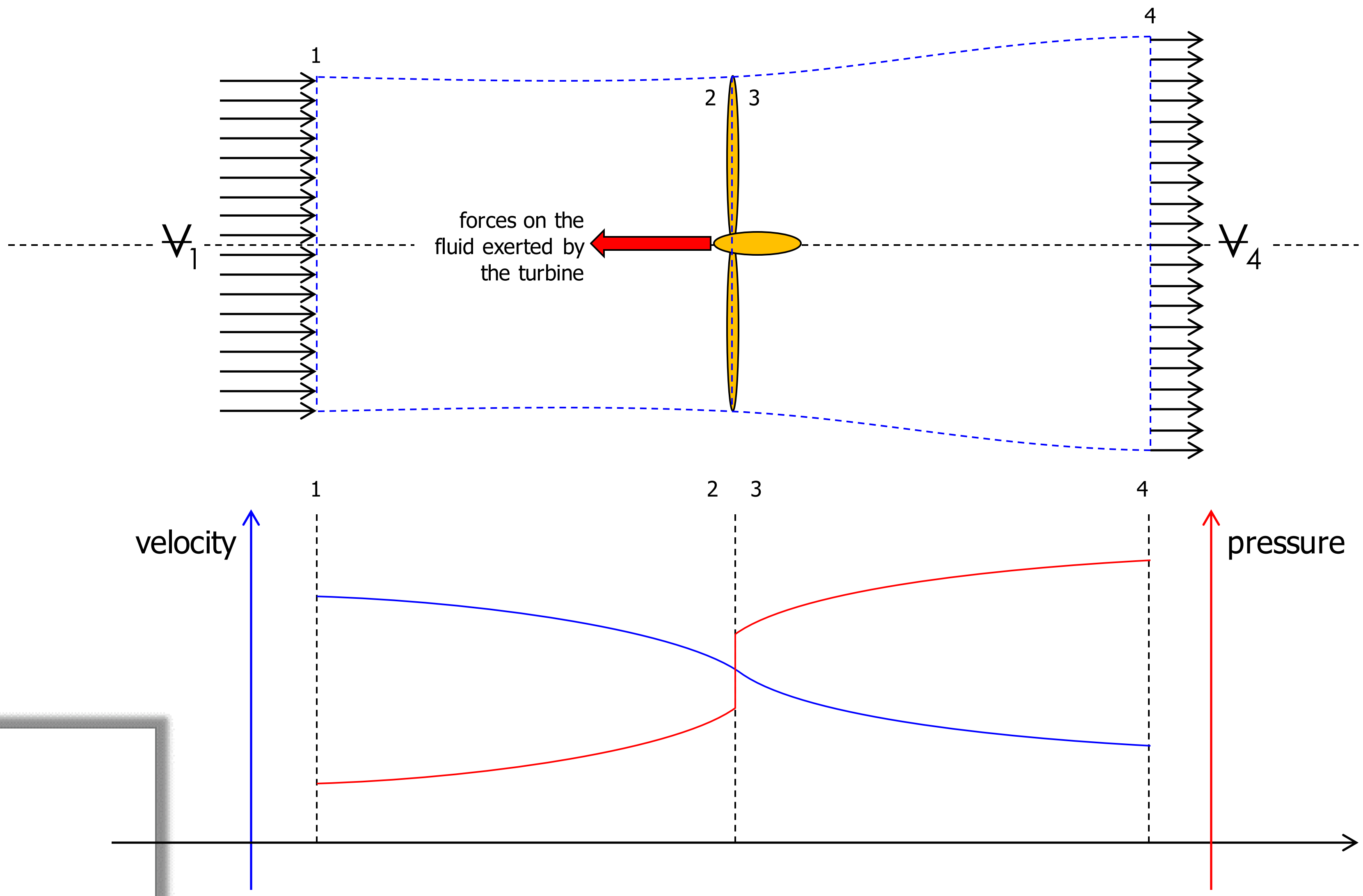


$$\cancel{\frac{dE_{VC}}{dt}} = \cancel{\dot{Q}} - \dot{W} - \left[\sum_{sai}\dot{m}_k \cdot \left(\cancel{h_k} + gz_k + \forall_k^2/2\right) - \sum_{entra}\dot{m}_k \cdot \left(\cancel{h_k} + gz_k + \forall_k^2/2\right)\right]$$

T=cte T=cte

$$\dot{W} = \left[\sum_{entra}\dot{m}_k \cdot \left(P_k/\rho_k + gz_k + \forall_k^2/2\right) - \sum_{sai}\dot{m}_k \cdot \left(P_k/\rho_k + gz_k + \forall_k^2/2\right)\right]$$

Application to an impulse turbine



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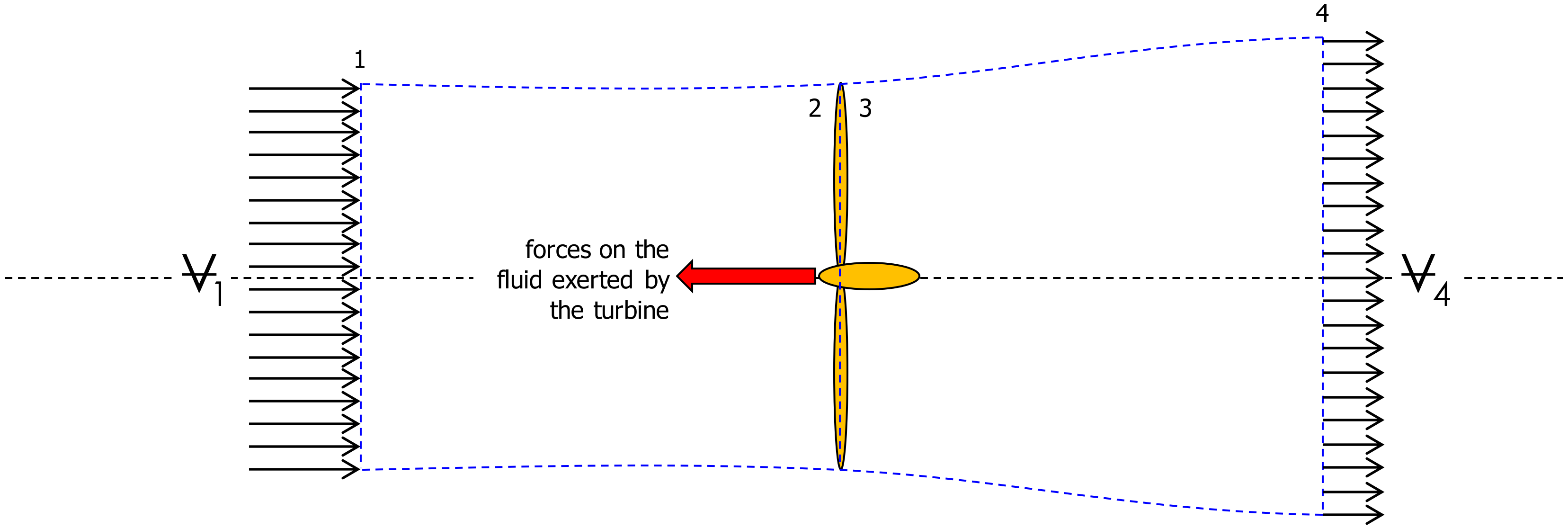


$$F = (P_3 - P_2) \cdot A = \dot{m} \cdot (\forall_1 - \forall_4)$$

Saint-Venant

momentum variation

Application to an impulse turbine

$$F = (P_3 - P_2)\cdot A = \dot{m}\cdot(\forall_1 - \forall_4)$$

$$F = (P_3 - P_2)\cdot A = \rho A \forall_{med}\cdot(\forall_1 - \forall_4)$$

$$0 = \dot{m}\cdot\left[\left(\frac{P_1}{\rho_1} + \frac{\forall_1^2}{2}\right) - \left(\frac{P_2}{\rho_2} + \frac{\forall_2^2}{2}\right)\right]$$

$$0 = \dot{m}\cdot\left[\left(\frac{P_3}{\rho_3} + \frac{\forall_3^2}{2}\right) - \left(\frac{P_4}{\rho_4} + \frac{\forall_4^2}{2}\right)\right]$$

$P_1 = P_4$
$\forall_2 = \forall_3$

1ª lei →

$T = cte$
$z = cte$

$$\left(\frac{P_3}{\rho_3} - \frac{P_2}{\rho_2}\right) = \left(\frac{\forall_1^2}{2} - \frac{\forall_4^2}{2}\right)$$

$$\rho_2 \cong \rho_3 \rightarrow \quad \forall_{med} = \frac{\forall_1 + \forall_4}{2}$$

Application to an impulse turbine

$$\dot{W} = F \cdot \forall_{med} = \rho A \forall_{med}^{2} \cdot (\forall_1 - \forall_4)$$

$$\dot{W} = F \cdot \forall_{med} = \rho A \cdot \left(\frac{\forall_1 + \forall_4}{2} \right)^2 \cdot (\forall_1 - \forall_4)$$

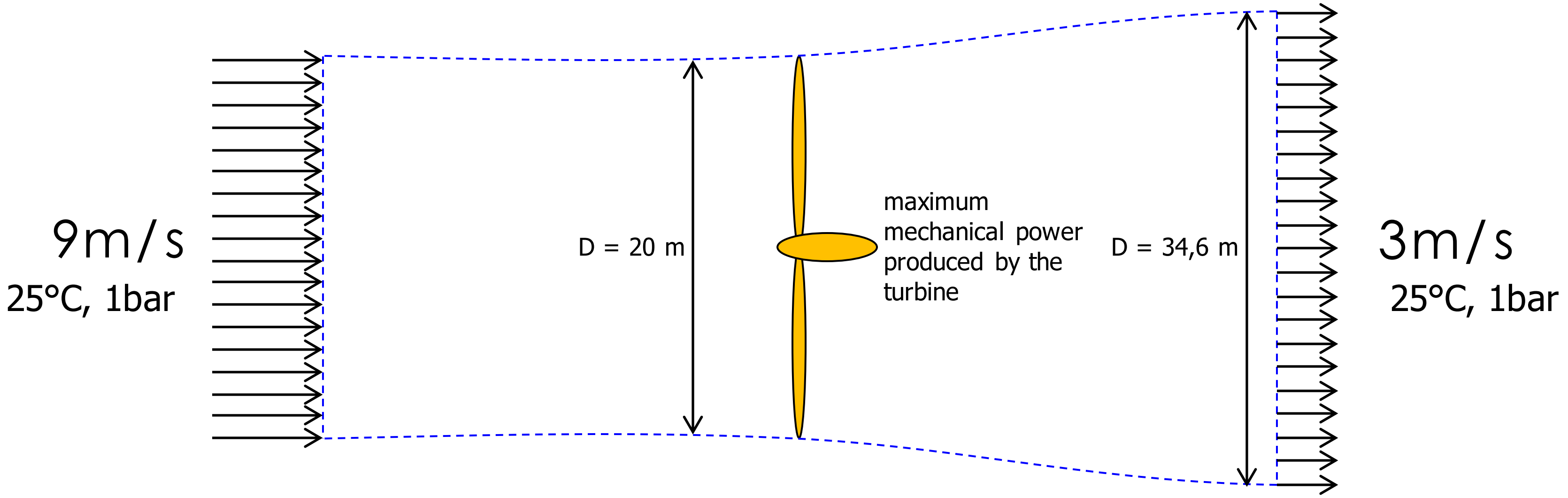
$$\Downarrow \quad \xi = \forall_4 / \forall_1$$

$$\dot{W} = \rho A \forall_1^3 \cdot \left(\frac{1 + \xi}{2} \right)^2 \cdot (1 - \xi)$$

$$\Downarrow \quad \partial \dot{W} / \partial \xi = 0 \Rightarrow \xi = 1/3 \ \text{ ou } \ \xi = -1$$

$$\dot{W}_{max} = \frac{16}{27} \cdot \rho A \frac{\forall_1^3}{2}$$

Application to an impulse turbine



$$\dot{W}_{max} = \frac{16}{27} \cdot \rho A \frac{V_1^3}{2}$$

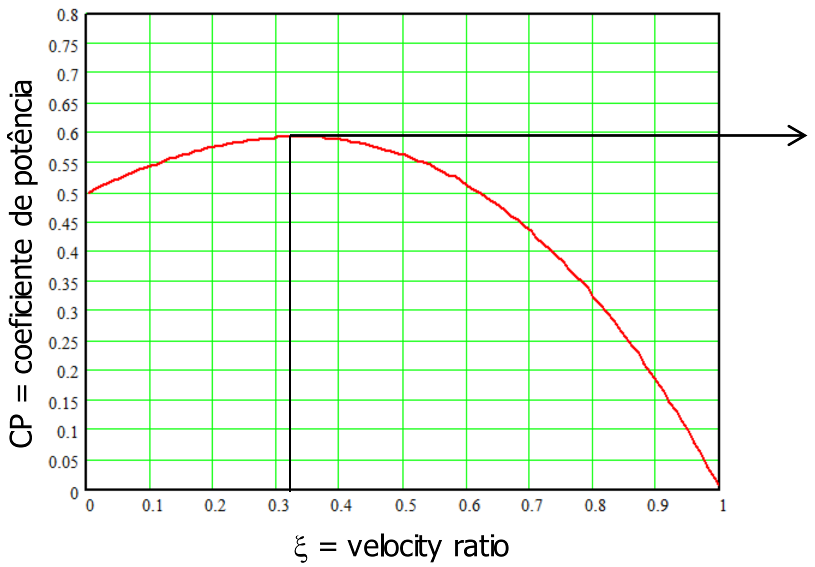
$$\dot{W}_{max} = \frac{16}{27} \cdot 1{,}17 \frac{kg}{m_3} \frac{\pi \cdot (20m)^2}{4} \frac{(9m/s)^3}{2}$$

$$\dot{W}_{max} = 158{,}789kW$$

Working Definitions and Equations

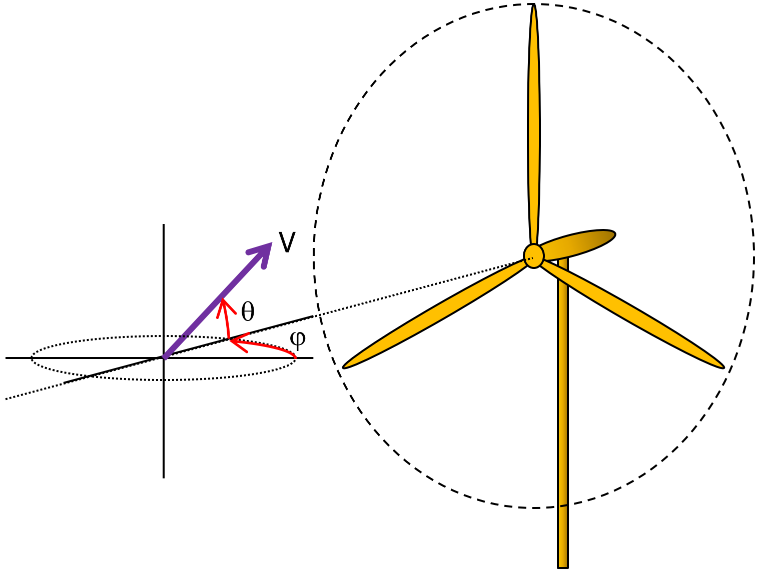
$$\dot{W} = \rho A \forall_1^3 \cdot \left(\frac{1+\xi}{2} \right)^2 \cdot (1-\xi) \quad \rightarrow \quad \dot{W} = \underbrace{\frac{1}{2}\rho A \forall_1^3}_{\text{wind power}} \cdot \underbrace{\frac{1}{2}(1+\xi)^2 \cdot (1-\xi)}_{\text{power coefficient}}$$

$$CP(\xi) = \frac{\dot{W}}{\rho A \forall_1^3 / 2} = \frac{\text{turbine power}}{\text{wind power}} = \frac{1}{2}(1+\xi)^2 \cdot (1-\xi)$$



$$CP_{max} = \frac{16}{27} \cong 59{,}3\ \%$$

Working Definitions and Equations

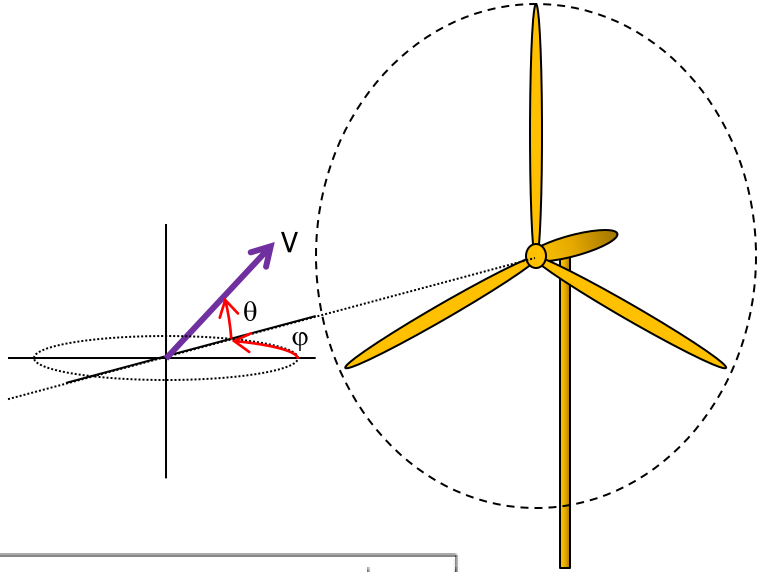


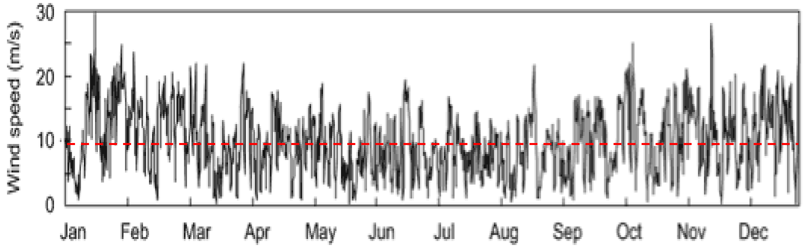
$$\eta = \frac{\text{actual power}}{\text{maximum power}} = \frac{\dot{W}}{CP(\xi)\cdot\rho A \forall_{med}^{3}/2}$$

design: ξ=1/3

wind power capacity

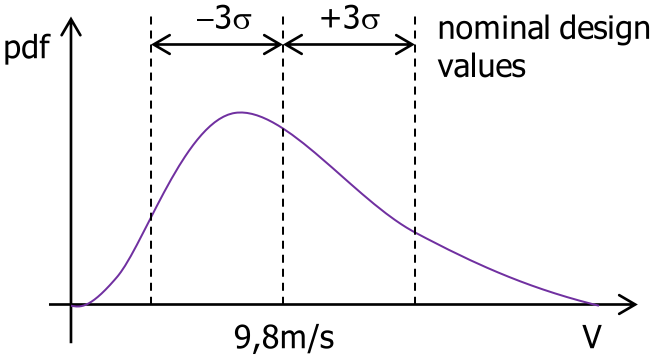
Working Definitions and Equations



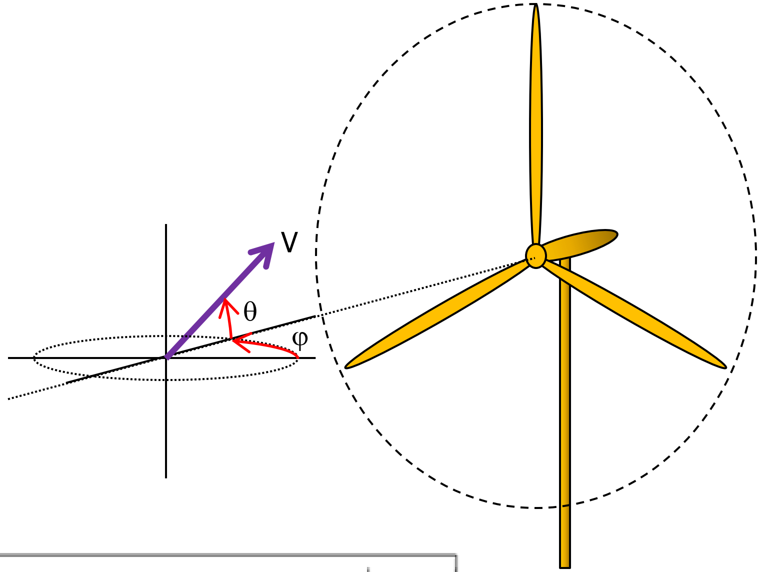


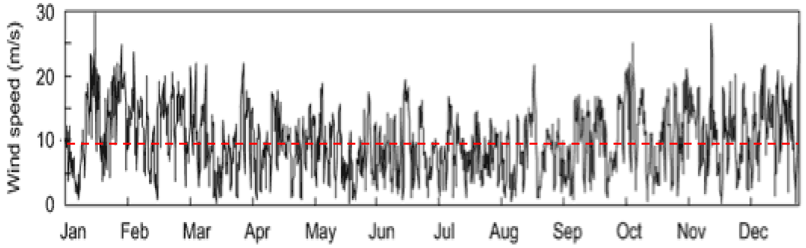
Burgar Hill, Orkney; 60 m measurement height; 4 hour averages

$$\eta = \frac{\dot{W}}{CP(\xi)\cdot \rho A V_{med}^{3}/2}$$



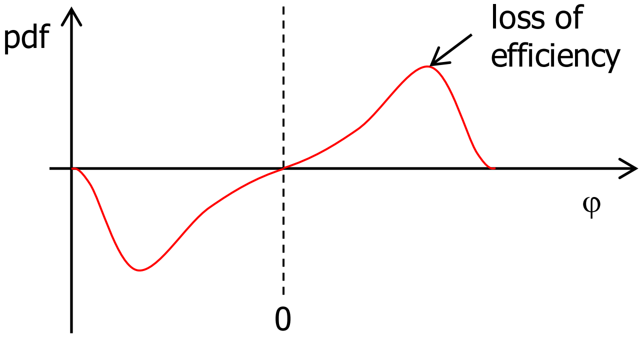
Working Definitions and Equations



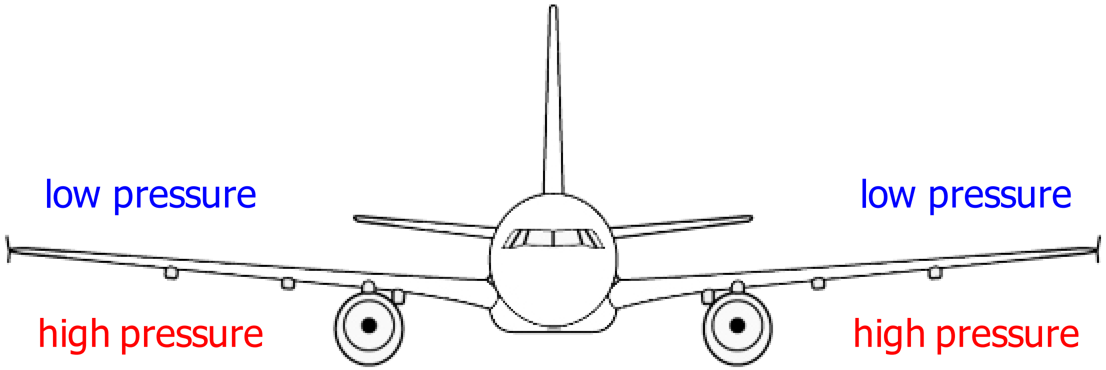


Burgar Hill, Orkney; 60 m measurement height; 4 hour averages

$$\eta = \frac{\dot{W}}{CP(\xi) \cdot \rho A \forall_{med}^{3} / 2}$$



Factors Causing Efficiency Losses



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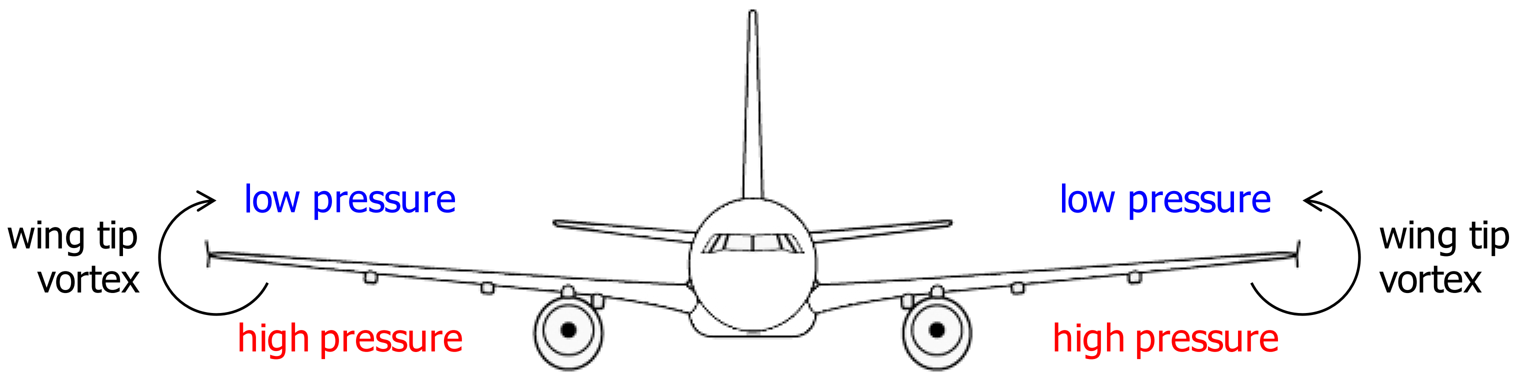

