



OPTIMIERUNG DER DIMENSIONIERUNG VON BESS-SYSTEMEN IN HYBRIDEN PHOTOVOLTAIK-WINDPARKS IN BRASILIAN

DR MONT IZABELLA CARNEIRO BASTOS

DR. PAULO FRANCO BARBOSA

TIAGO SAK, MSC

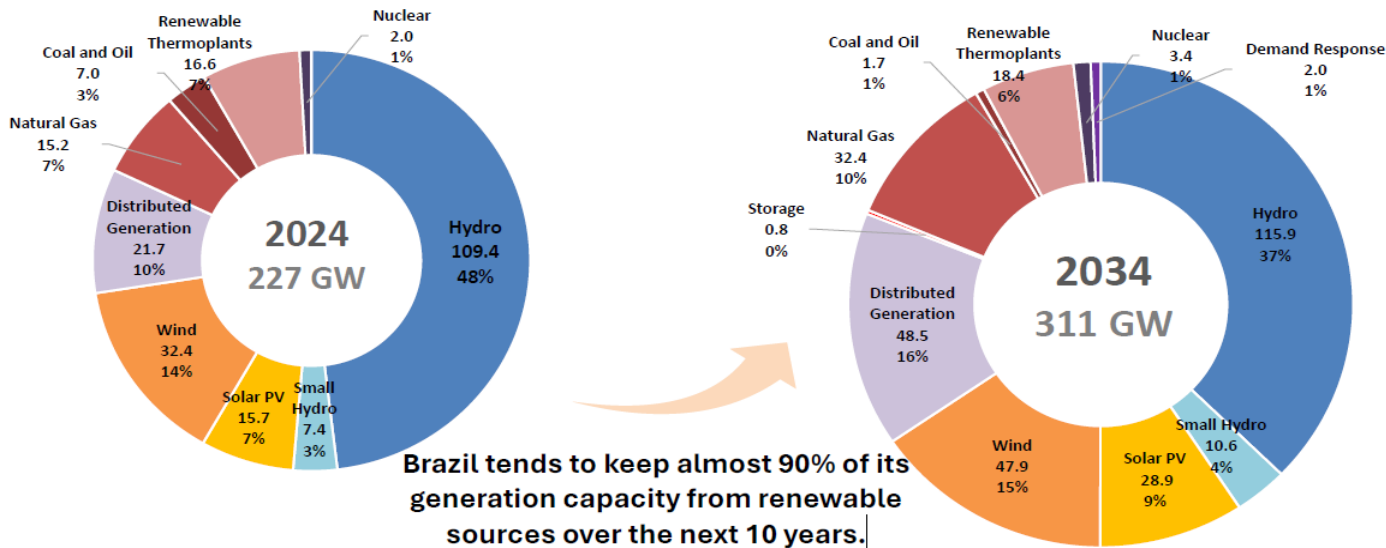
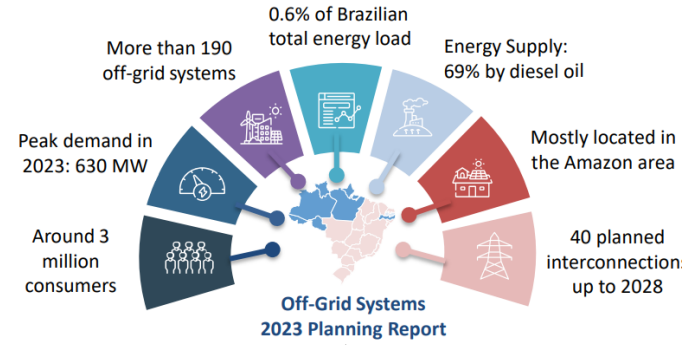
DR. TECH THOMAS KIENBERGER

ENINNOV CONFERENCE

FEBRUAR 2026

BRAZILIAN POWER SECTOR

- Installed generation capacity: 230 GW, 48% hydro
- HV transmission system length: 187,000 km / 230 kV to 800 kV
- Average annual load growth rates:
 - 2004 – 2010: +4.3%; 2010 – 2016: +1.9% - PDE 2034 – Ten Year Expansion Plan: 3,4%
- Private participation in G, T, D and trading