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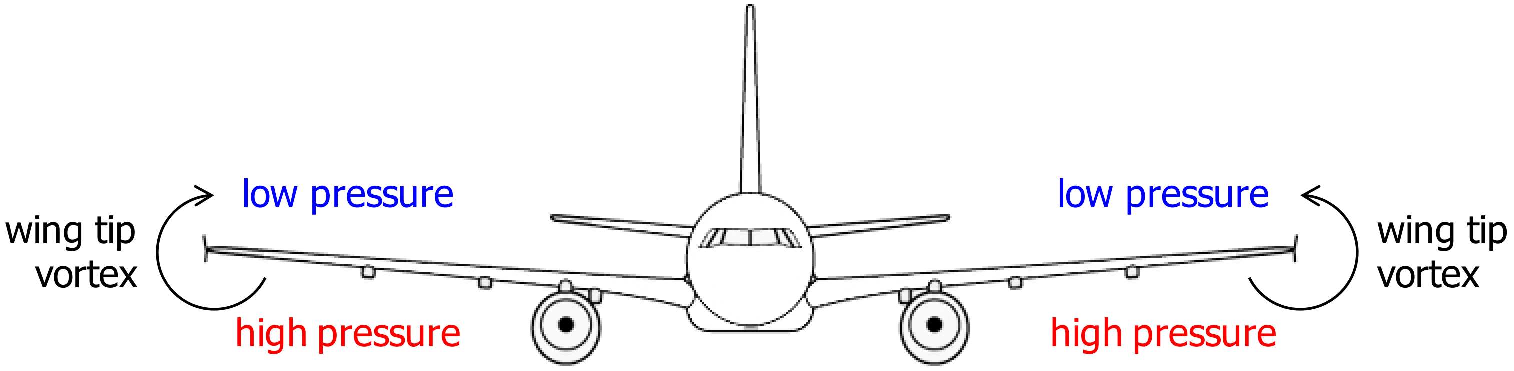
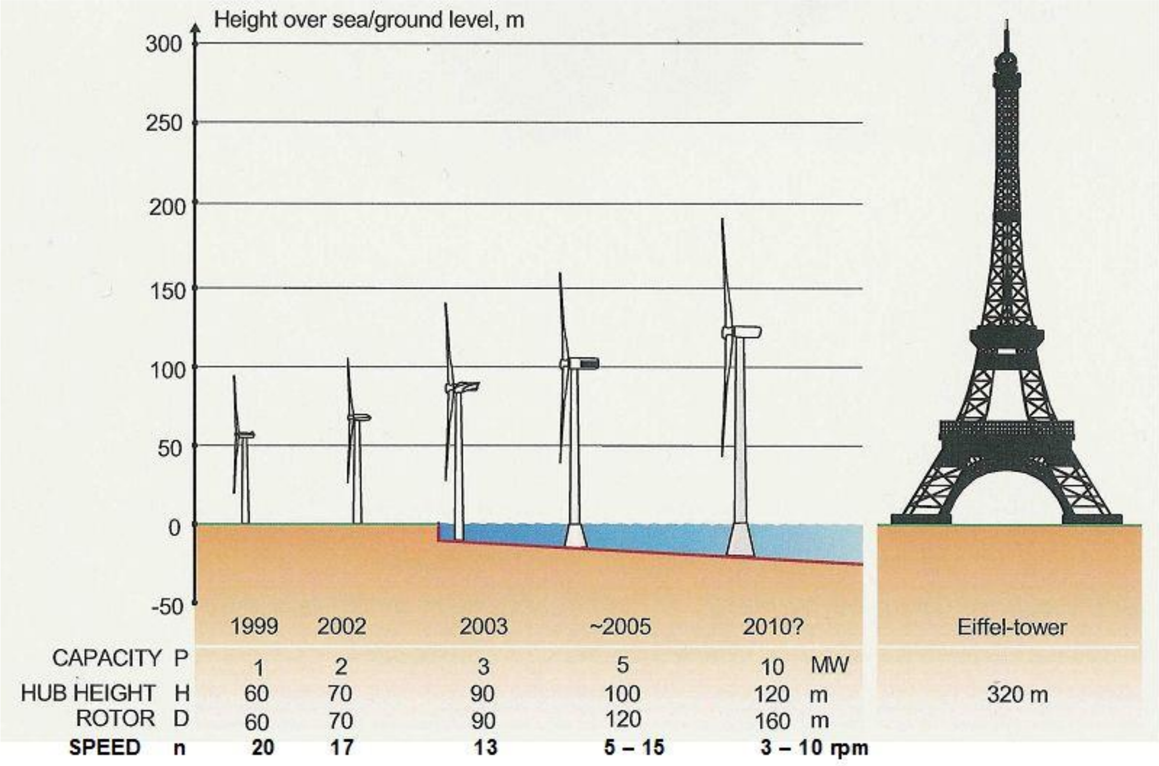


Evolution of Wind Power Technology



Current LCOE 4,50 ¢/kWh

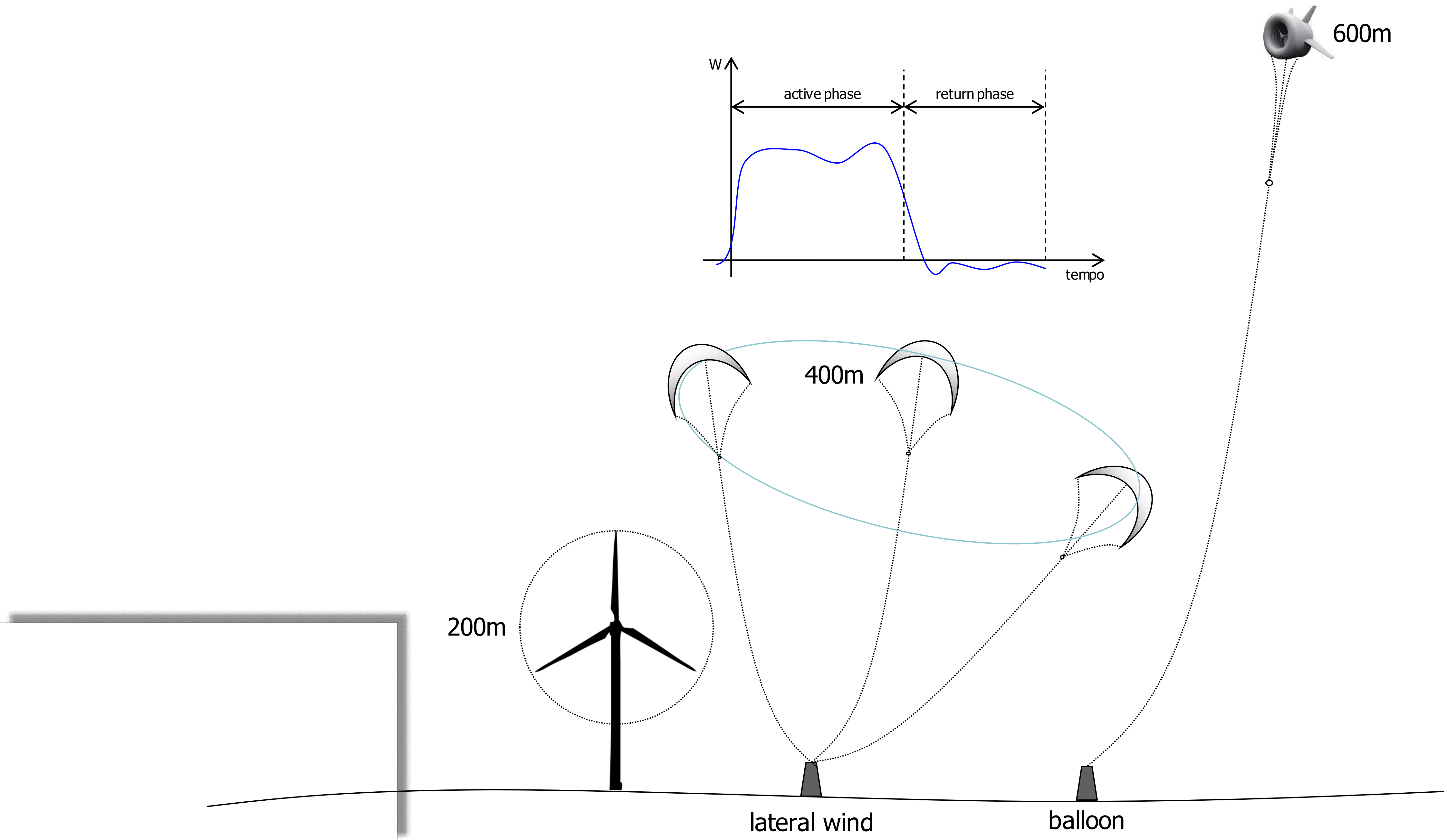
25% reduction in CAPEX

Blade	2%
Controls/Sensors	3%
Drivetrain	2%
Generator	2%
Electrical	1%
Tower	2%
Pitch System	1%
Foundation	1%
Nacelle	1%
Pitch Control	2%
Condition Monitoring	2%
SCADA	2%
Yaw System	1%
Castings/Forgings	1%
Systems	1%
Yaw Control	1%

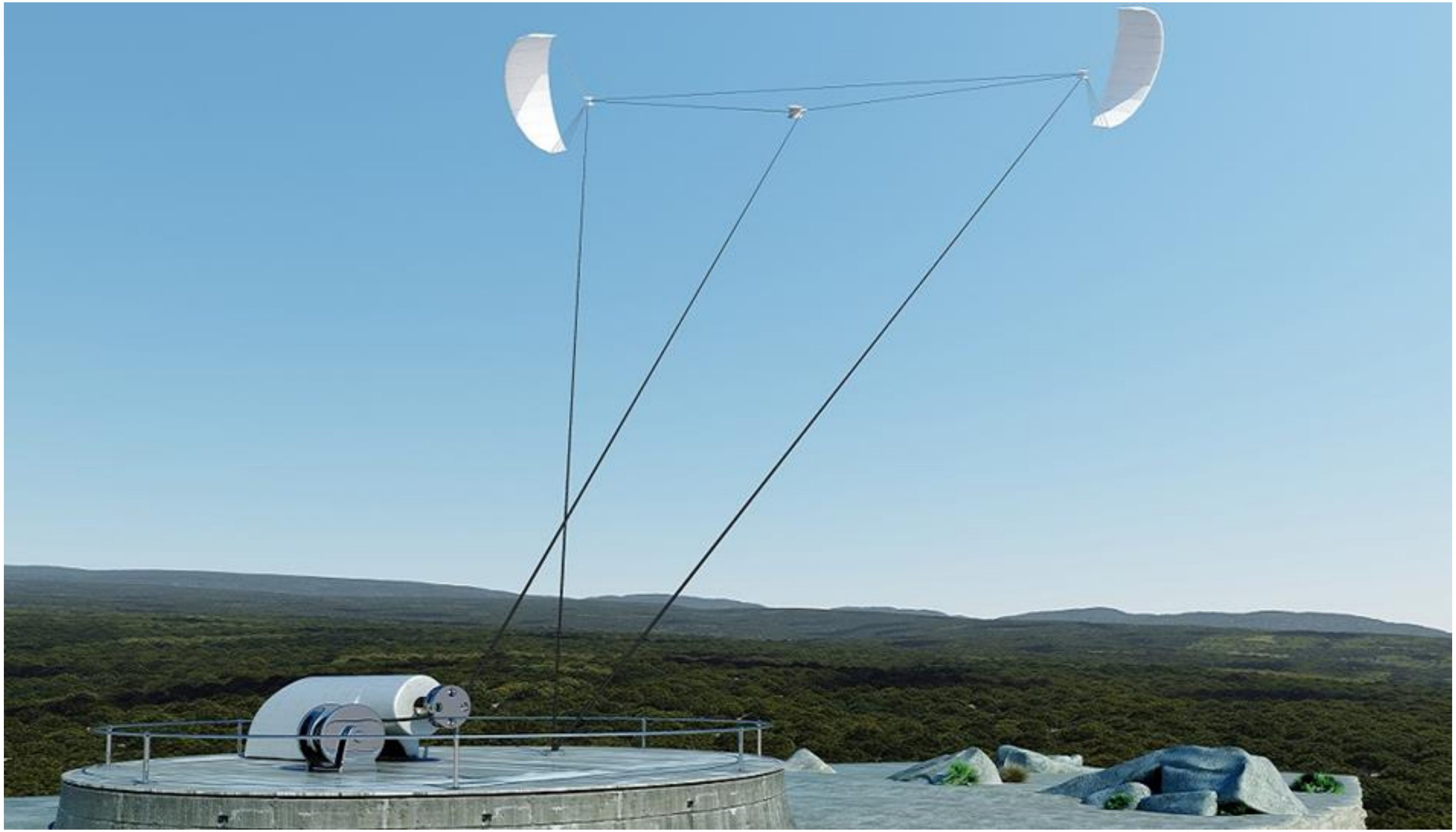
2025 LCOE 3,75 ¢/kWh

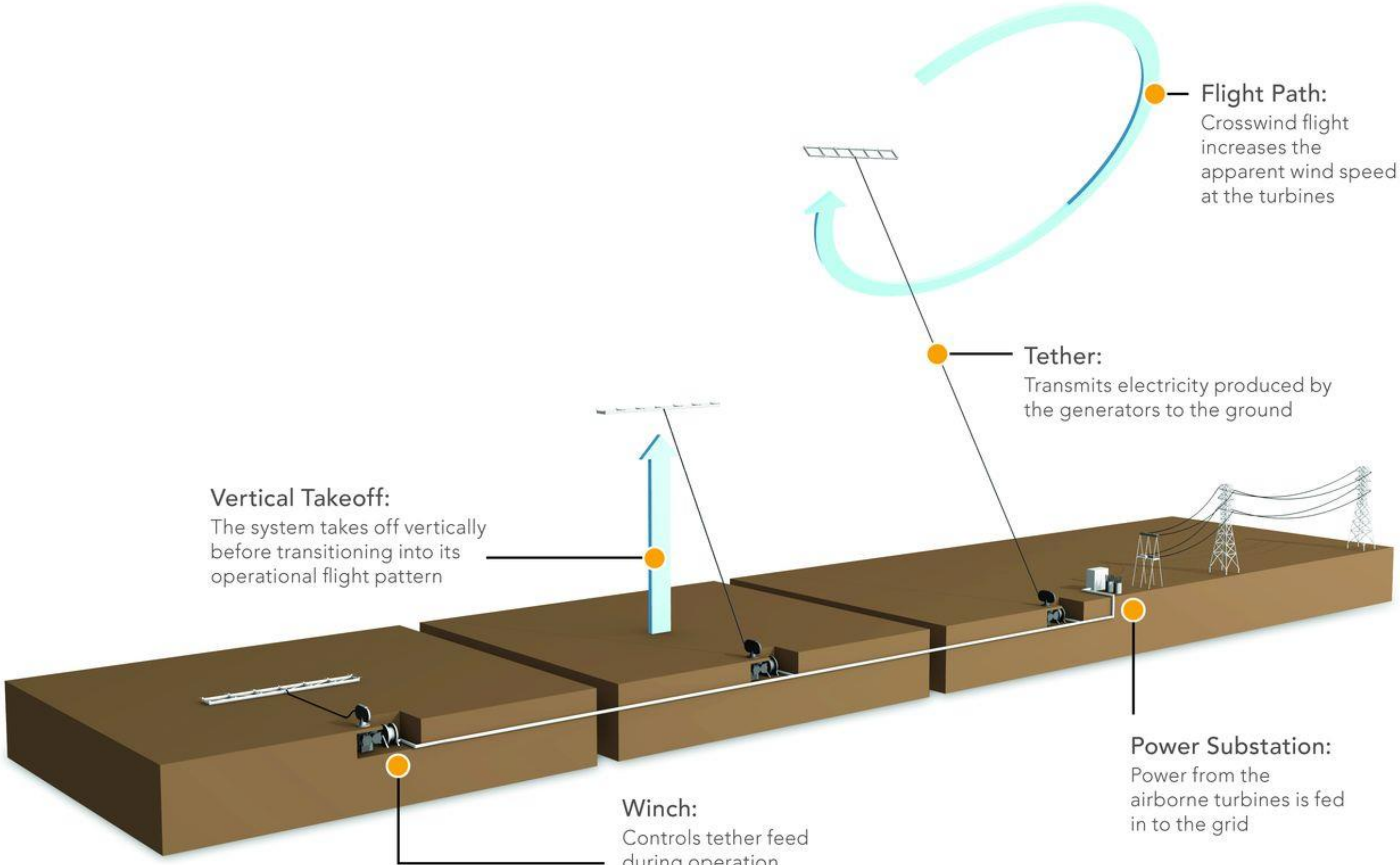




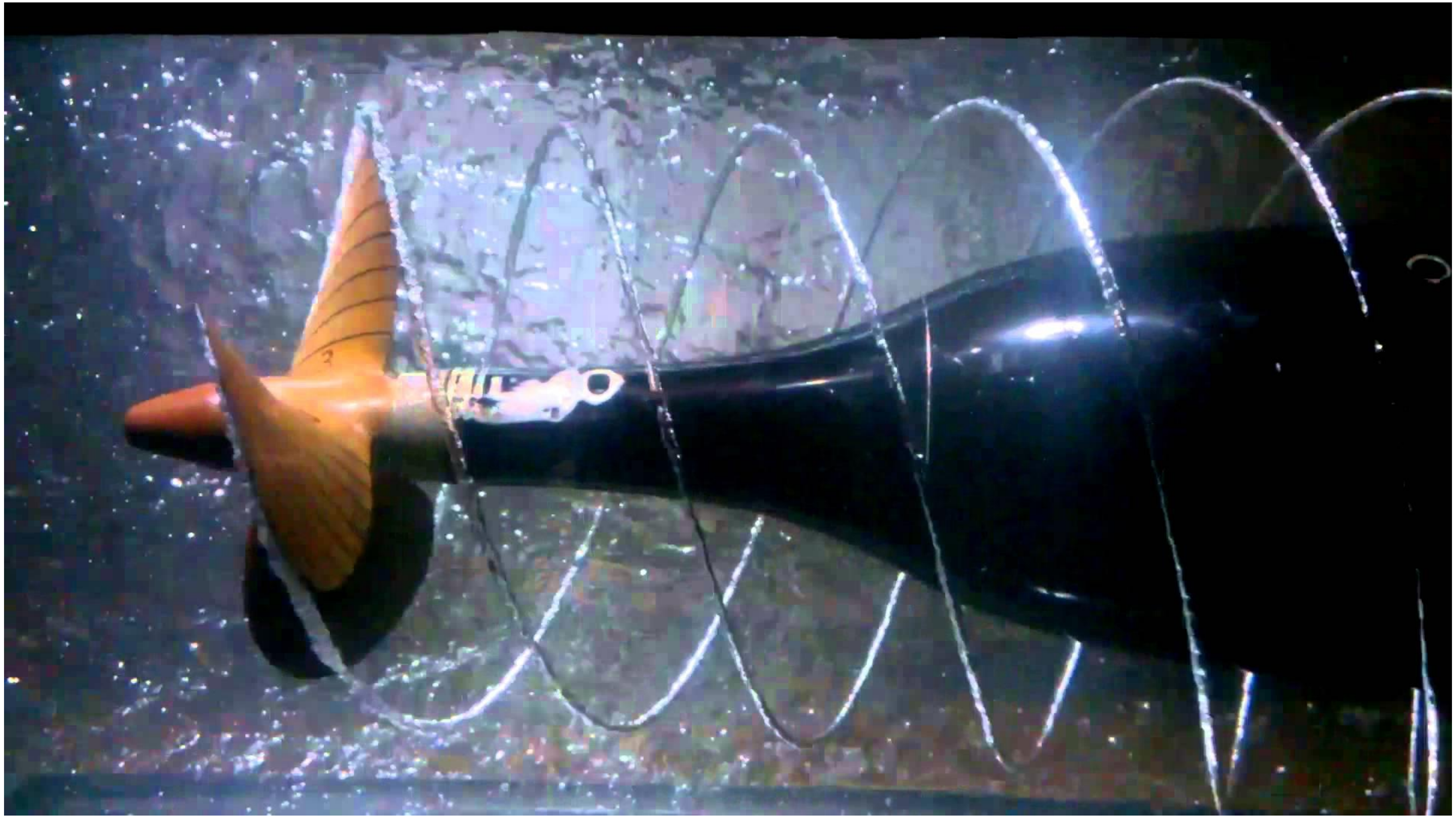


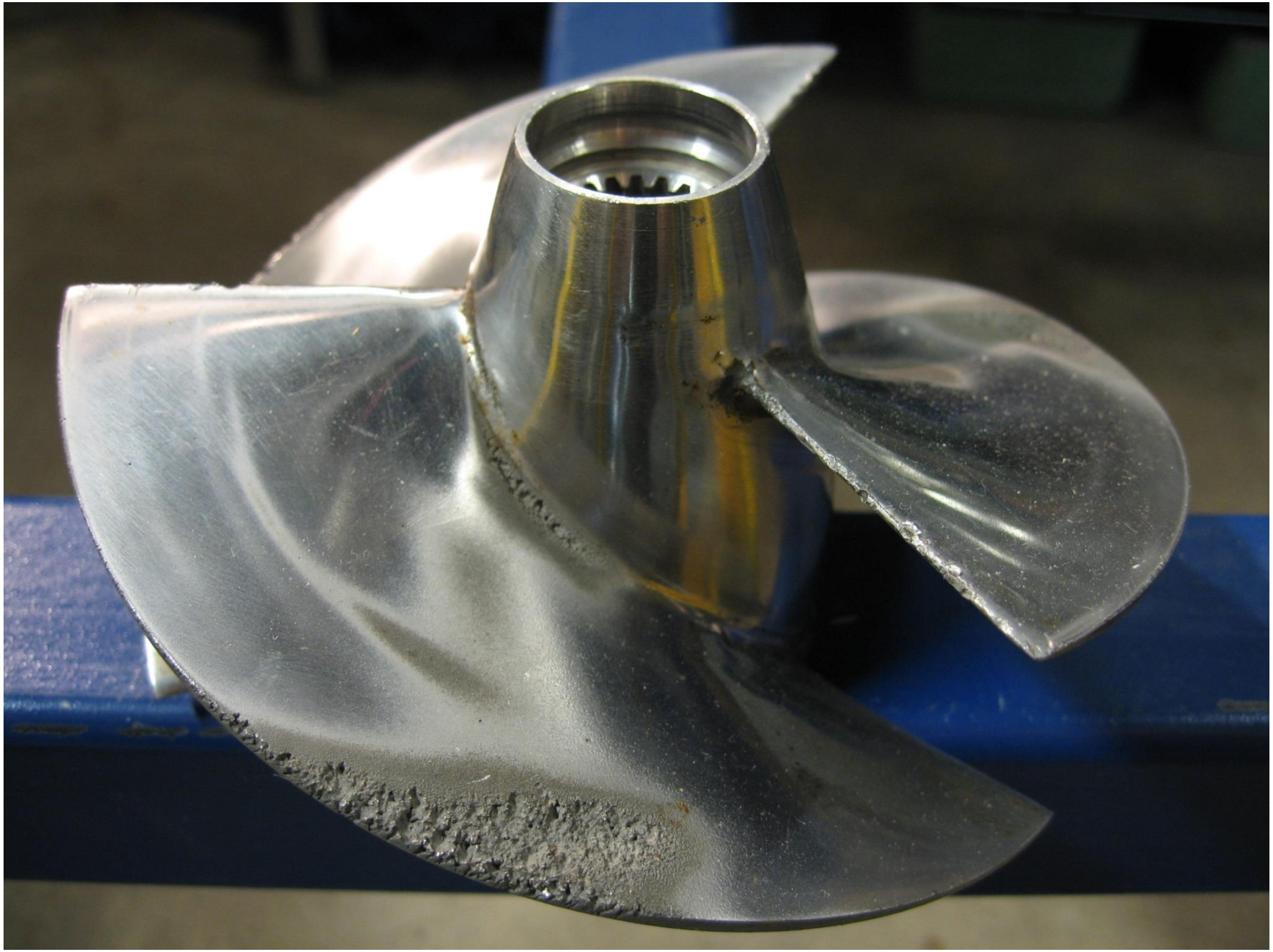
W
active phase
return phase
tempo
600m
400m
200m
lateral wind
balloon




Flight Path:
Crosswind flight increases the apparent wind speed at the turbines
Tether:
Transmits electricity produced by the generators to the ground
Vertical Takeoff:
The system takes off vertically before transitioning into its operational flight pattern
Winch:
Controls tether feed during operation
Power Substation:
Power from the airborne turbines is fed in to the grid

COURTESY OF MEYGEN





HYDROELECTRIC POWER PLANTS:
design and operation

Rank	Name	Country	River	Installed capacity (MW)	Annual electricity production (TW-hour)[5]	Years of completion	Area flooded (km²)
1	Three Gorges Dam	China	Yangtze	22,500	98.8[6]	2008	
2	Itaipu Dam	Brazil Paraguay	Paraná	14,000	98.6[1]	1984/1991, 2003[7]	1,350
3	Xiluodu	China	Jinsha	13,860[8]		2014[9]	
4	Guri	Venezuela	Caroní	10,235	53.41	1978, 1986	4,250
5	Tucuruí	Brazil	Tocantins	8,370	41.43	1984	3,014
6	Grand Coulee	United States	Columbia	6,809	20[10]	1942/1950, 1973, 1975/1980, 1984/1985[11]	324
7	Xiangjiaba	China	Jinsha	6,448		2014[12]	
8	Longtan Dam	China	Hongshui	6,426	18.7[13]	2007/2009	
9	Sayano–Shushenskaya	Russia	Yenisei	6,400	26.8	1985/1989, 2010/2014[14]	621
10	Krasnoyarsk	Russia	Yenisei	6,000	15	1972	2,000
11	Nuozhadu	China	Mekong	5,850		2014[15]	
12	Robert-Bourassa	Canada	La Grande	5,616[16][17]	26.5	1979/1981	2,835
13	Churchill Falls	Canada	Churchill	5,428[18]	35	1971/1974	6,988
14	Jinping-II	China	Yalong	4,800		2014	
15	Bratsk	Russia	Angara	4,500	22.6	1967	5,470
16	Laxiwa Dam	China	Yellow	4,200[19]	10.2	2010	
17	Xiaowan Dam	China	Mekong	4,200[20]	19	2010	190
18	Ust Ilimskaya	Russia	Angara	3,840	21.7	1980	
19	Jinping-I	China	Yalong	3,600		2014	
20	Tarbela Dam	Pakistan	Indus	3,478	13	1976	250
21	Ilha Solteira Dam	Brazil	Paraná	3,444	17.9	1973	
22	Ertan Dam	China	Yalong	3,300	17	1999	
23	Pubugou Dam	China	Dadu	3,300	14.6	2009/2010	
24	Macagua	Venezuela	Caroní	3,167.5	15.2	1961/1996	47.4
25	Xingó Hydroelectrical Power Plant	Brazil	São Francisco	3,162	18.7[21]	1994/1997	
26	Yacyretá	Argentina Paraguay	Paraná	3,100	20.09	1994/1998, 2011	1,600
27	Nurek Dam	Tajikistan	Vakhsh	3,015	11.2	1972/1979, 1988	98
28	Bath County PSP	United States	-	3,003	3.32	1985, 2004	
29	Goupitan Dam	China	Wu	3,000[22]	9.67	2009/2011	94
30	Guanyinyan Dam	China	Jinsha	3,000	13.62	2014/2016	
31	Boguchany Dam	Russia	Angara	2,997	17.6	2012/2014	2,326
32	W. A. C. Bennett Dam	Canada	Peace	2,876	13.1	1968, 2012	
33	La Grande-4	Canada	La Grande	2,779[17]		1986	765
34	Gezhouba Dam	China	Yangtze	2,715	17.01	1988	
35	Manic-5 and Manic-5-PA	Canada	Manicouagan	2,656[23]		1970/1971, 1989/1990	1,950

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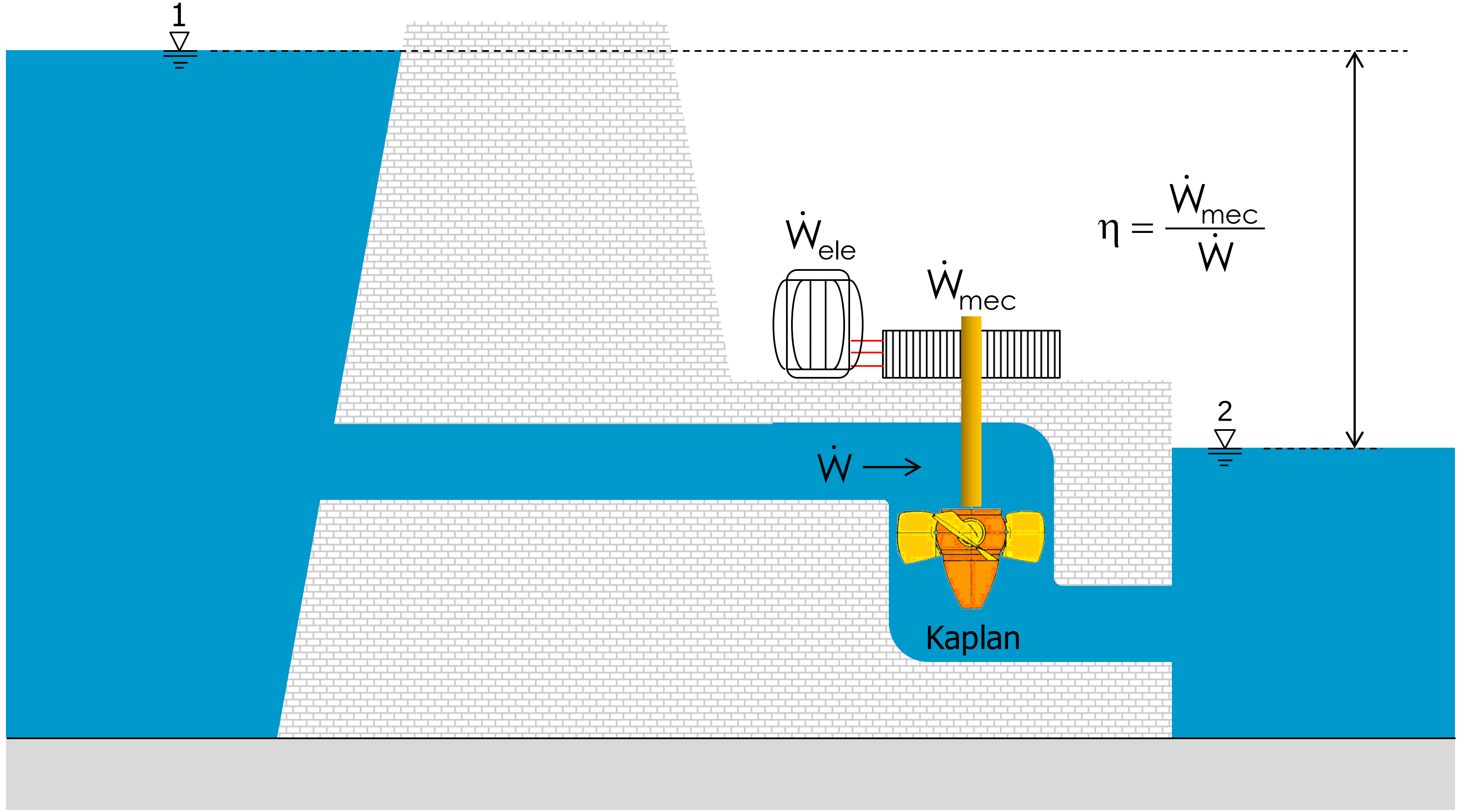
25	Xingó Hydroelectrical Power Plant	Brazil	São Francisco	3,162	18.7[21]	1994/1997	
26	Yacyretá	Argentina Paraguay	Paraná	3,100	20.09	1994/1998, 2011	1,600
27	Nurek Dam	Tajikistan	Vakhsh	3,015	11.2	1972/1979, 1988	98
28	Bath County PSP	United States	-	3,003	3.32	1985, 2004	
29	Goupitan Dam	China	Wu	3,000[22]	9.67	2009/2011	94
30	Guanyinyan Dam	China	Jinsha	3,000	13.62	2014/2016	
31	Boguchany Dam	Russia	Angara	2,997	17.6	2012/2014	2,326
32	W. A. C. Bennett Dam	Canada	Peace	2,876	13.1	1968, 2012	
33	La Grande-4	Canada	La Grande	2,779[17]		1986	765
34	Gezhouba Dam	China	Yangtze	2,715	17.01	1988	
35	Manic-5 and Manic-5-PA	Canada	Manicouagan	2,656[23]		1970/1971, 1989/1990	1,950

Power generation	
Nameplate capacity	22,500 MW
Capacity factor	45%
Annual generation	87 TWh (310 PJ) (2015)
Turbines	32 × 700 MW 2 × 50 MW Francis-type

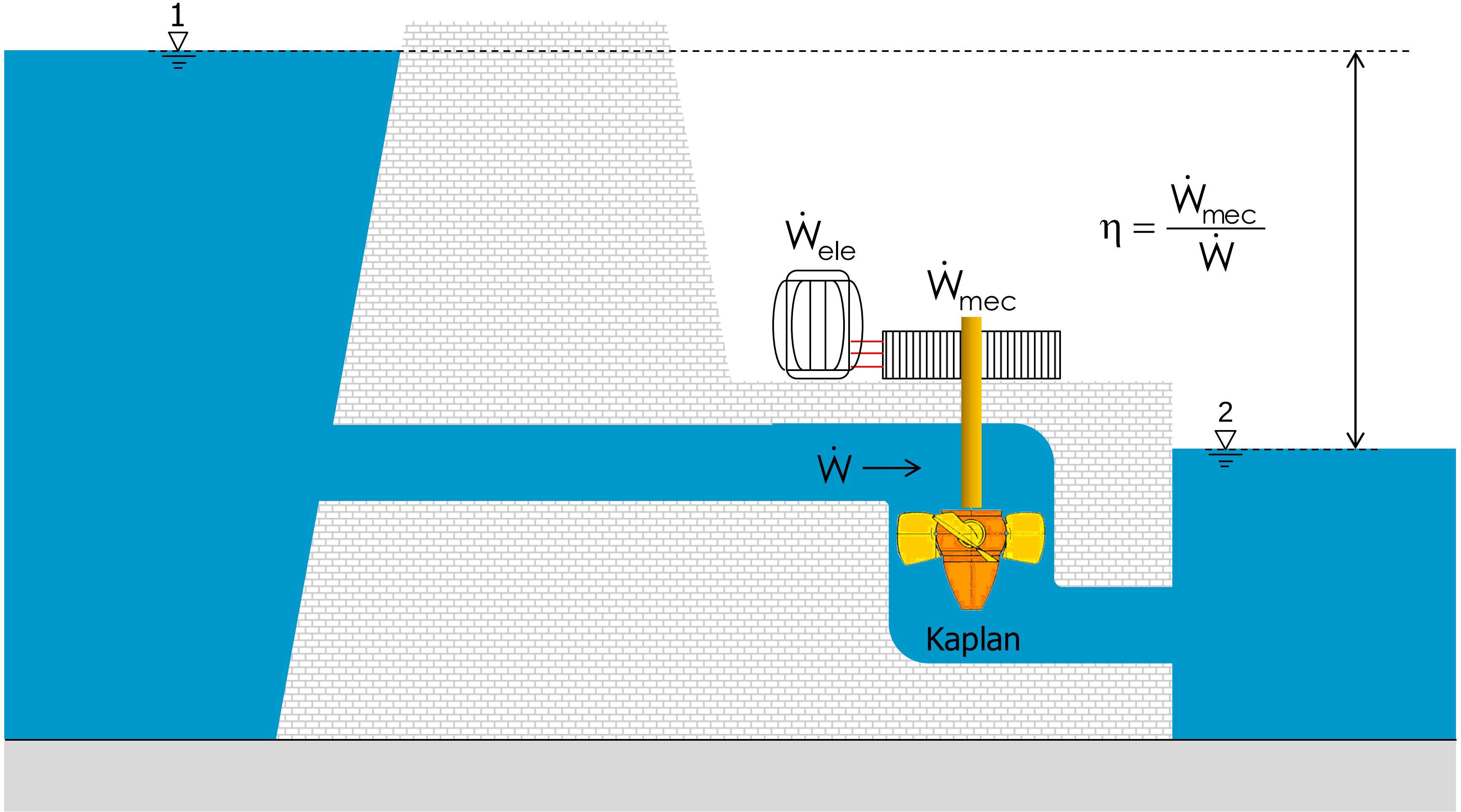
Power station	
Type	Conventional
Hydraulic head	118 m (387 ft)
Turbines	20 × 700 MW (940,000 hp) Francis-type
Installed capacity	14 GW (19,000,000 hp)
Annual generation	89.5 TWh (322 PJ)

Usina	Itaipu	Três Gargantas
Turbinas	20	32+2 (6 subterrâneas)
Potência nominal	700 MW	700 MW
Potência instalada	14.000 MW	22.500 MW (prevista)
Recorde de produção anual	93,4 bilhões kWh/ano (2000)	61,6 bilhões kWh/ano (2007)
Concreto utilizado	12,57 milhões m^3	27,94 milhões m^3
Altura	196 metros	181 metros
Comprimento da barragem	7.750 metros	4.149 metros
Vertedouro	62.200 m^3/s	102.600 m^3/s
Escavações	63,85 milhões m^3	102,59 milhões m^3

Reservatório	Itaipu	Três Gargantas
Extensão	170 km	600 km
Área	1.350 km^2	1.084 km^2
Armazenamento	29 km^3	39,3 km^3
Nível normal de operação	220 m	175 m
Número de pessoas reassentadas	40 mil	1,13 milhão

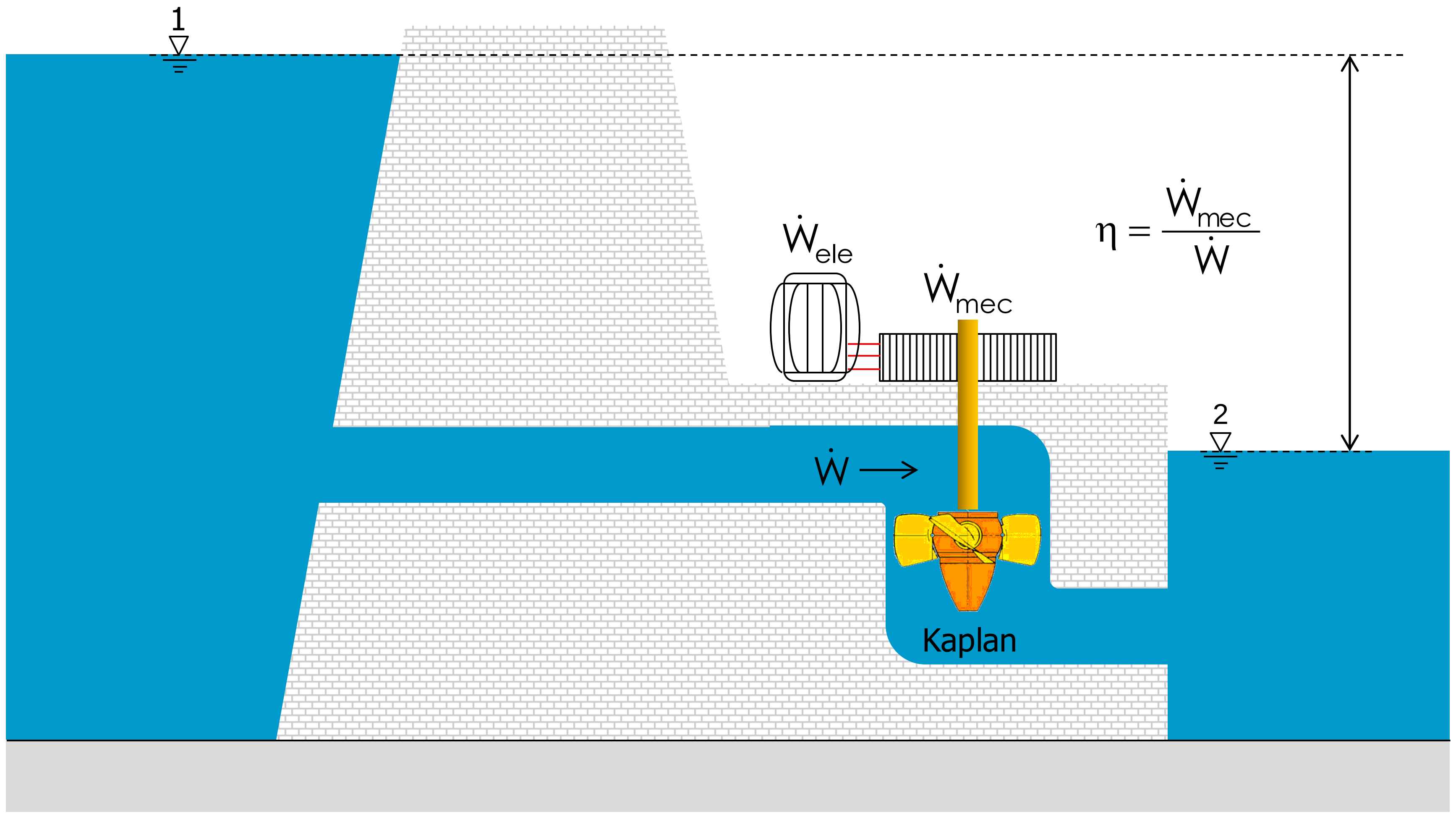


$$\dot{W} = \dot{m} \cdot \left[\left(P_1/\rho_1 + gz_1 + V_1^2/2\right) - \left(P_2/\rho_2 + gz_2 + V_2^2/2\right)\right]$$



$$\dot{W} = \dot{m} \cdot \left[\left(P_1/\rho_1 + gz_1 + V_1^2/2 \right) - \left(P_2/\rho_2 + gz_2 + V_2^2/2 \right) \right]$$

$$\dot{W} = \dot{m} \cdot \left[\left(P_1/\rho_1 - P_2/\rho_2 \right) + g\left(z_1 - z_2 \right) + \left(V_1^2/2 - V_2^2/2 \right) \right]$$



$$\dot{W} = \dot{m} g \Delta z$$

Hydroelectric Power Generation Potential in the World

$$\dot{W} = \dot{m} g \Delta z$$

Average continental height: 840m

Average annual pluviosity: $505 \cdot 10^3$ km^3

- at sea: $398 \cdot 10^3$ km^3
- on land: $107 \cdot 10^3$ km^3

$$\dot{W}_{max,teo} = \frac{107 \cdot 10^3 \cdot (10^3 m)^3}{365 \times 24 \times 3600 s} \cdot 997 \frac{kg}{m^3} \cdot 9{,}8 \frac{m}{s^2} \cdot 840 m$$

$$\dot{W}_{max,theo} = 27{,}8\ TW$$

Assuming that all in land precipitation can be used for power generation

Hydroelectric Power Generation Potential in the World

$$\dot{W}_{max,UNDP} = 3{,}84\,TW$$

World Energy Assessment: 2004 - United Nations Development Programme

$$\dot{W}_{cons,2012} = 2{,}21\,TW$$

The potential growth of hydroelectric generation is substantially limited, however...

RESERVOIR:	Capacity of storing water for energy generation
COMPLEMENTARITY:	Stabilization of supply in face of fluctuations in generation conditions (intermittencies) and also of the demand

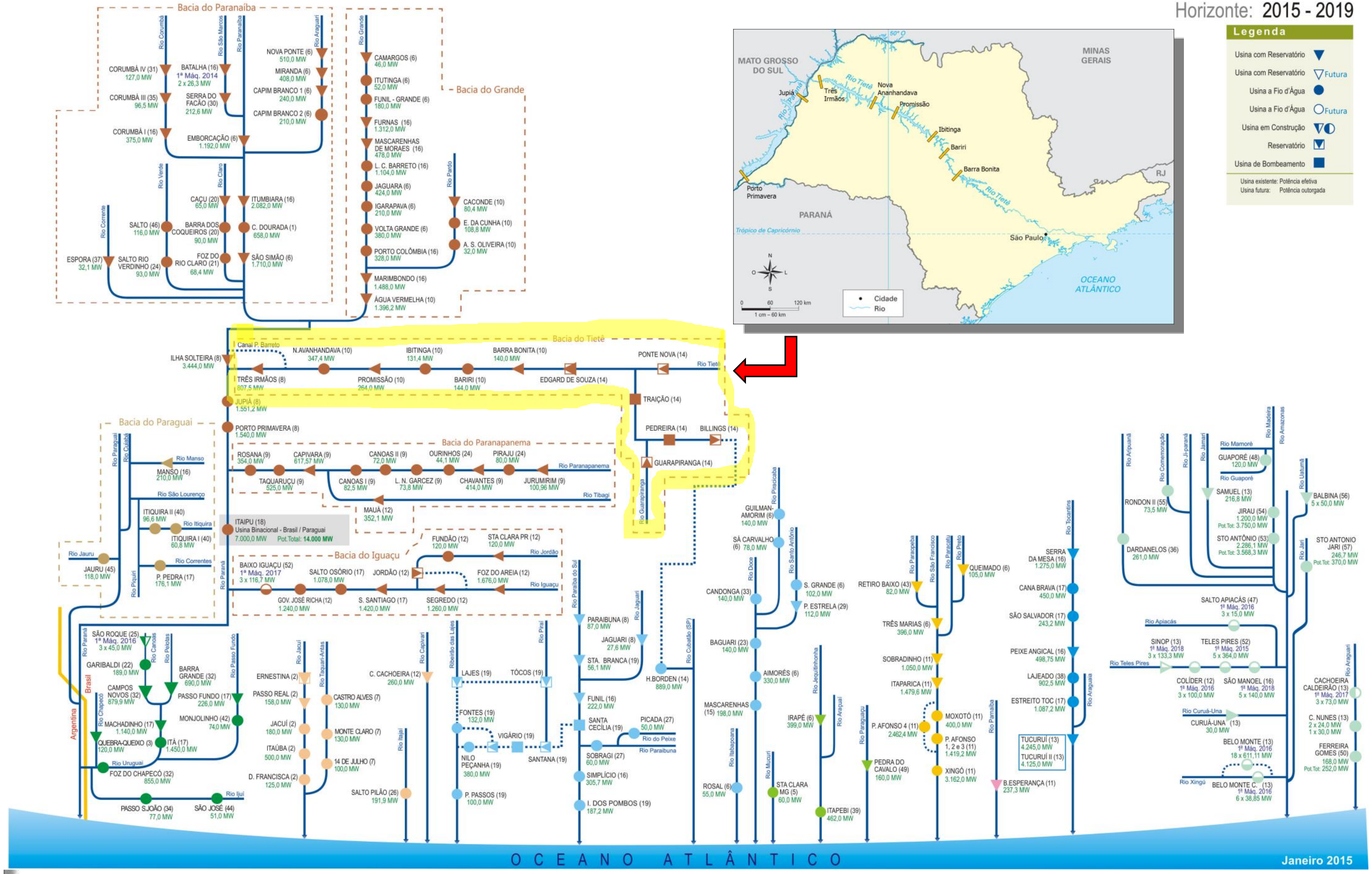

50° O
MATO GROSSO DO SUL
MINAS GERAIS
RJ
PARANÁ
Rio Paraná
Rio Tietê
Jupiá
Três Irmãos
Nova Ananhandava
Promissão
Ibitinga
Bariri
Barra Bonita
Rio Tietê
Porto Primavera
Trópico de Capricórnio
São Paulo
OCEANO ATLÂNTICO
N
O
L
S
0
60
120 km
1 cm – 60 km
Cidade
Rio

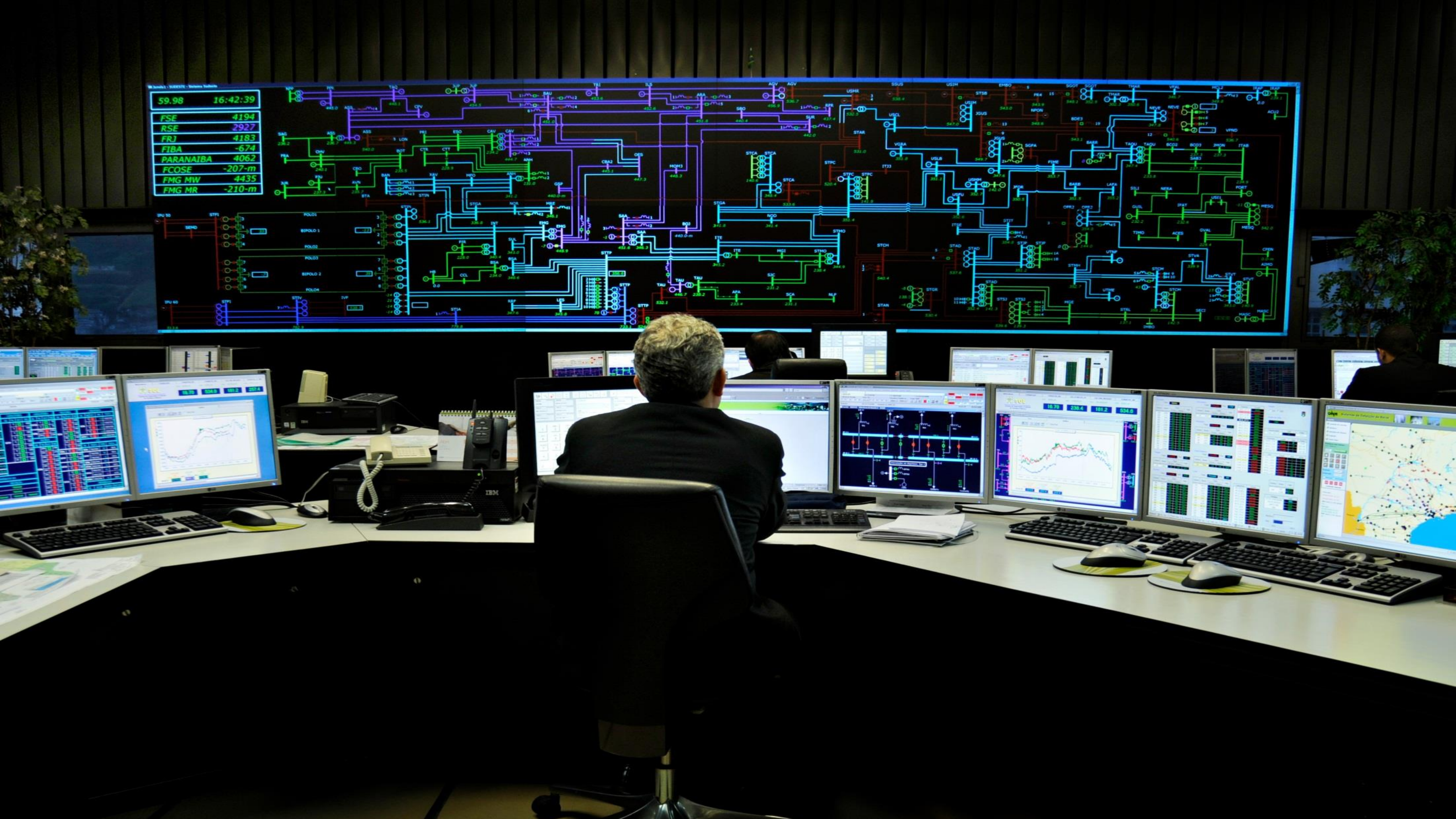
Diagrama Esquemático das Usinas Hidroelétricas do SIN

ONS Operador Nacional do Sistema Elétrico

Usinas Hidroelétricas Despachadas pelo ONS na Otimização da Operação Eletroenergética do Sistema Interligado Nacional

Horizonte: 2015 - 2019

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FSE 4194
RSE 2927
FRJ 4183
FIBA -674
PARANAIBA 4062
FCOSE -207-m
FMG MW 4435
FMG MR -210-m
IBM

Institutions of the Electricity Sector in Brazil

CNPE
National Counsel of Energy Policies

CMSE
Electrical Sector Monitoring Comity

MME
Mines and Energy Ministry

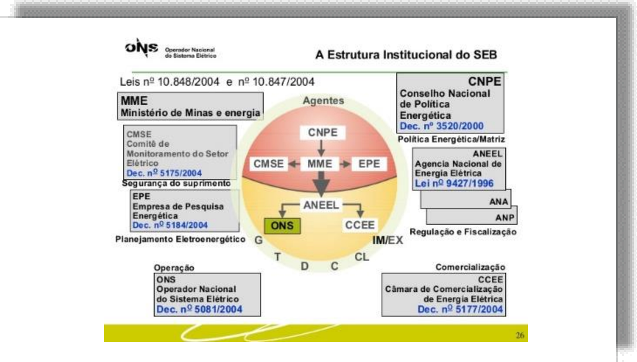
EPE
Energetic Research Corporation

ANEEL
Electrical Energy National Agency

CCEE
Electrical Energy Commercialization Chamber

ONS
National System Operator

Geradores
Distribuidores
Consumidores



Energy Bids Consolidated Results

	Documento	Descrição	Tipo de Documento	Data de referência
−	Resultado consolidado dos leilões - 02/2016	Planilha de fevereiro de 2016 com o resultado consolidado dos leilões.	Resultado Consolidado	15/02/2016

Nome do documento
Resultado consolidado dos leilões - 02/2016

Descrição
Planilha de fevereiro de 2016 com o resultado consolidado dos leilões.

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resultado_consolidado_leiloes_publicacao_fevereiro_2016.xlsx

	Documento	Descrição	Tipo de Documento	Data de referência
+	Resultado consolidado dos leilões - 01/2016	Planilha de janeiro de 2016 com o resultado consolidado dos leilões.	Resultado Consolidado	15/01/2016
+	Resultado consolidado dos leilões - 12/2015	Planilha de dezembro de 2015 com o resultado consolidado dos leilões.	Resultado Consolidado	15/12/2015
+	Resultado consolidado dos leilões - 11/2015	Planilha de novembro de 2015 com o resultado consolidado dos leilões.	Resultado Consolidado	16/11/2015
+	Resultado consolidado dos leilões - 10/2015	Planilha de outubro de 2015 com o resultado consolidado dos leilões.	Resultado Consolidado	19/10/2015
+	Resultado consolidado dos leilões - 09/2015 - Errata	Planilha de setembro de 2015 com o resultado consolidado dos leilões.	Resultado Consolidado	01/10/2015
+	Resultado consolidado dos leilões - 09/2015	Planilha de setembro de 2015 com o resultado consolidado dos leilões.	Resultado Consolidado	15/09/2015

Resultado Consolidado dos Leilões de Energia Elétrica por Contrato

Importante: O conteúdo desta publicação foi produzido pela CCEE com base em dados e informações de conhecimento público. É de responsabilidade exclusiva dos

Colunas referentes aos resultados originais dos leilões.
Colunas referentes às informações passíveis de alteração ou atualização, conforme regulamentação, que podem ser diferentes dos resultados originais dos leilões.

OBS.: NÃO UTILIZAR OS DADOS ANTES DE VERIFICAR A COLUNA "SITUAÇÃO" E AS PLANILHAS "GLOSSÁRIO" E "NOTAS EXPLICATIVAS".

Leilão (1)	Tipo de leilão	Produto	Sigla do vendedor (2)	Razão social do vendedor	CNPJ do vendedor	Sigla do comprador (3)	Razão social do comprador	CNPJ do comprador	Nome da usina (4)
01ºLEE	LEE	2005-8	CEEE	COMPANHIA ESTADUAL DE GERACAO E TRANSMISSAO D	92715812000131	AES SUL	AES - SUL DISTRIBUIDORA GAÚCHA DE ENERGIA S.A.	02016440000162	-
01ºLEE	LEE	2005-8	CEEE	COMPANHIA ESTADUAL DE GERACAO E TRANSMISSAO D	92715812000131	AMPLA	AMPLA ENERGIA E SERVIÇOS S.A.	33050071000158	-
01ºLEE	LEE	2005-8	CEEE	COMPANHIA ESTADUAL DE GERACAO E TRANSMISSAO D	92715812000131	BANDEIRANTE	BANDEIRANTE ENERGIA S.A.	02302100000106	-
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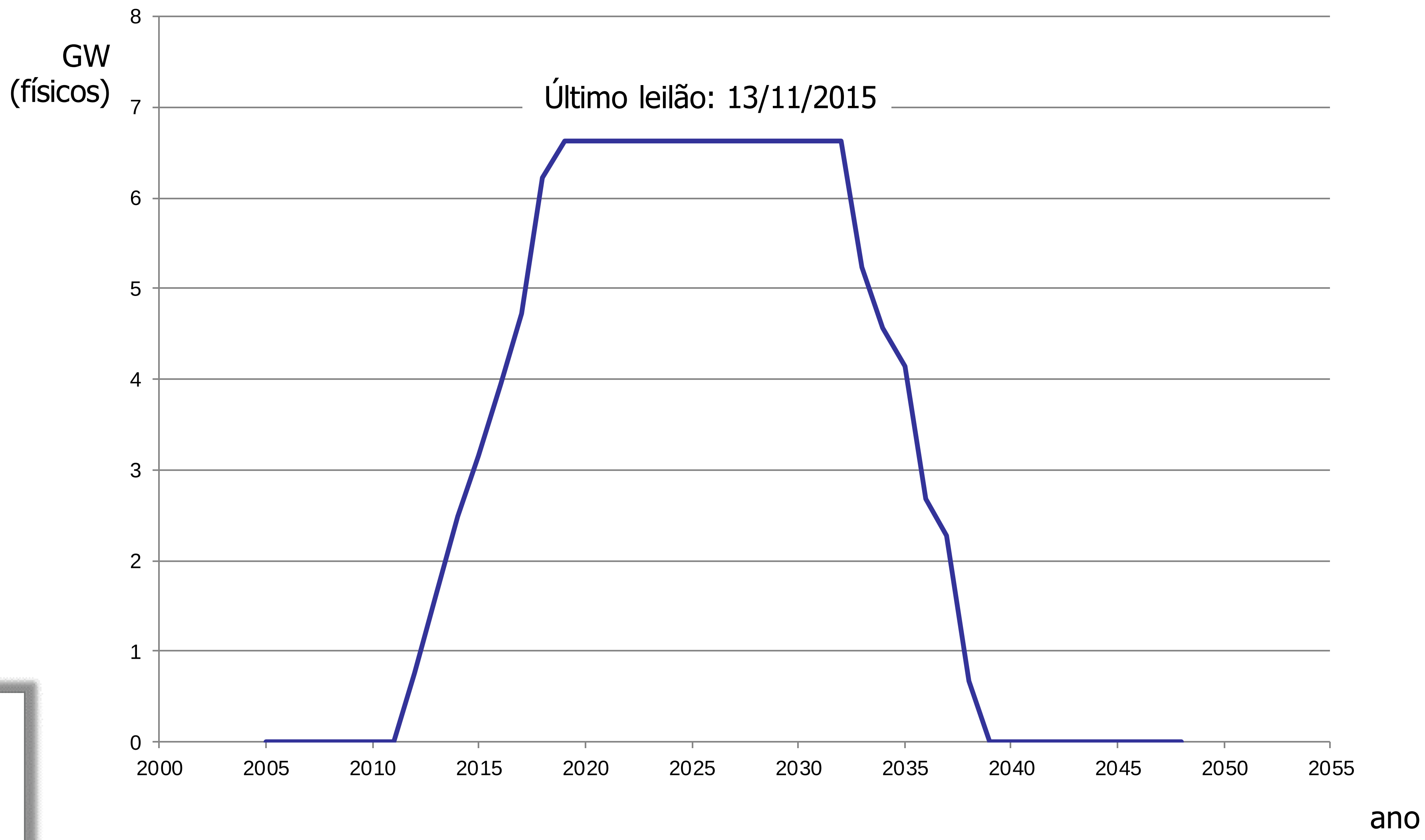
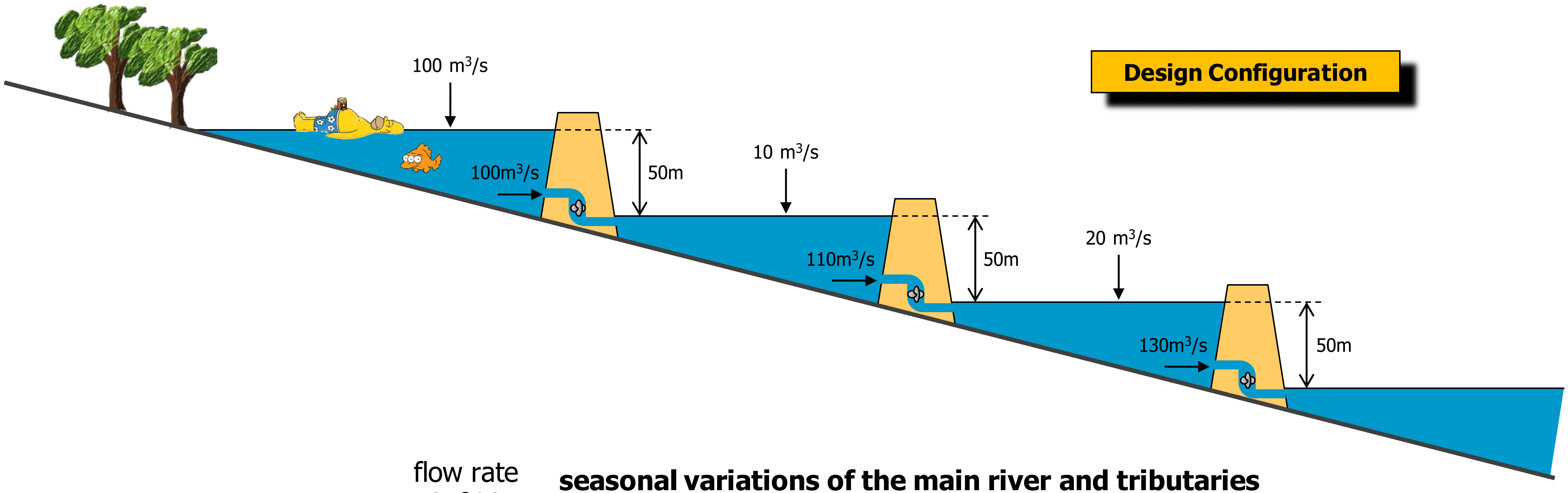
Leia-me | Glossário | Notas Explicativas | Resumo de alterações | Resultado Consolidado Leilões | Resultado Original Comprador | Resultado Original Vendedor

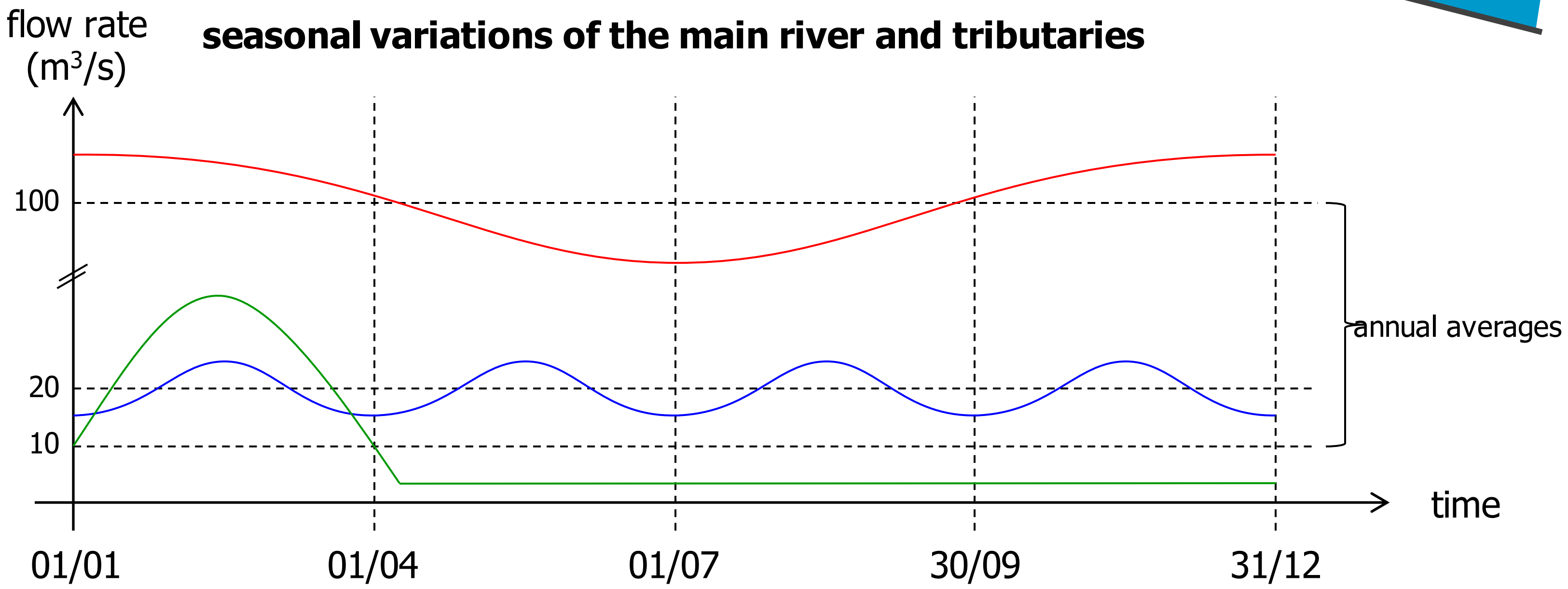
Energy Bids Consolidated Results



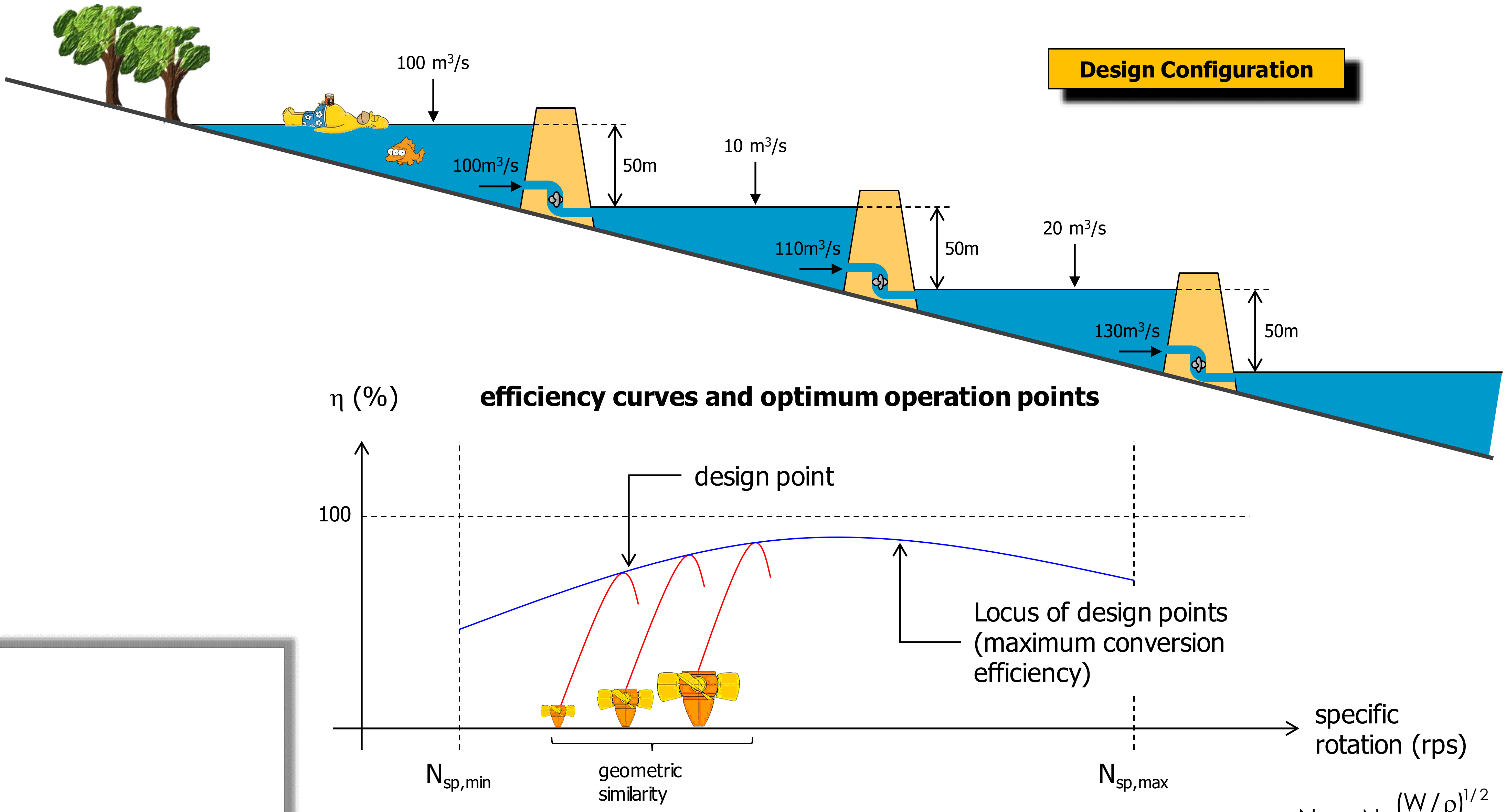
APPLICATION EXAMPLE:
optimized design and operation

HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION



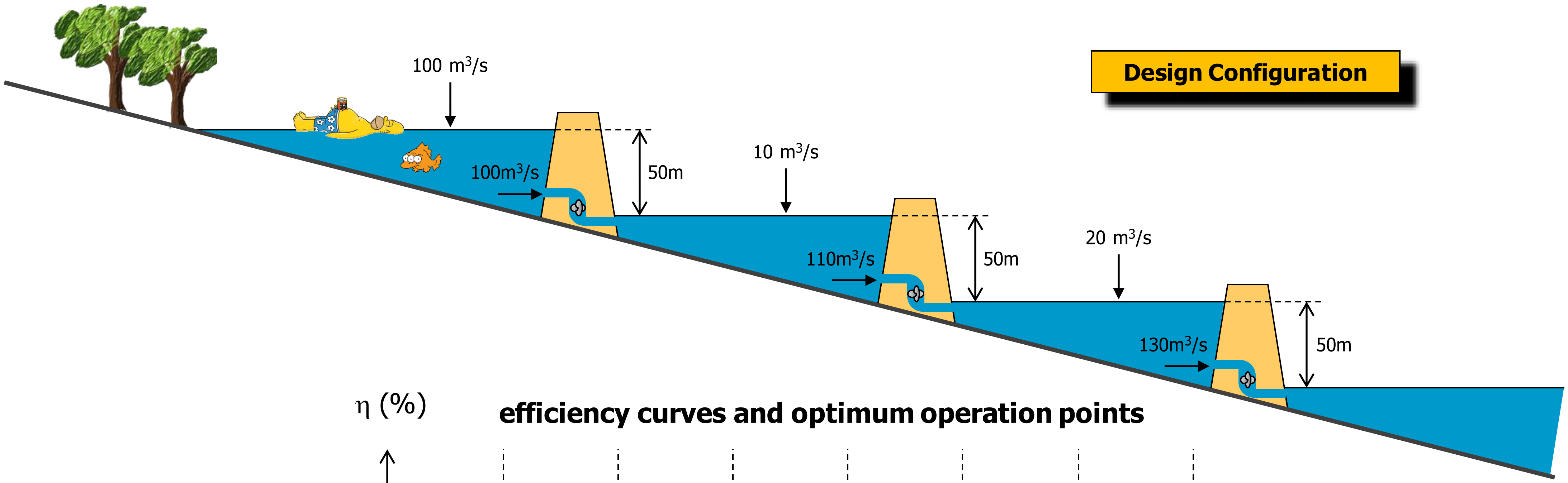


HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION

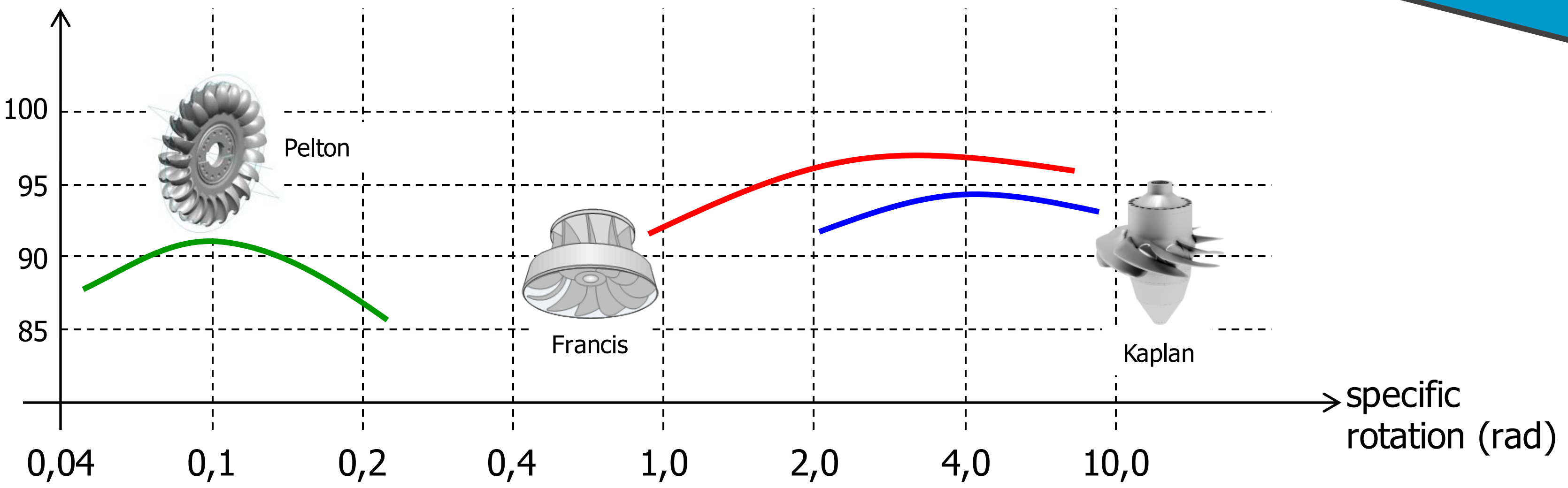


$$N_{sp} = N \cdot \frac{(W/\rho)^{1/2}}{(g\Delta H)^{5/4}}$$

HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION

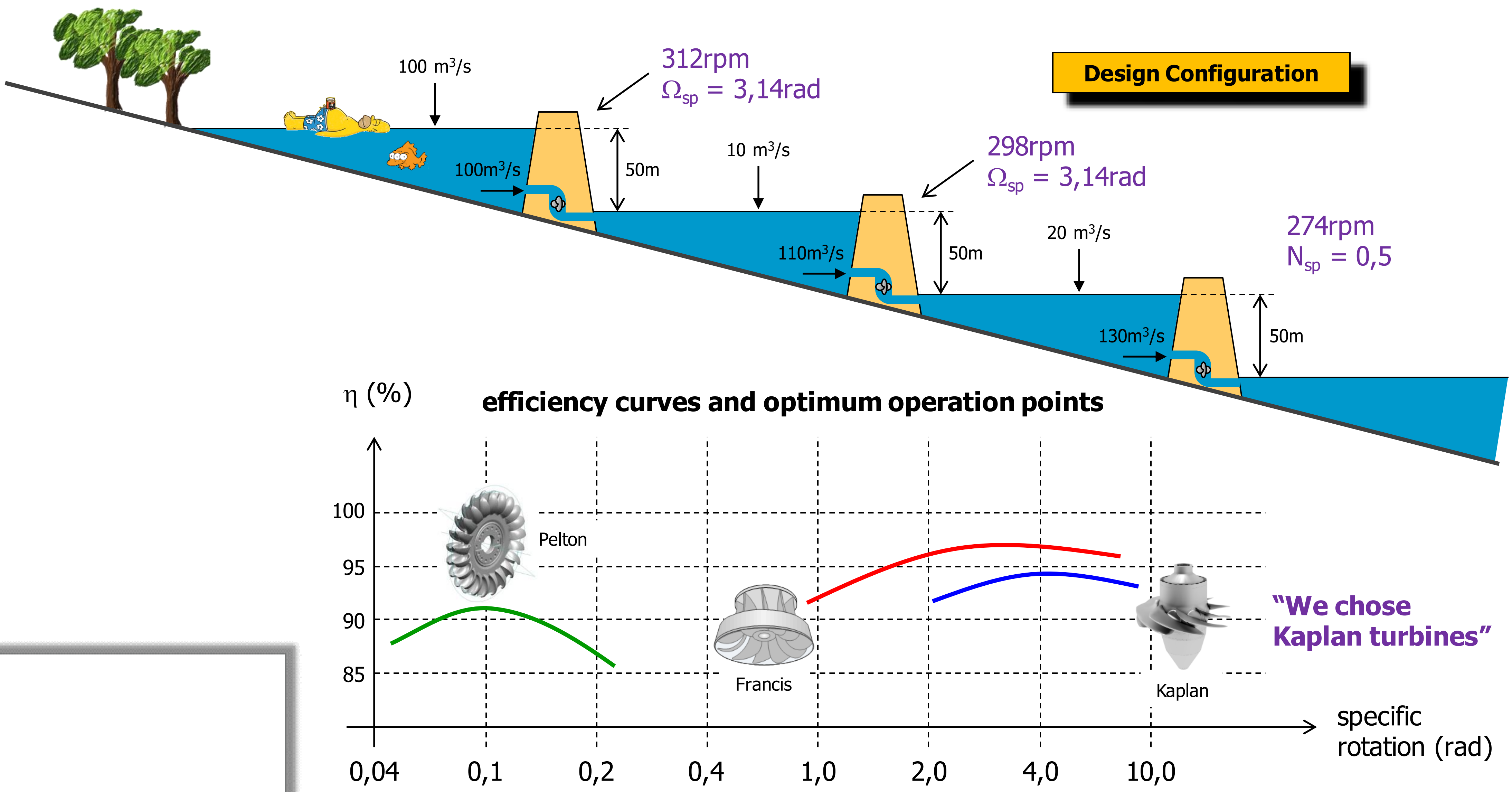


efficiency curves and optimum operation points



$$\Omega_{sp} = \Omega \cdot \frac{(W/\rho)^{1/2}}{(g\Delta H)^{5/4}}$$

HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION



$$\Omega_{sp} = \Omega \cdot \frac{(W/\rho)^{1/2}}{(g\Delta H)^{5/4}}$$

HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION

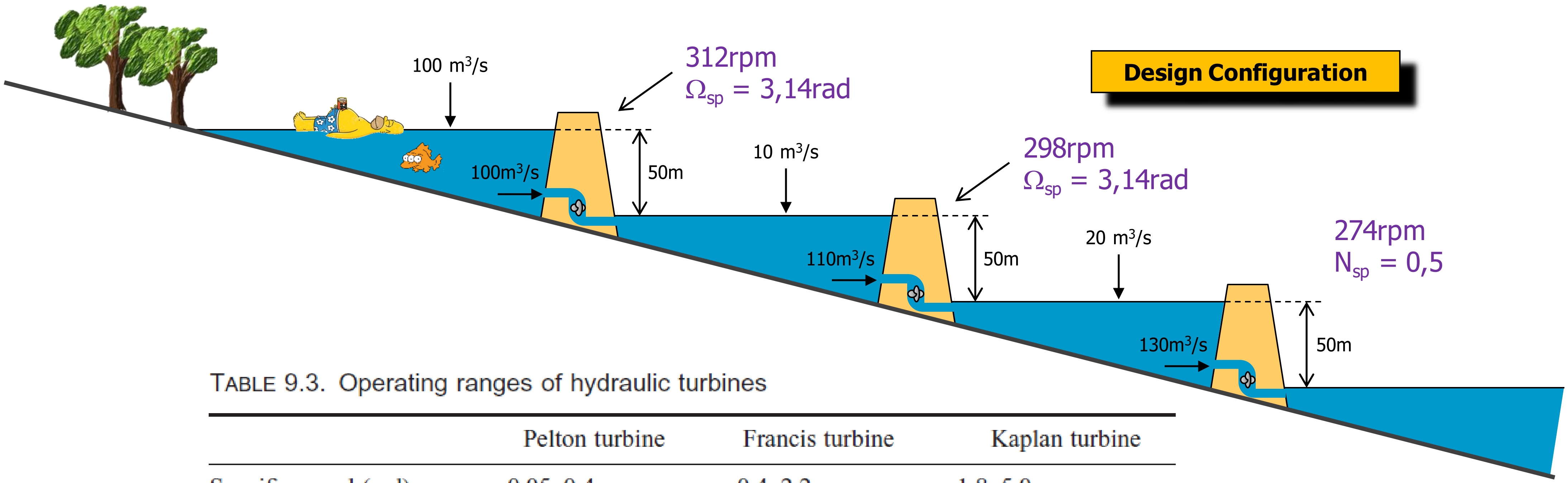
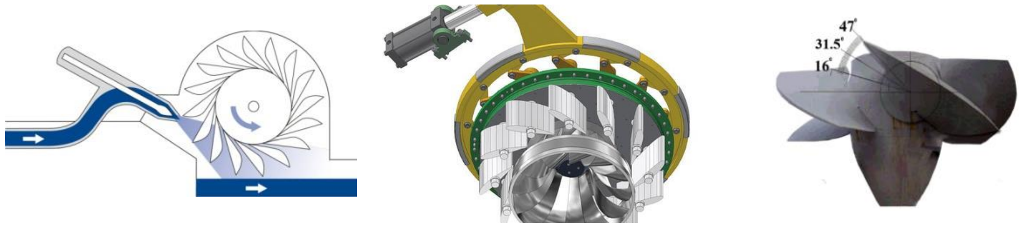


TABLE 9.3. Operating ranges of hydraulic turbines

	Pelton turbine	Francis turbine	Kaplan turbine
Specific speed (rad)	0.05–0.4	0.4–2.2	1.8–5.0
Head (m)	100–1770	20–900	6–70
Maximum power (MW)	500	800	300
Optimum efficiency, %	90	95	94
Regulation method	Needle valve and deflector plate	Stagger angle of guide vanes	Stagger angle of rotor blades



HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION

The design is based on nominal parameters (annual or pluriannual averages) that result in an optimized performance (maximum efficiency)

Operating parameters vary with respect to nominal parameters (tributaries flow rates e.g.)

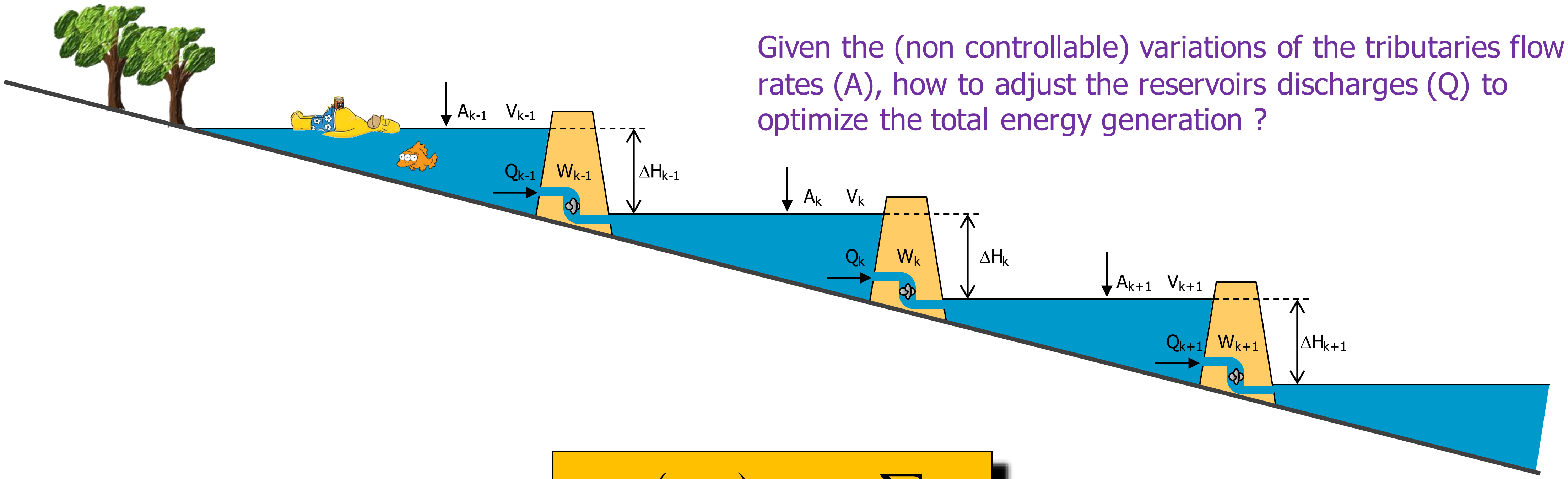
The problem: how to adjust the overall system operation, acting on controllable variables, in order to optimize performance ?

$$\max\left(\Phi_{sist}\right) = \max \sum_{k} \Phi_k$$ → performance criterium

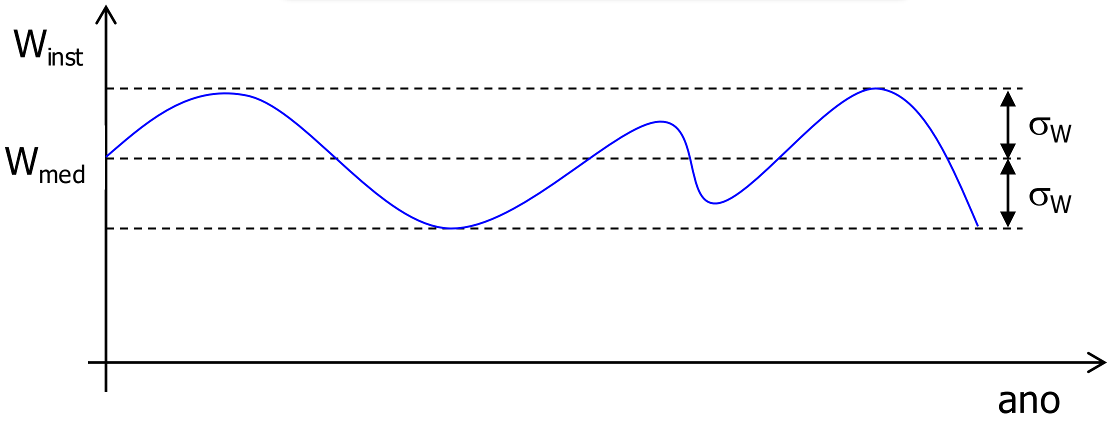
$$\max\left(\Phi_{sist}\right) = \max \prod_{k} \Phi_k$$ → performance criterium

HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION

Given the (non controllable) variations of the tributaries flow rates (A), how to adjust the reservoirs discharges (Q) to optimize the total energy generation ?



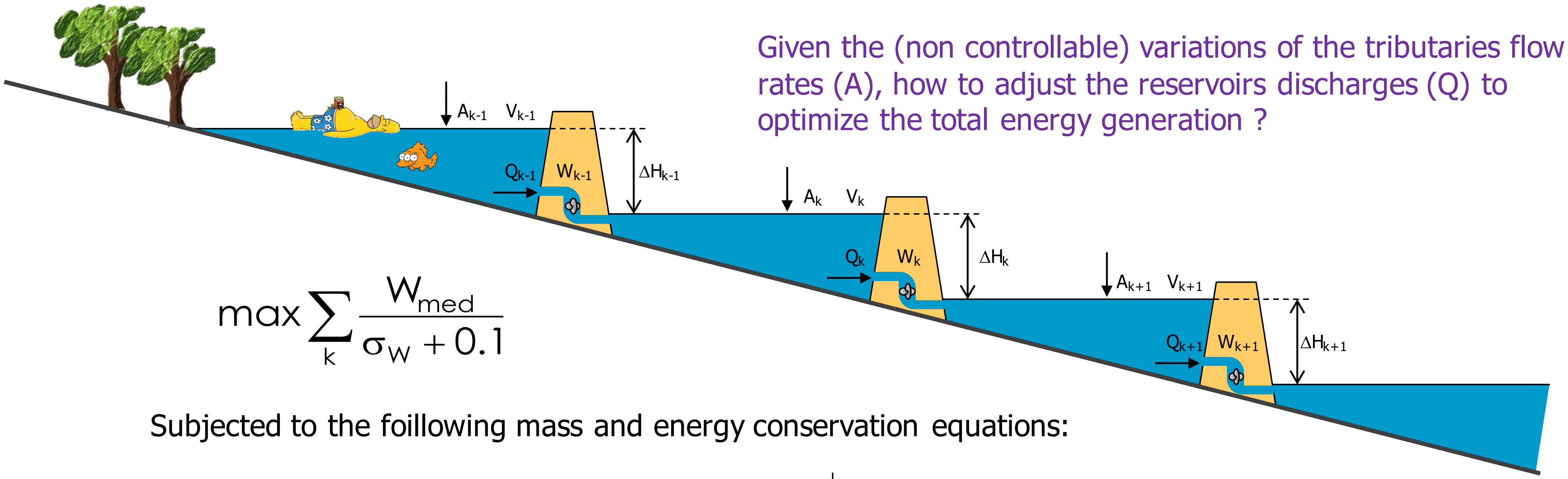
$$\max\left(\Phi_{sist}\right) = \max \sum_k \Phi_k$$



$$\Phi_{sist} \stackrel{def}{=} \sum_k \frac{W_{med}}{\sigma_W + 0.1}$$

$W_{med} \uparrow$ $\sigma_W \downarrow$

HYDROELECTRIC POWER PLANTS OPTIMIZED OPERATION



Given the (non controllable) variations of the tributaries flow rates (A), how to adjust the reservoirs discharges (Q) to optimize the total energy generation ?

$$\max \sum_k \frac{W_{med}}{\sigma_W + 0.1}$$

Subjected to the foillowing mass and energy conservation equations:

$$\frac{dV_k}{dt} = Q_{k-1} + A_k - Q_k$$

$$\dot{W}_k = \rho g \eta_k Q_k \Delta H_k$$

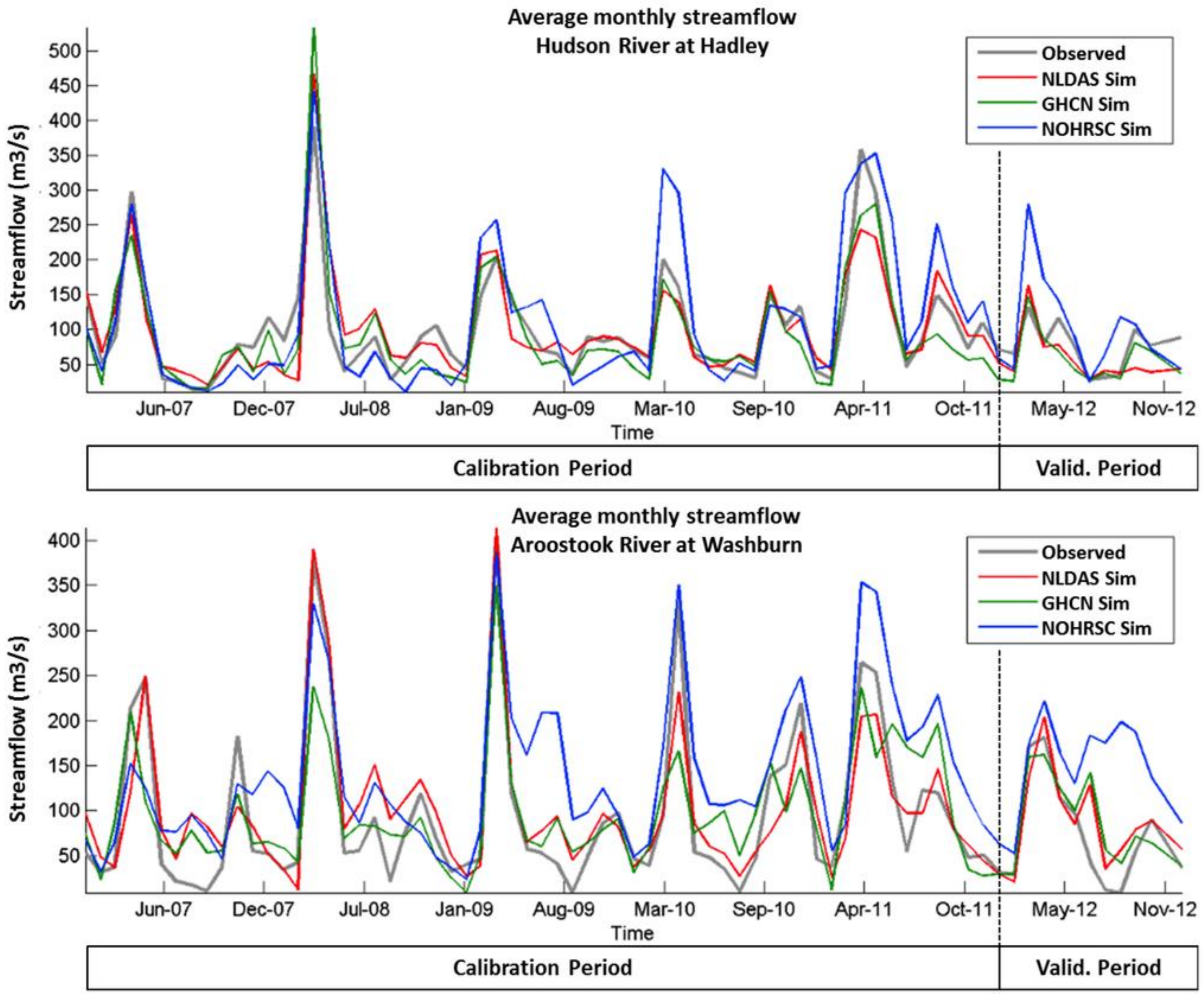
$$E_k = \int_T \dot{W}_k \cdot dt$$

To which the following performance characterization equation apply

$$\eta_k = \eta_k(N_{sp,k})$$ Efficiency curves

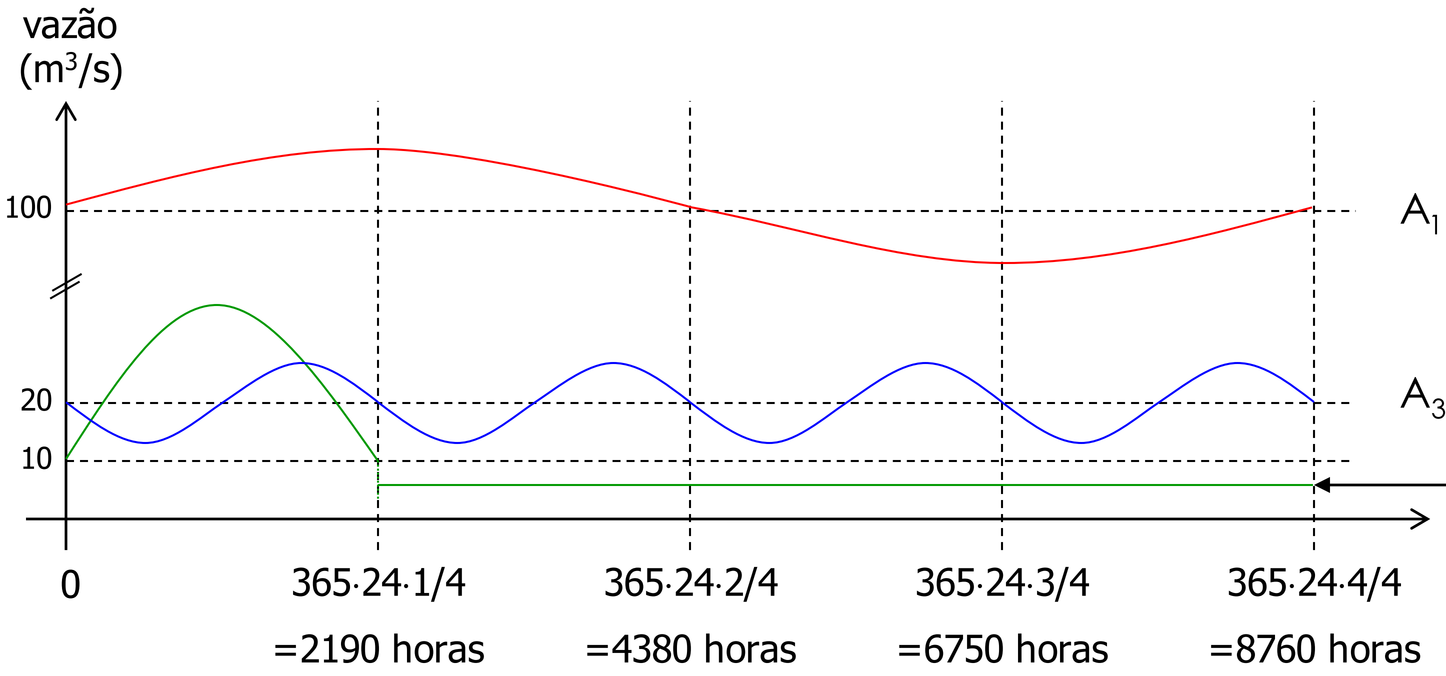
$$\Delta H_k = f_k(V_k)$$ Water height at in function of the accumulated volume

TRIBUTARIES FLOW RATES: STOCHASTIC MODELS



Hydrology 2014, 1(1), 89-111; doi:10.3390/hydrology1010089

TRIBUTARIES FLOW RATES: STOCHASTIC MODELS

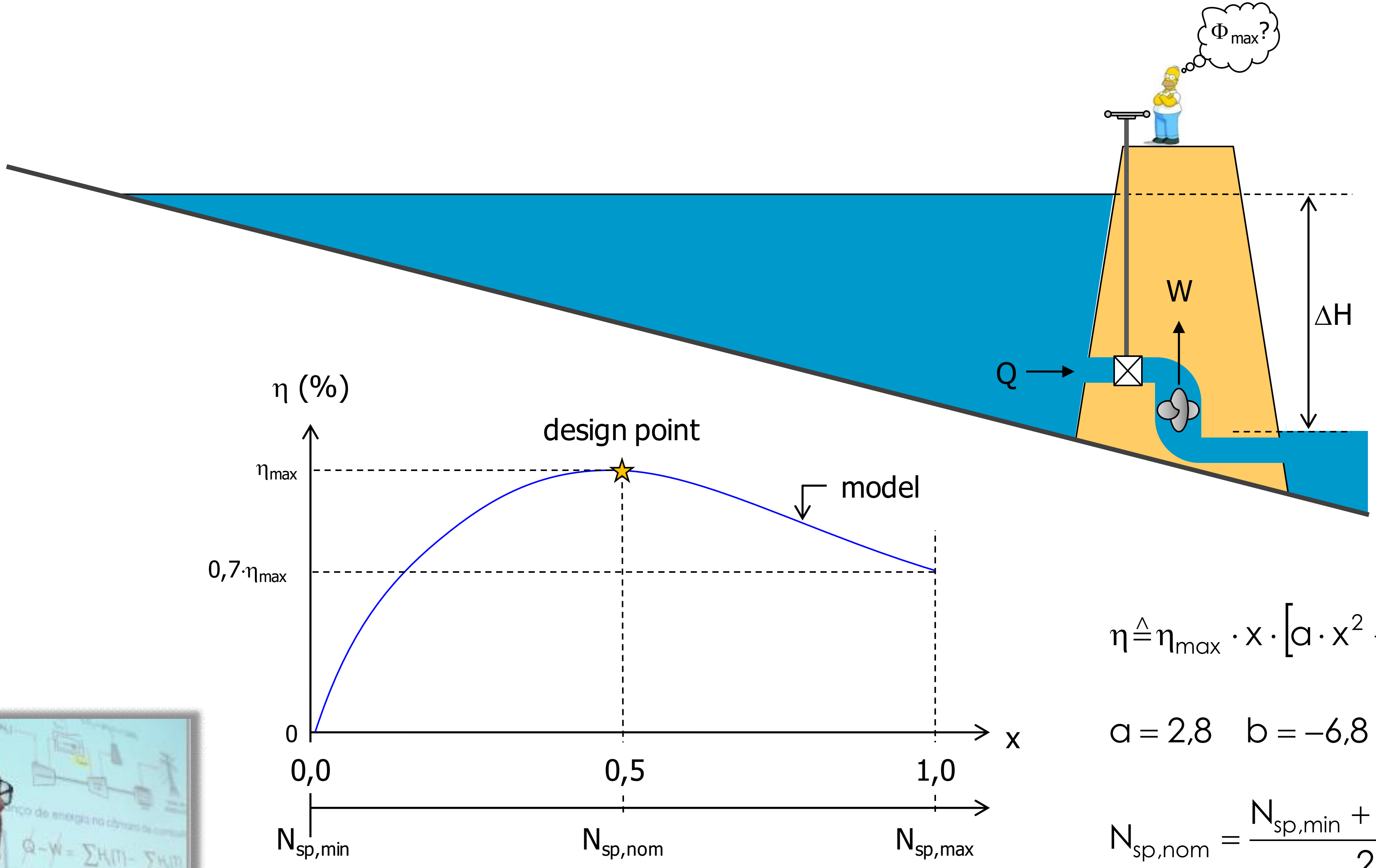


$$A_1 = 100 + 10 \cdot \sin\left(\frac{2\pi \cdot t}{365 \cdot 24}\right)$$

$$A_3 = 20 - 10 \cdot \sin\left(\frac{2\pi \cdot t}{365 \cdot 24}\right)$$

$$A_2 = \begin{cases} 10 + 10 \cdot \sin\left(\frac{2\pi \cdot t}{2 \cdot 2190}\right) & \text{se } 0 \le t \le 2190 \\ 7{,}878 \text{ se } t > 2190 \end{cases}$$

TURBINE PERFORMANCE EQUATIONS



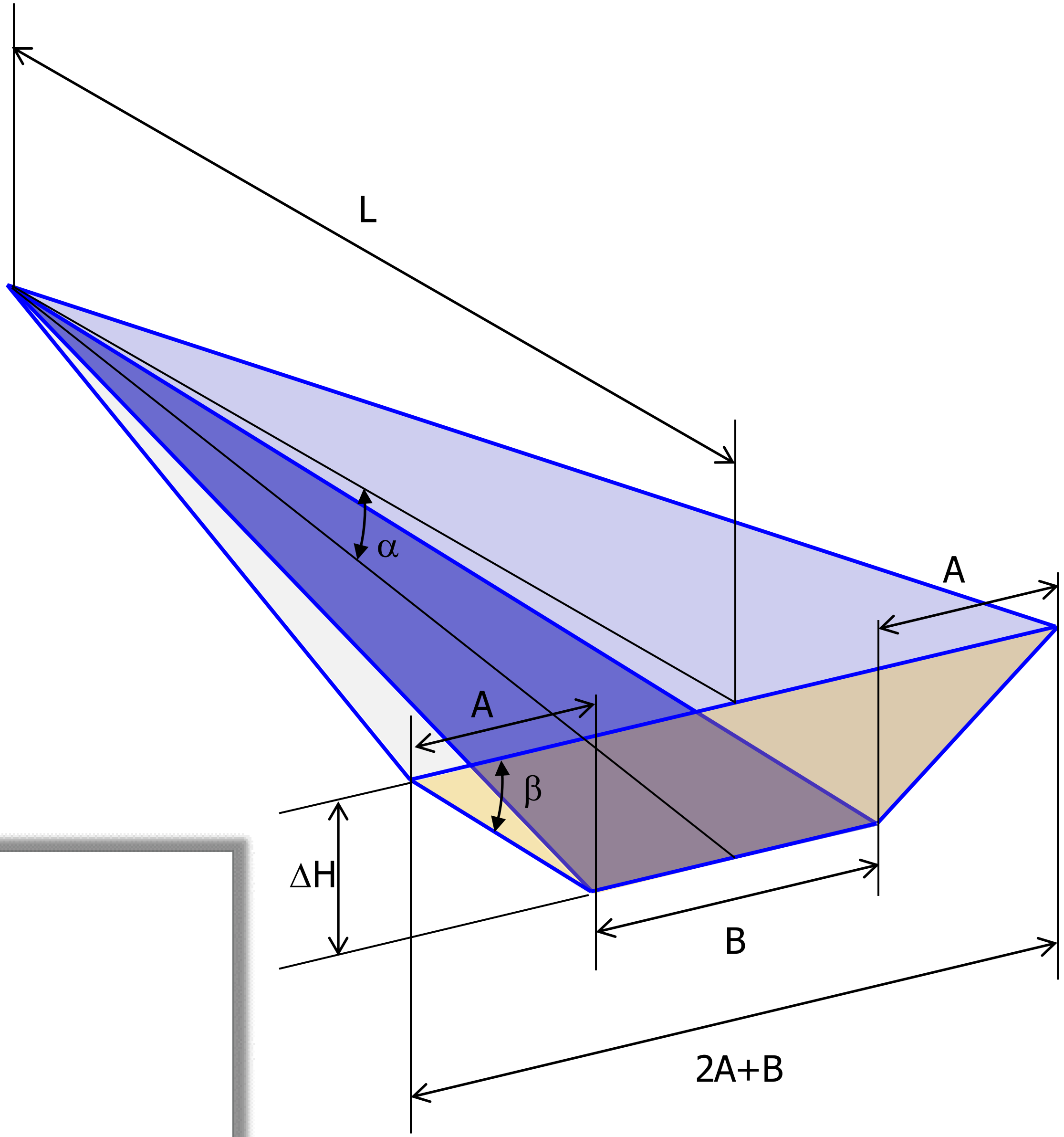
$$\eta \triangleq \eta_{max} \cdot x \cdot \left[a \cdot x^2 + b \cdot x + c\right]$$

$$a = 2{,}8 \quad b = -6{,}8 \quad c = 4{,}7$$

$$N_{sp,nom} = \frac{N_{sp,min} + N_{sp,max}}{2}$$

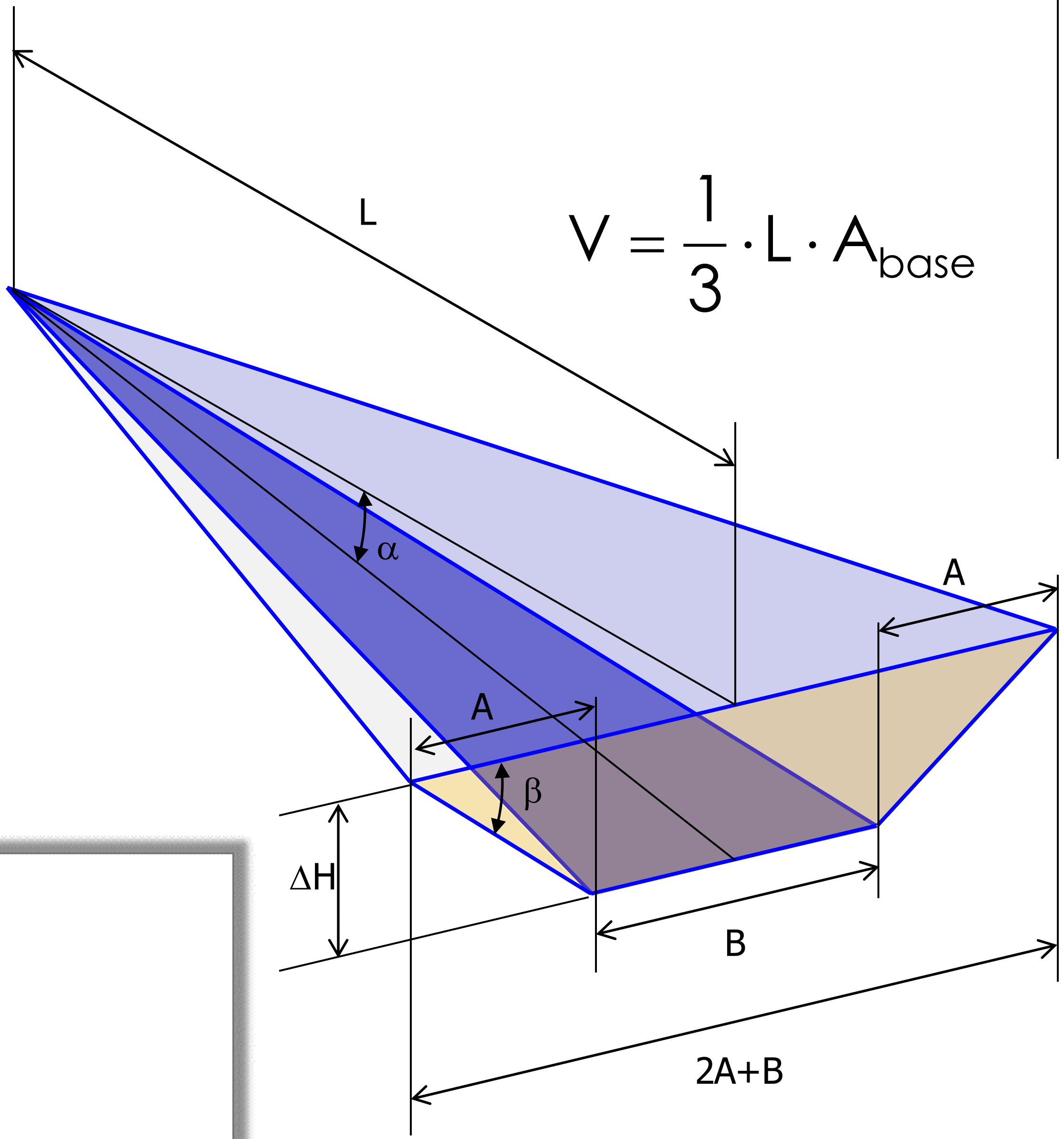
$$N_{sp} = N \cdot \frac{Q^{1/2}}{(g\Delta H)^{3/4}}$$

RESERVOIR CHARACTERIZATION EQUATIONS



$$V = \frac{1}{3} \cdot L \cdot A_{base}$$

RESERVOIR CHARACTERIZATION EQUATIONS



$$V = \frac{1}{3} \cdot L \cdot A_{base}$$

$$Tg(\alpha) = \frac{\Delta H}{L} \qquad Tg(\beta) = \frac{\Delta H}{a}$$

$$A_{base} = b \cdot \Delta H + 2 \cdot \frac{a \cdot \Delta H}{2}$$

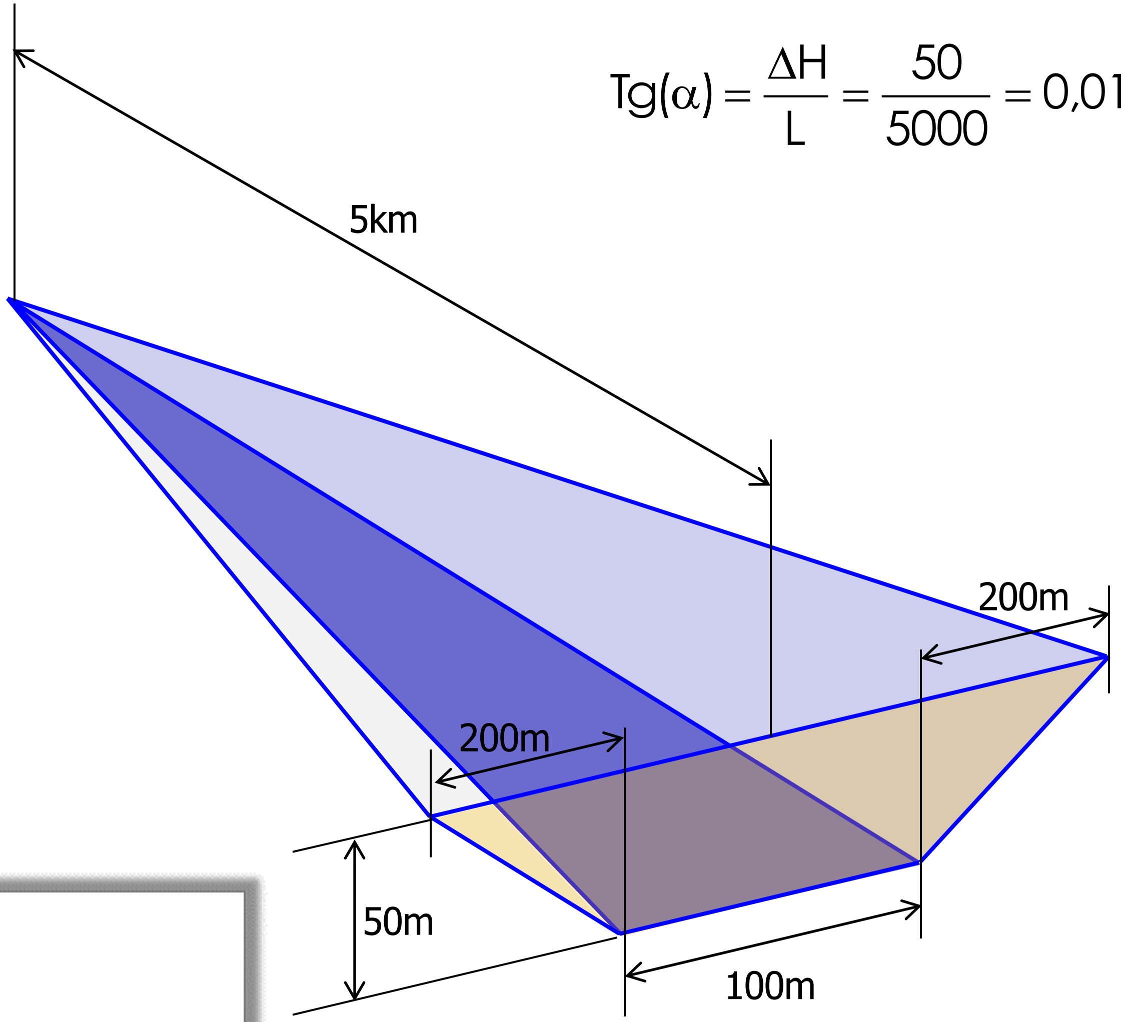
$$V = \frac{L}{3} \cdot \left(b \cdot \Delta H + 2 \cdot \frac{a \cdot \Delta H}{2} \right)$$

⇩

$$V = \frac{\Delta H^2}{3 \cdot Tg(\alpha)} \cdot \left(b + \frac{\Delta H}{Tg(\beta)} \right)$$

$$Tg(\alpha) = \frac{\Delta H}{L} \qquad Tg(\beta) = \frac{\Delta H}{a}$$

RESERVOIR CHARACTERIZATION EQUATIONS



$$Tg(\alpha) = \frac{\Delta H}{L} = \frac{50}{5000} = 0{,}01 \qquad Tg(\beta) = \frac{\Delta H}{a} = \frac{50}{200} = 0{,}25$$

$$V = \frac{\Delta H^2}{3 \cdot Tg(\alpha)} \cdot \left(b + \frac{\Delta H}{Tg(\beta)} \right)$$

$$V = \frac{50^2}{3 \cdot 0{,}01} \cdot \left(100 + \frac{50}{0{,}25} \right) \cdot 10^{-9}$$

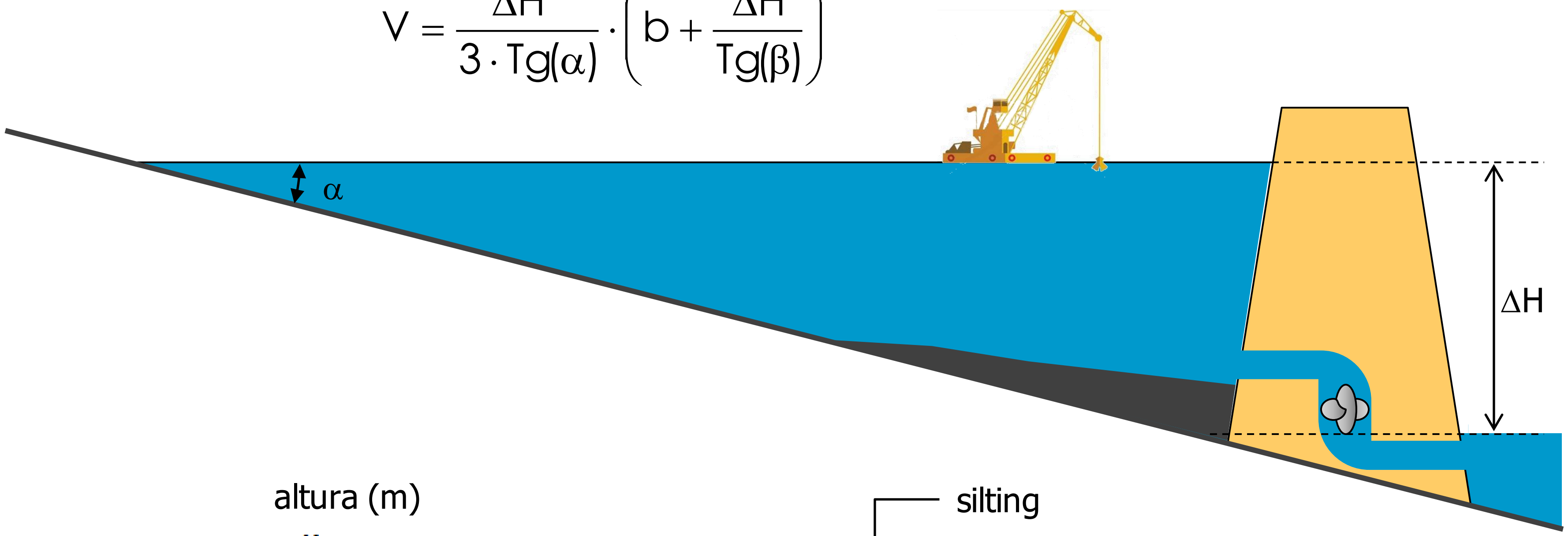
$$V_{nom} = 0{,}025\ km^3$$

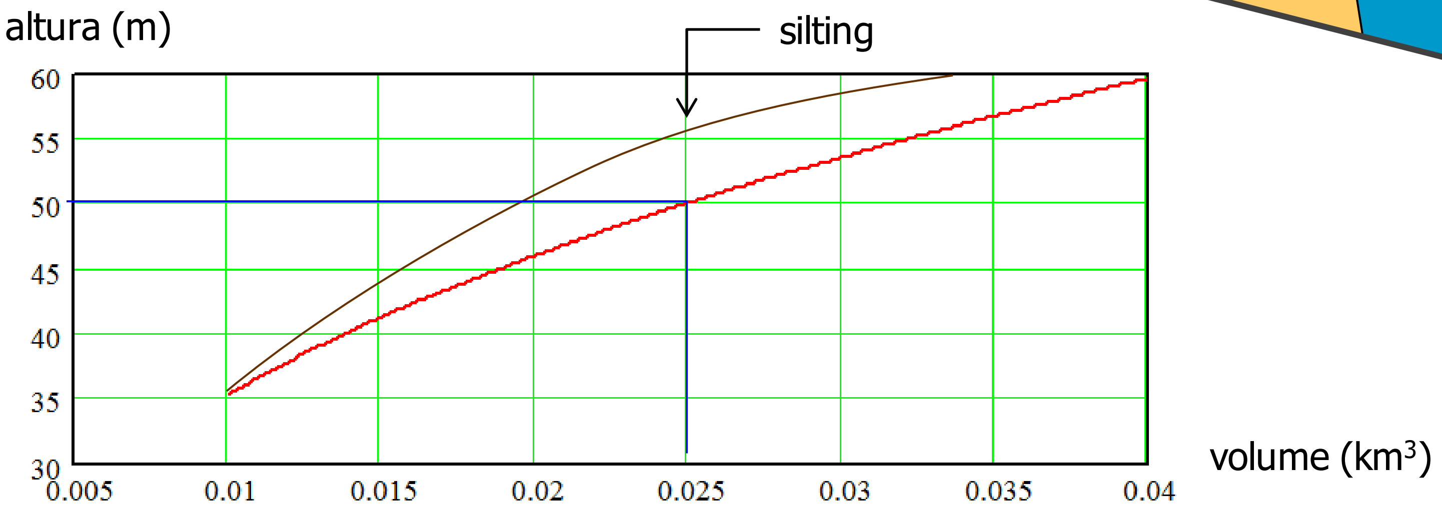
$$V_{B.Monte} = 2{,}5\ km^3$$

$$V_{Itaupú} = 19\ km^3$$

RESERVOIR CHARACTERIZATION EQUATIONS

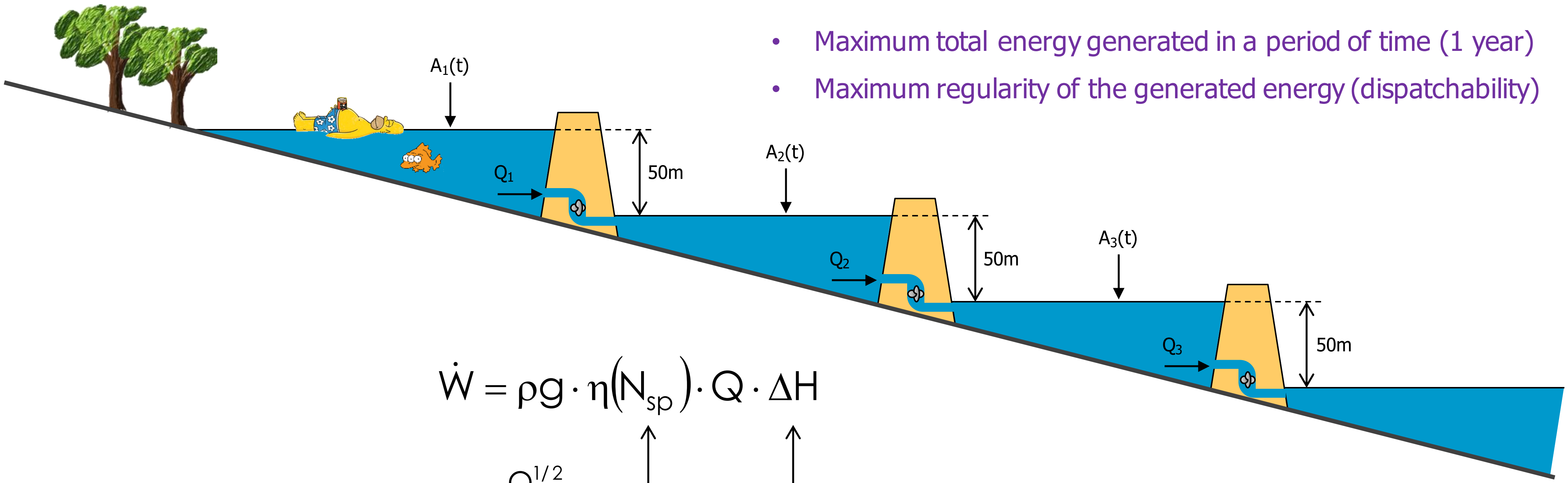
$$V = \frac{\Delta H^2}{3 \cdot Tg(\alpha)} \cdot \left(b + \frac{\Delta H}{Tg(\beta)} \right)$$





FORMULATION OF THE OPTIMIZATION PROBLEM

- Maximum total energy generated in a period of time (1 year)
- Maximum regularity of the generated energy (dispatchability)



$$\dot{W} = \rho g \cdot \eta(N_{sp}) \cdot Q \cdot \Delta H$$

$$N_{sp} = N \cdot \frac{Q^{1/2}}{(g\Delta H)^{3/4}}$$

$$\Delta H = \Delta H(Q, A)$$

Q e ΔH must be so that Nsp $\approx$ 0,5
to have η_{max}

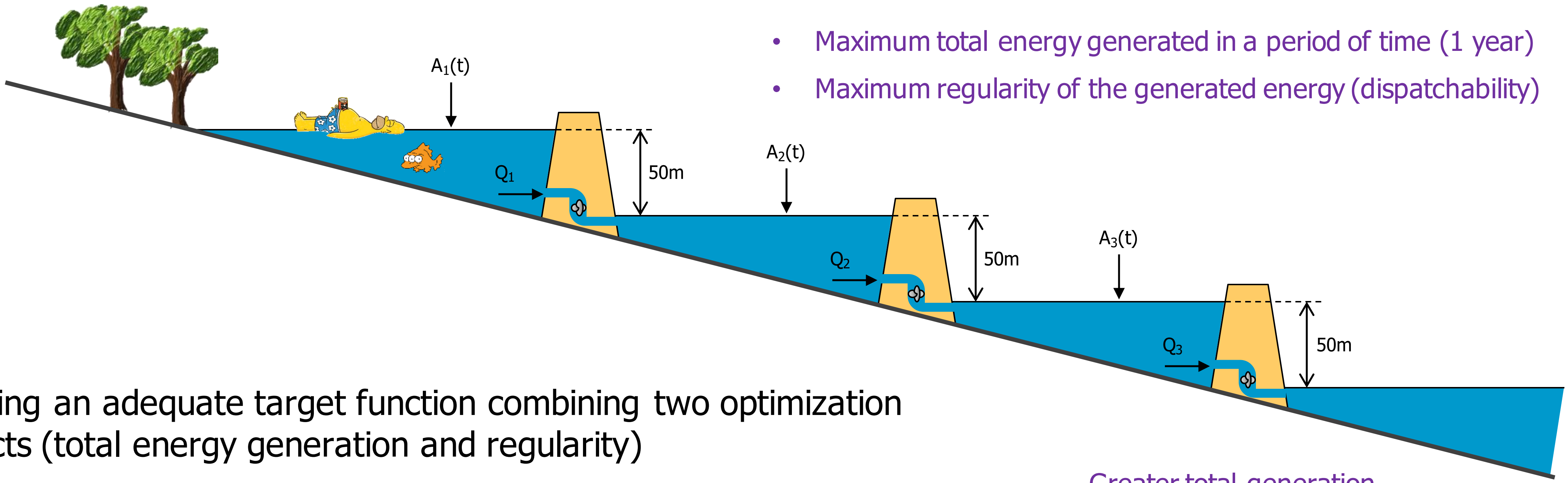
When $Q \uparrow \Rightarrow \Delta H \downarrow$
and when $A \uparrow \Rightarrow \Delta H \uparrow$

$$Q^{1/2} \cdot \Delta H^{-3/4} \approx cte$$

$$Q \cdot \Delta H^{-1} \approx cte$$

conflicting effects: trade-off solution

FORMULATION OF THE OPTIMIZATION PROBLEM



- Maximum total energy generated in a period of time (1 year)
- Maximum regularity of the generated energy (dispatchability)

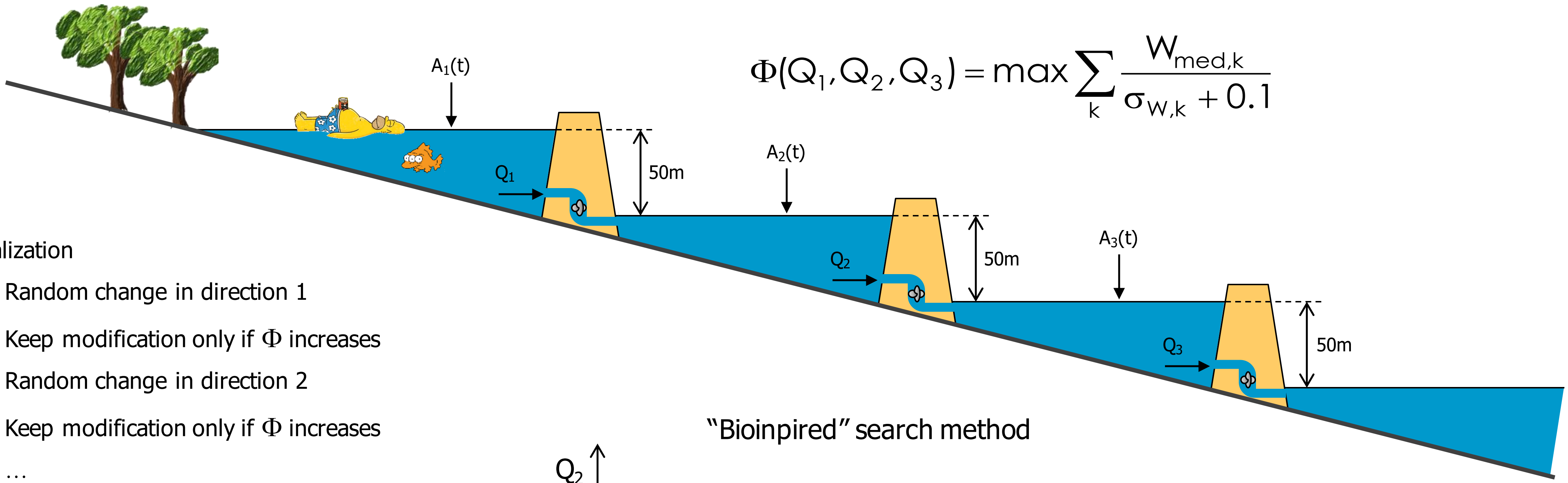
Defining an adequate target function combining two optimization aspects (total energy generation and regularity)

Greater total generation in the period

$$Q_1(t), Q_2(t) \, e \, Q_3(t) \rightarrow \max \sum_k \frac{W_{med,k}}{\sigma_{W,k} + 0.1}$$

Smaller dispersion around the average value

FORMULATION OF THE OPTIMIZATION PROBLEM



$$\Phi(Q_1, Q_2, Q_3) = \max \sum_k \frac{W_{med,k}}{\sigma_{W,k} + 0.1}$$

Initialization

Random change in direction 1

Keep modification only if Φ increases

Random change in direction 2

Keep modification only if Φ increases

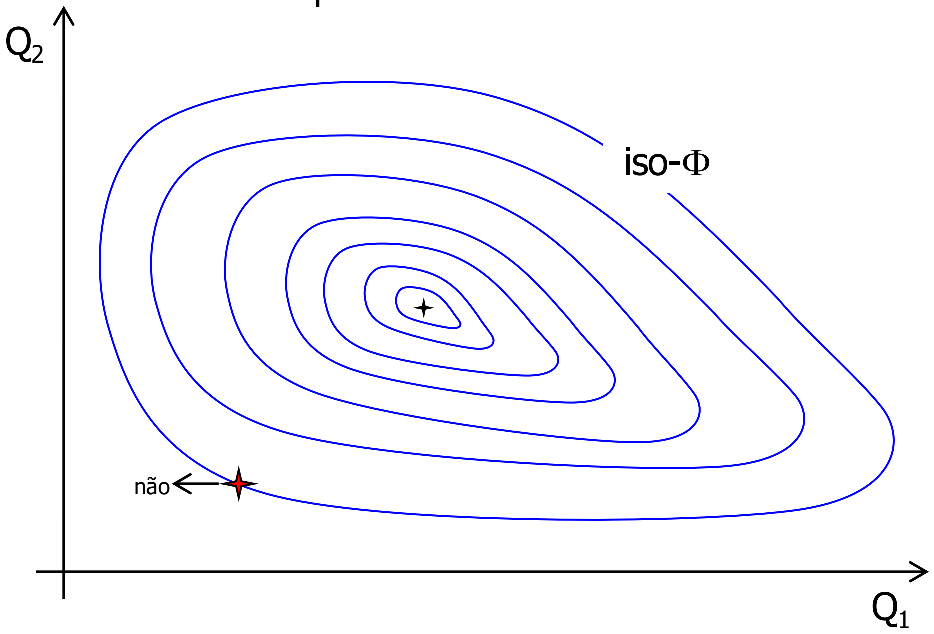
…

Random change in direction N

Keep modification only if Φ increases

Iterate

"Bioinpired" search method



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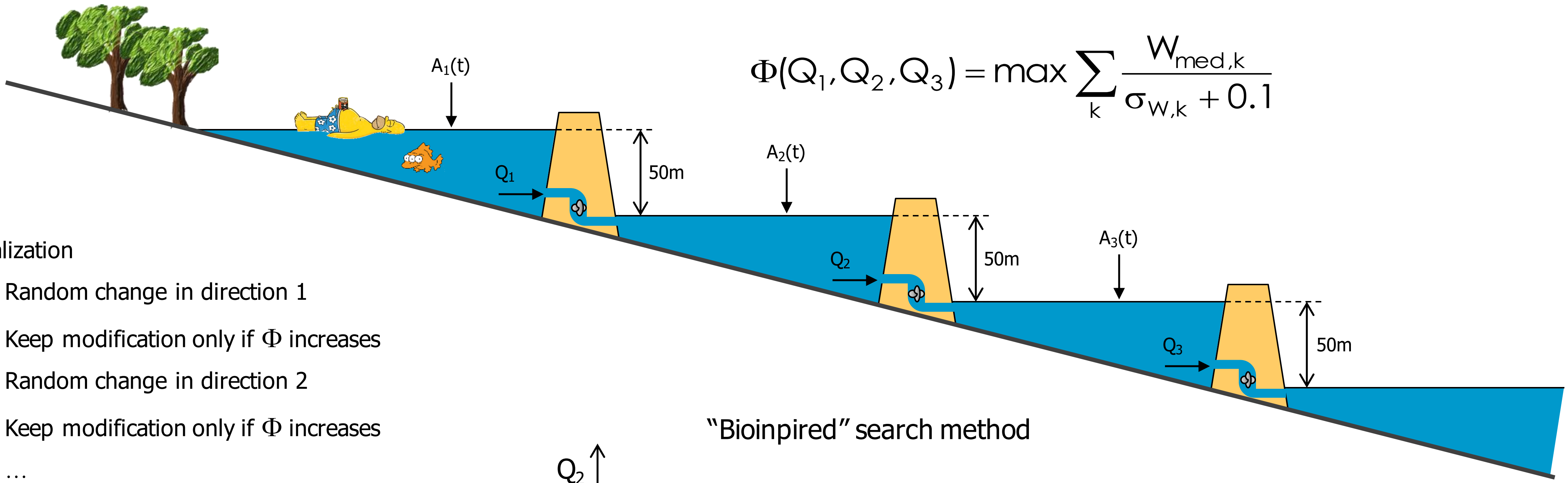

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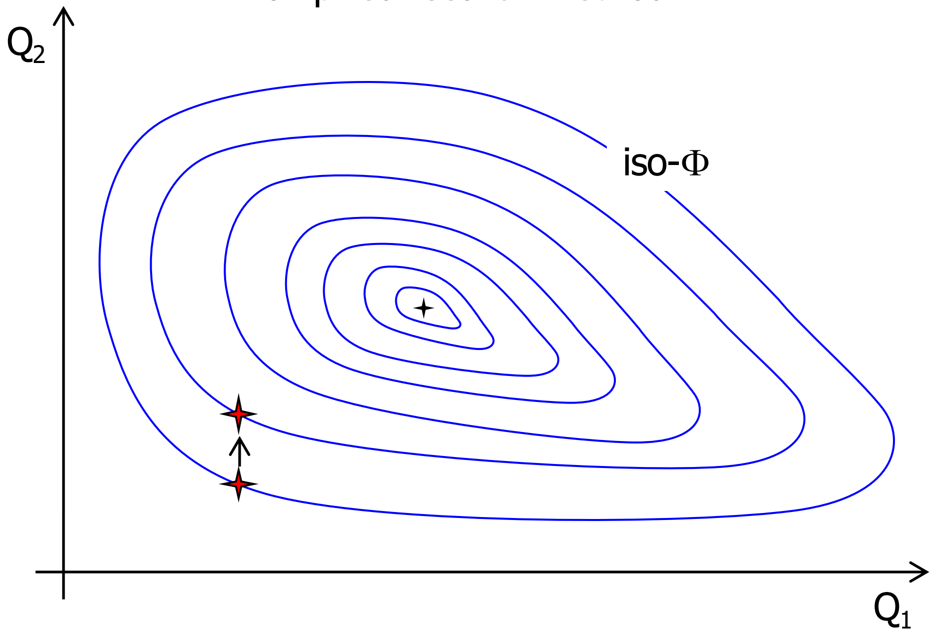

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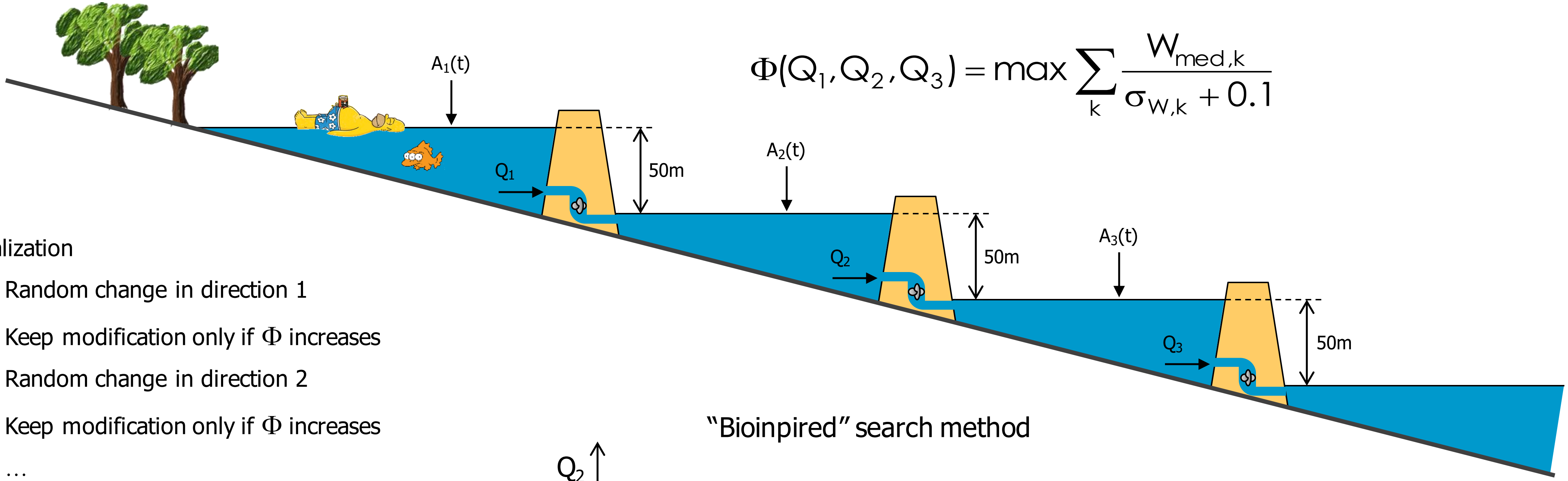

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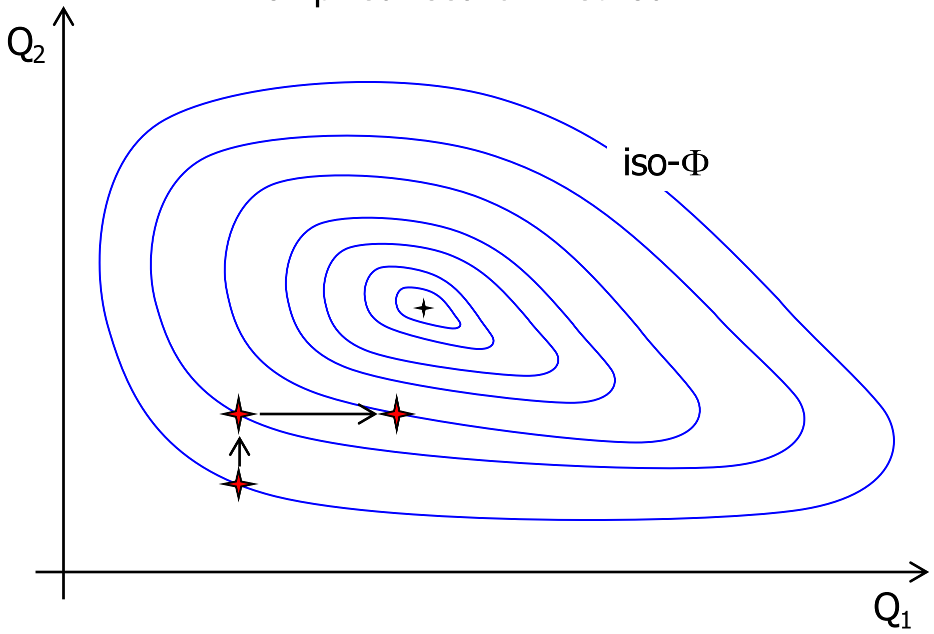

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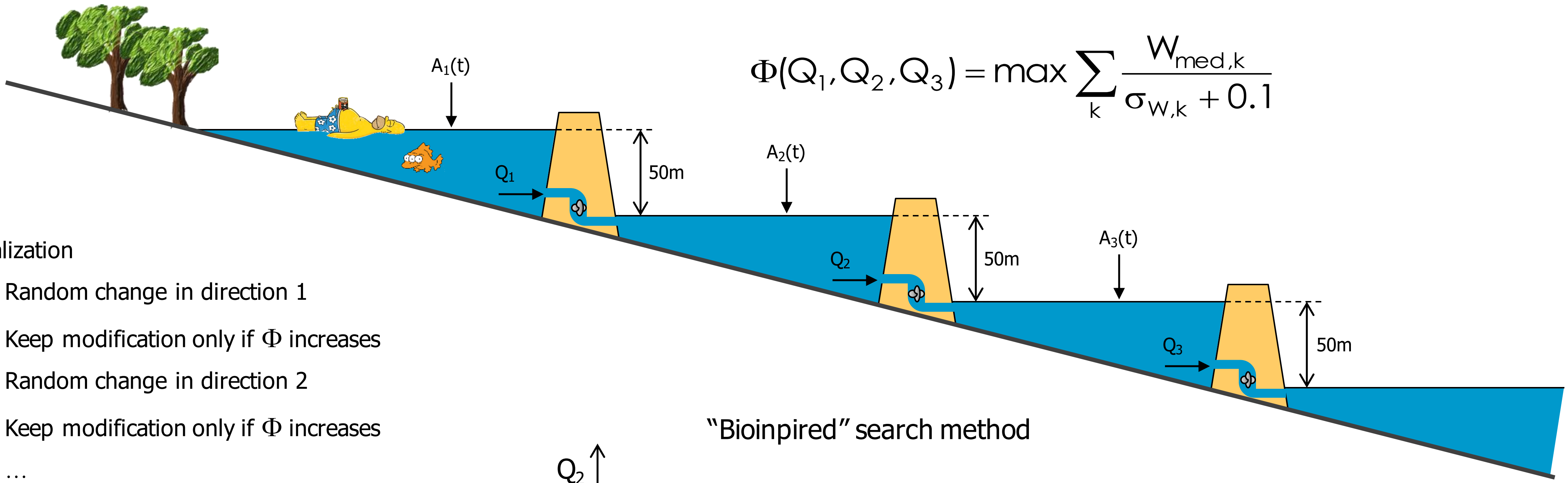

Initialization

Random change in direction 1

Keep modification only if Φ increases

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…

Random change in direction N

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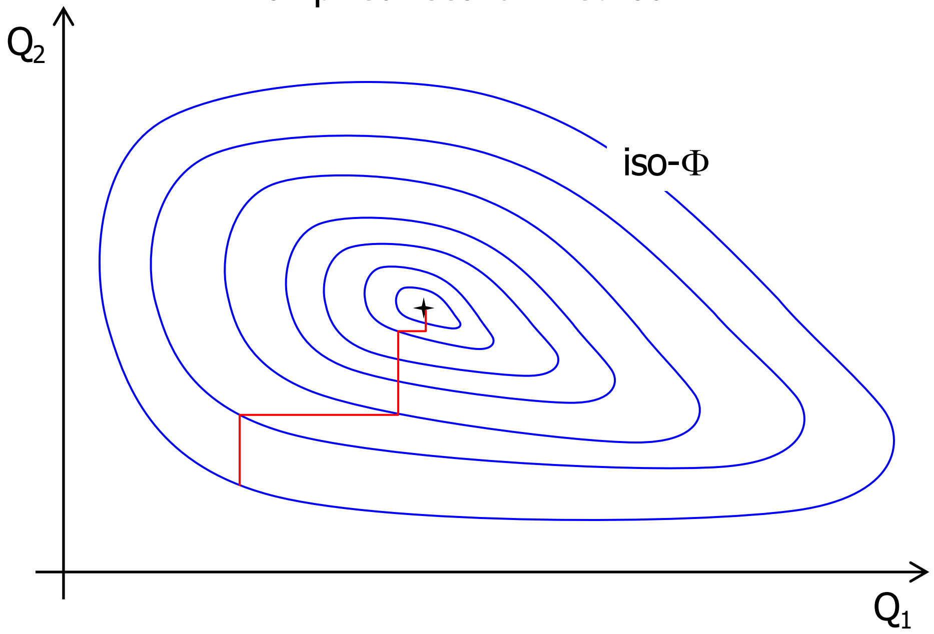
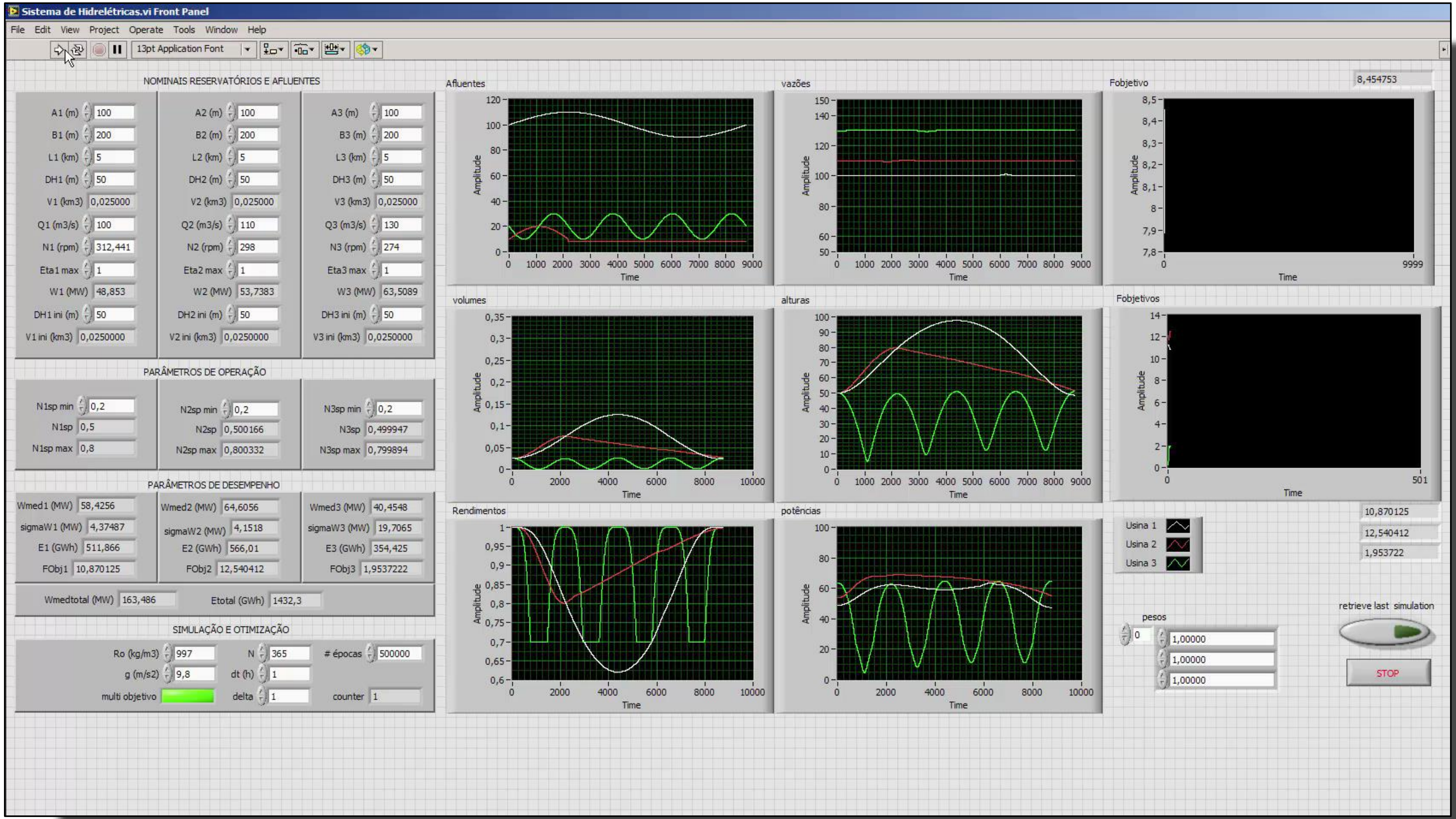
Iterate

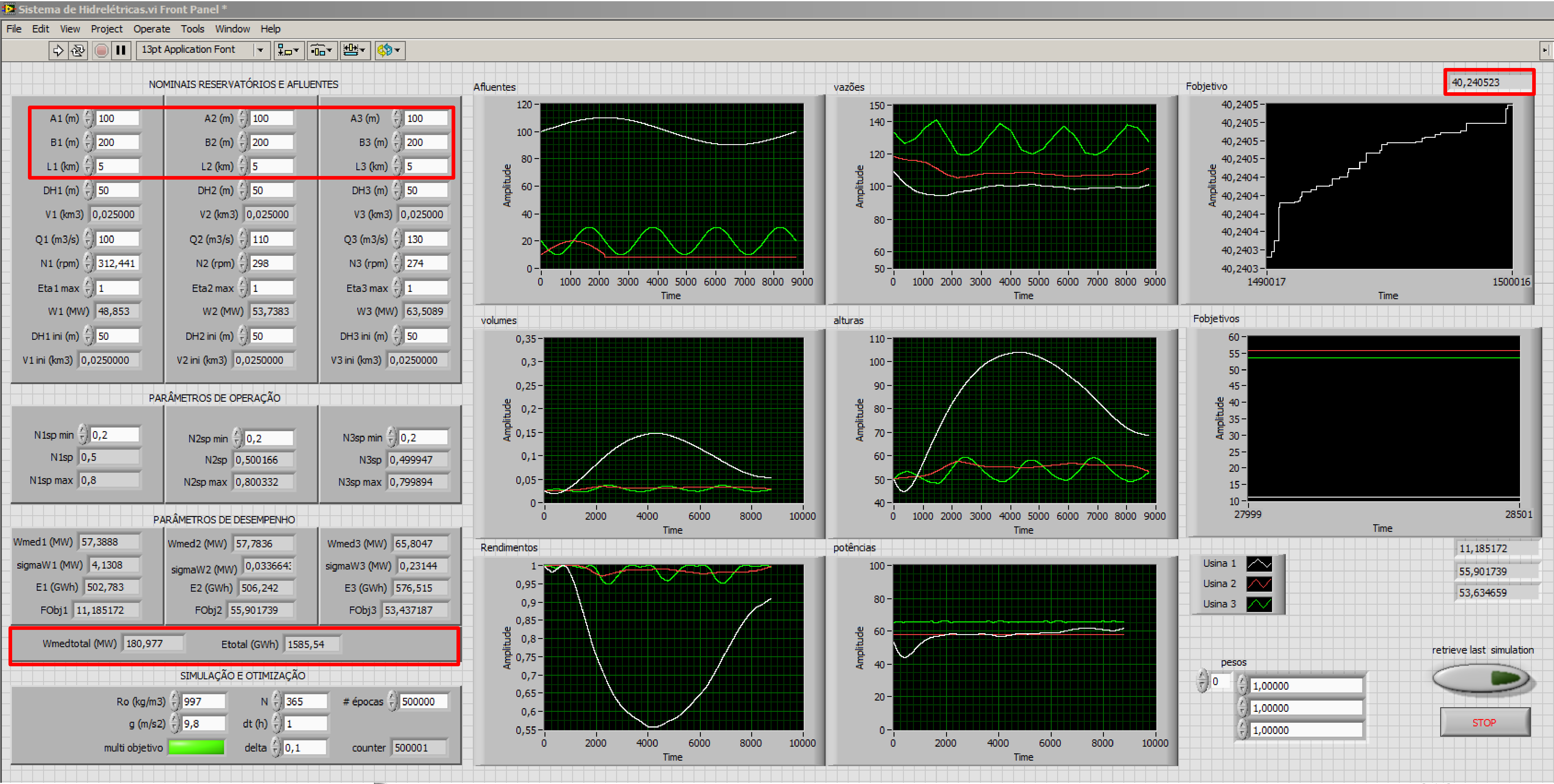
"Bioinpired" search method



NUMERICAL SIMULATIONS

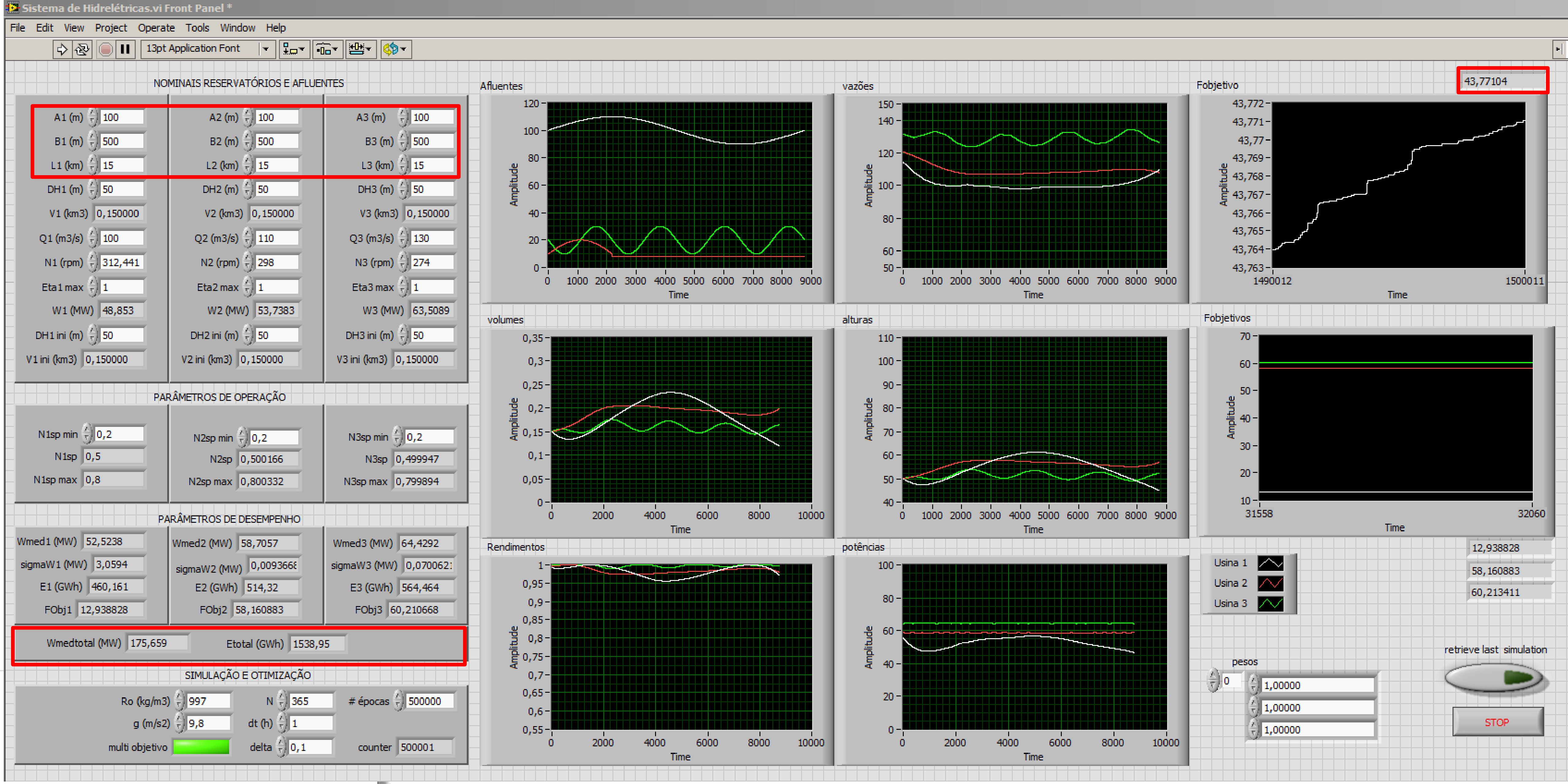


$$\Phi(Q_1,Q_2,Q_3)=\max\sum_{k}\frac{W_{med,k}}{\sigma_{W,k}+0.1}$$



SMALL VOLUME RESERVOIR

$$\Phi(Q_1, Q_2, Q_3) = \max \sum_k \frac{W_{med,k}}{\sigma_{W,k} + 0.1}$$



LARGE VOLUME RESERVOIR

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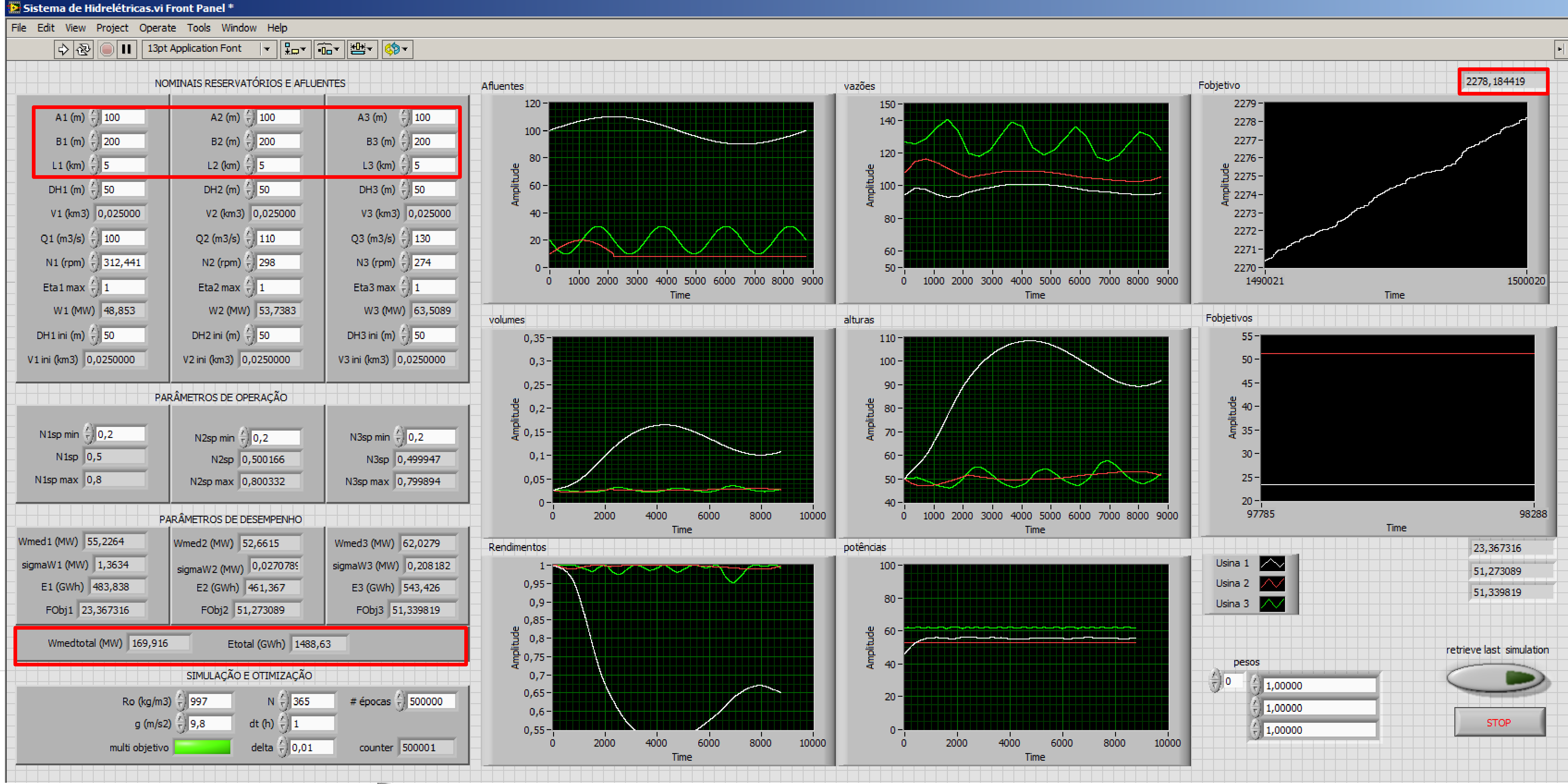
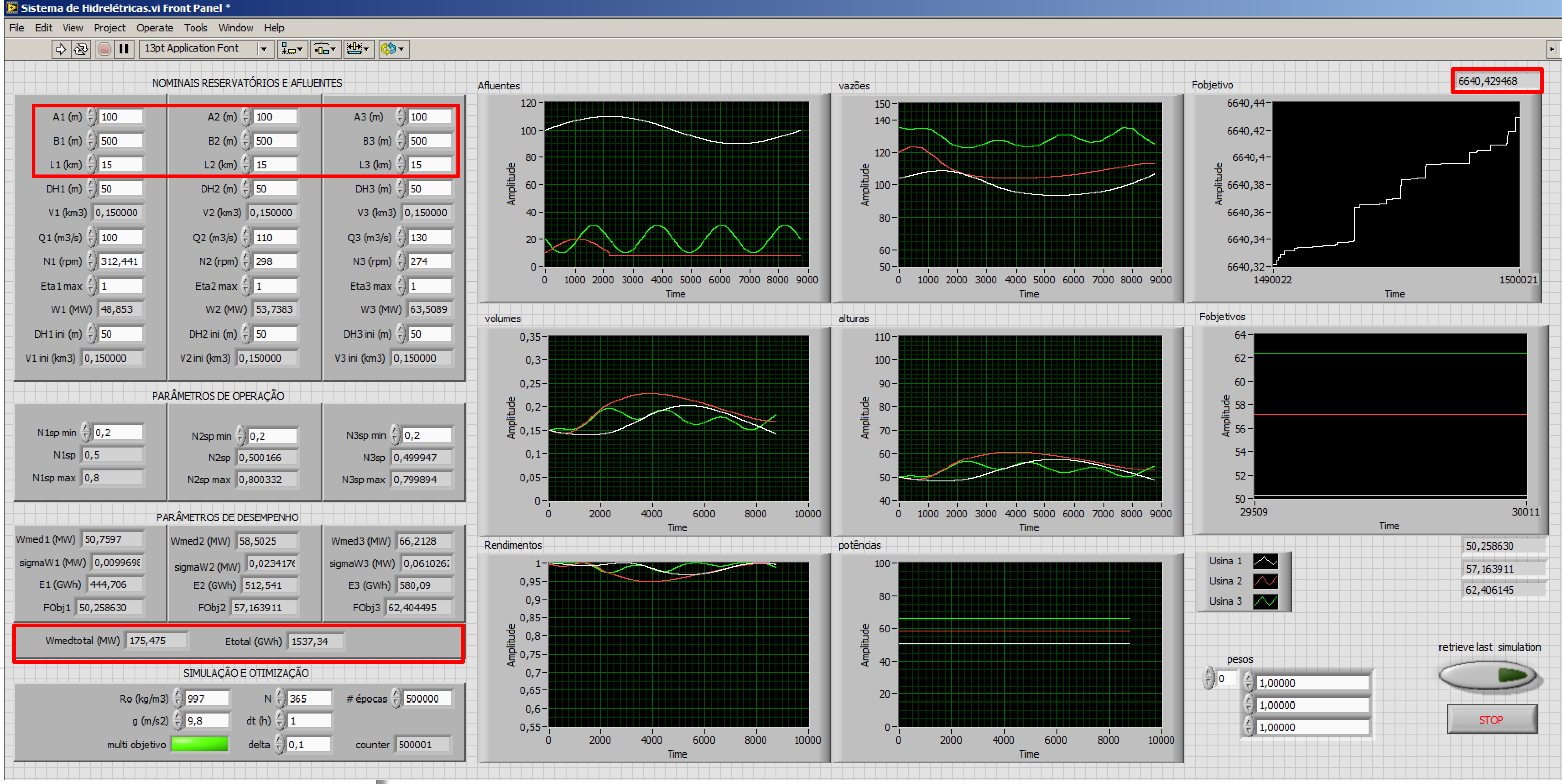


SMALL VOLUME RESERVOIR

$$\Phi(Q_1, Q_2, Q_3) = \max \prod_K \frac{W_{med,k}}{\sigma_{W,k} + 0.1}$$



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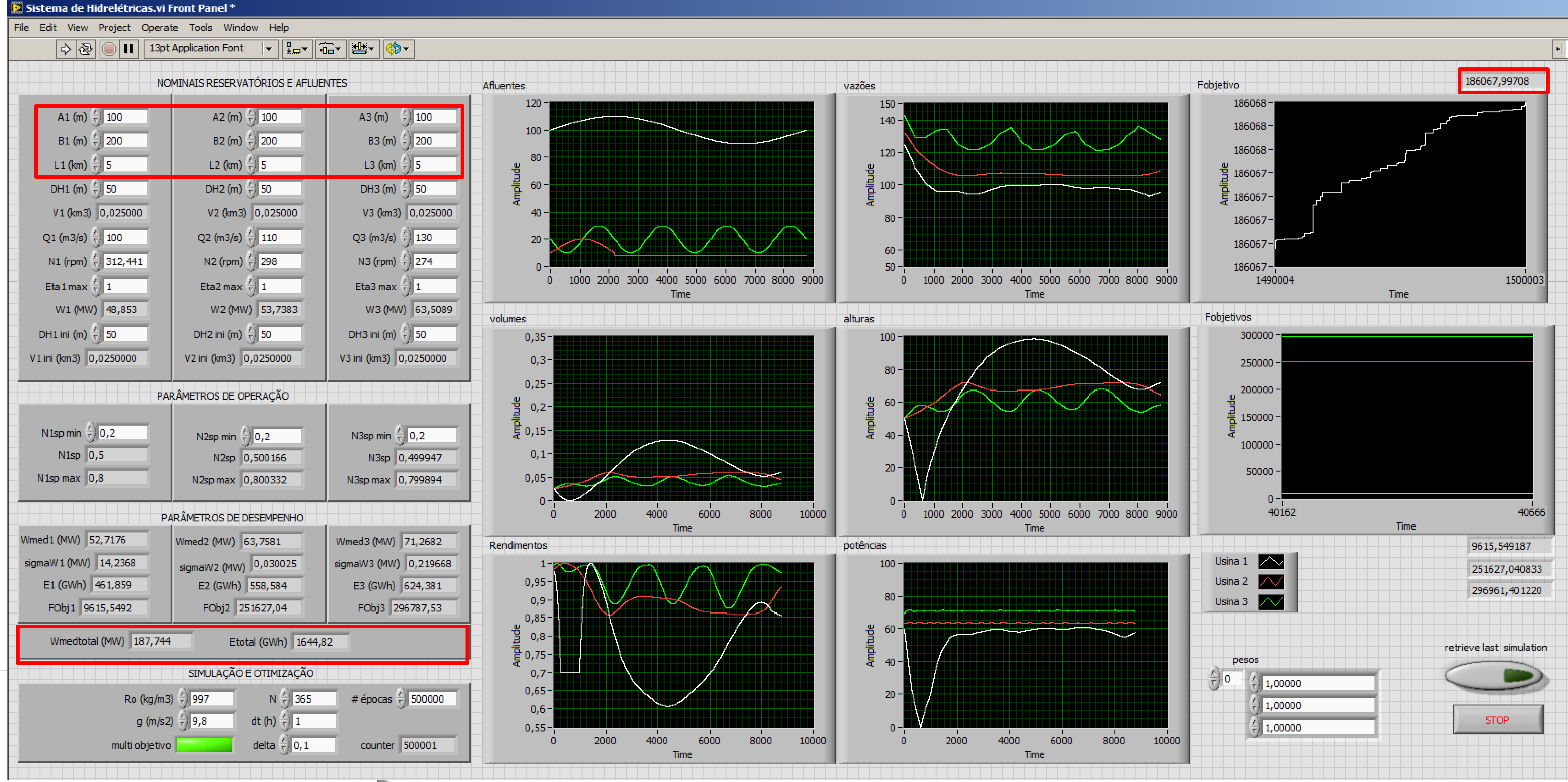
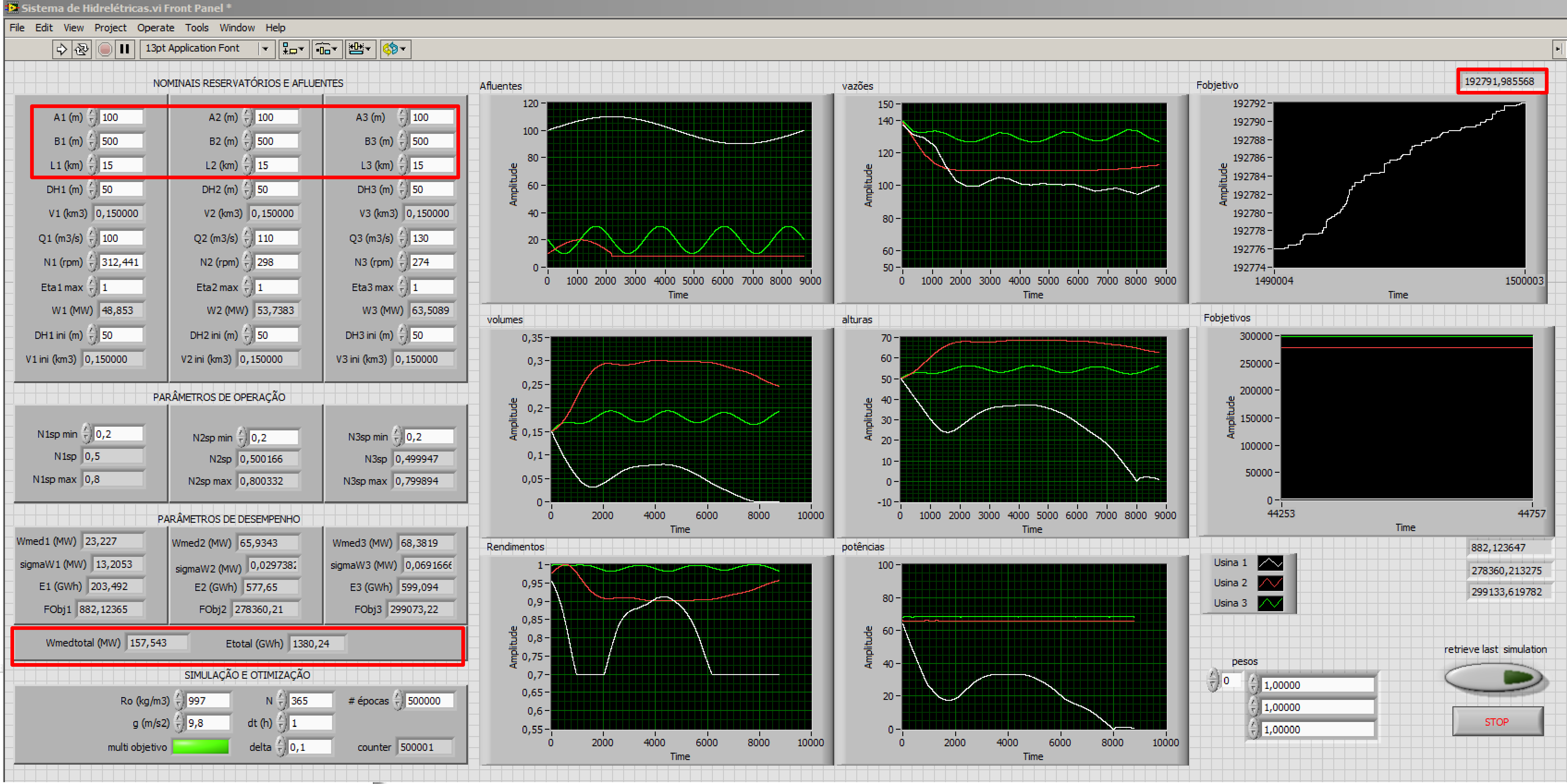


SMALL VOLUME RESERVOIR

$$\Phi(Q_1, Q_2, Q_3) = \max \sum_k \frac{(W_{med,k})^3}{\sigma_{W,k} + 0.1}$$



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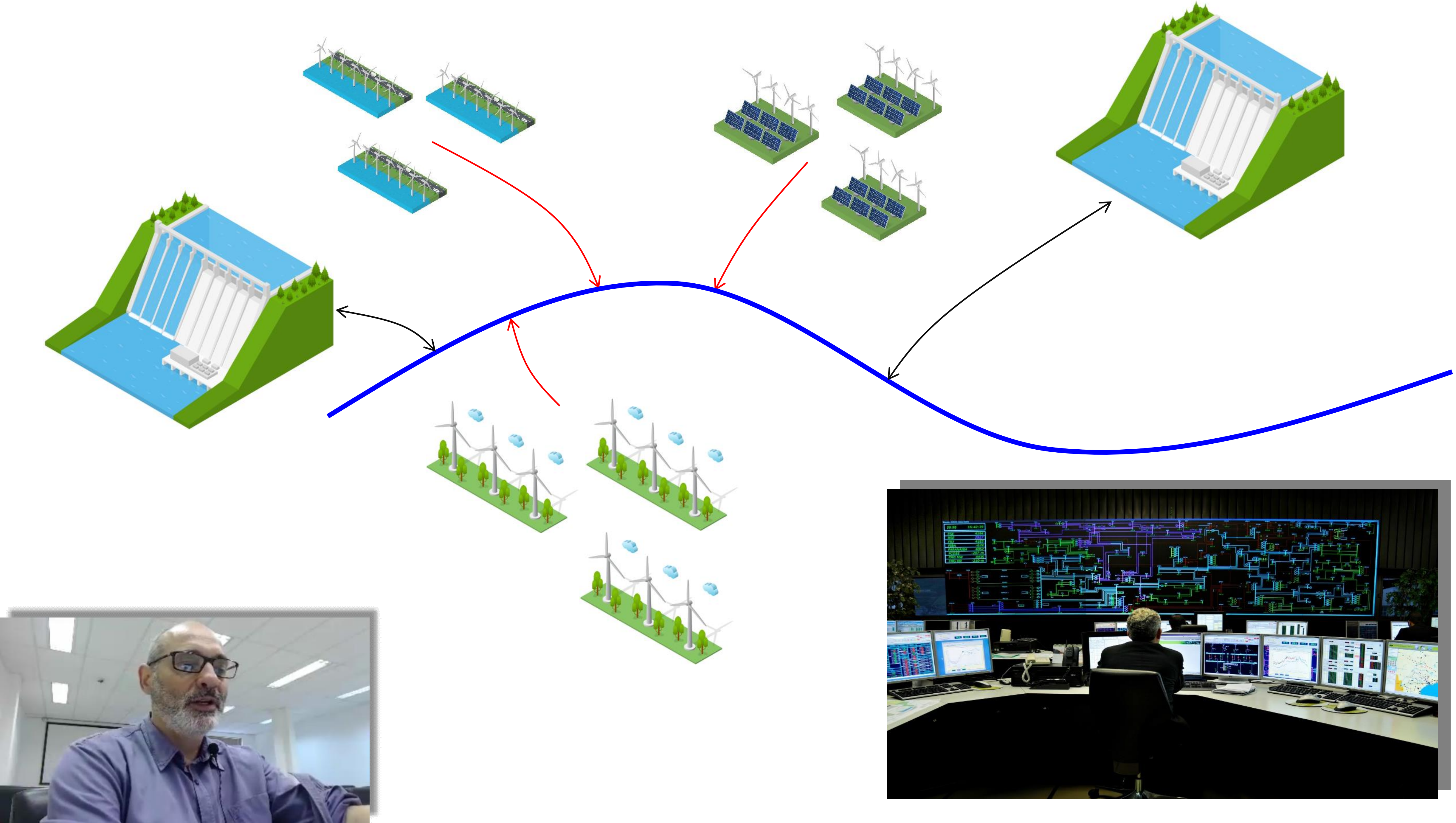

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