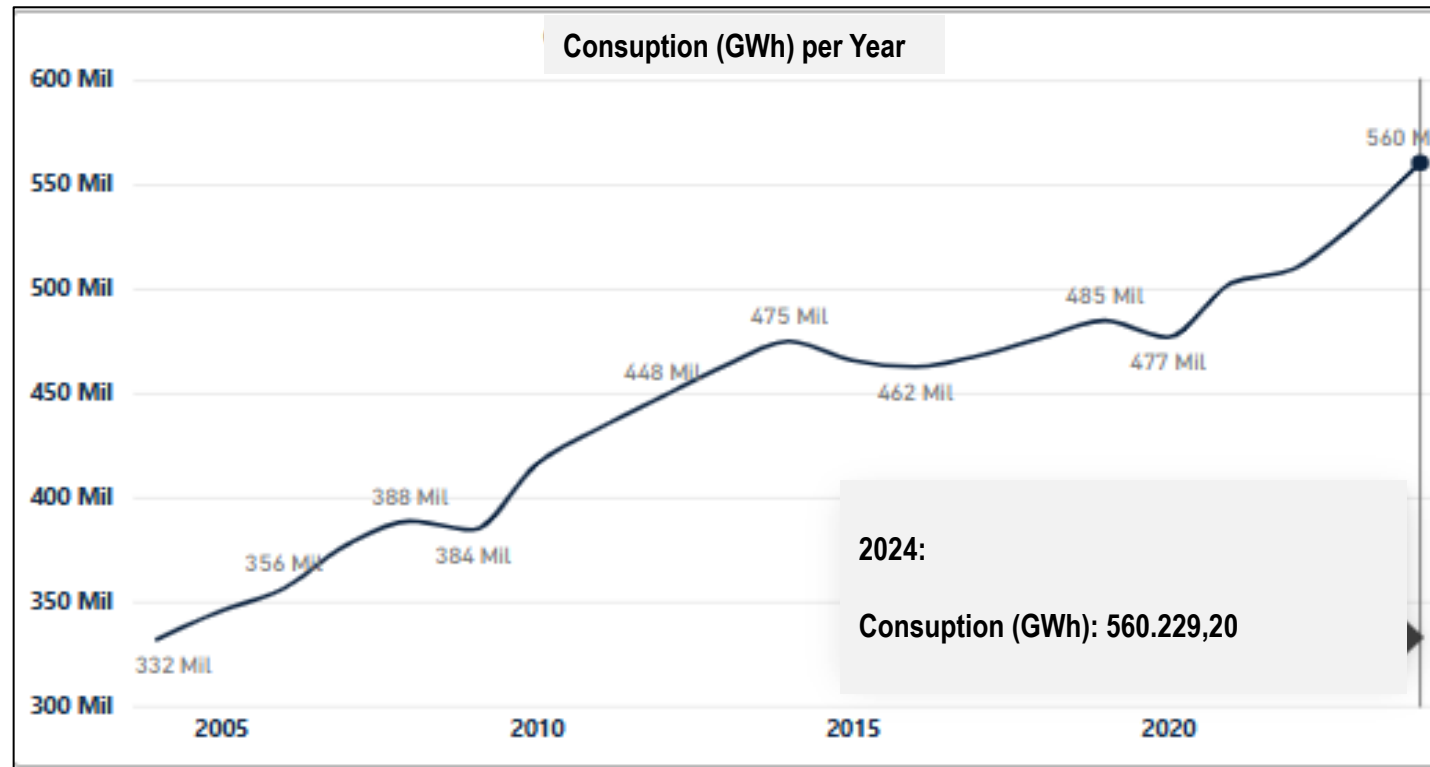


The SIN:
[Interconnected National System]



Source: EPE (Energy Research Office, Sept 2024)
BRAZIL'S ACTION PLAN FOR RAPID DECARBONIZATION OF POWER SECTORS

BRAZILIAN POWER SECTOR: ELECTRICITY CONSUMPTION



Distribution by Geographic Regions:

Southeast: 47.8%

South: 18,4%

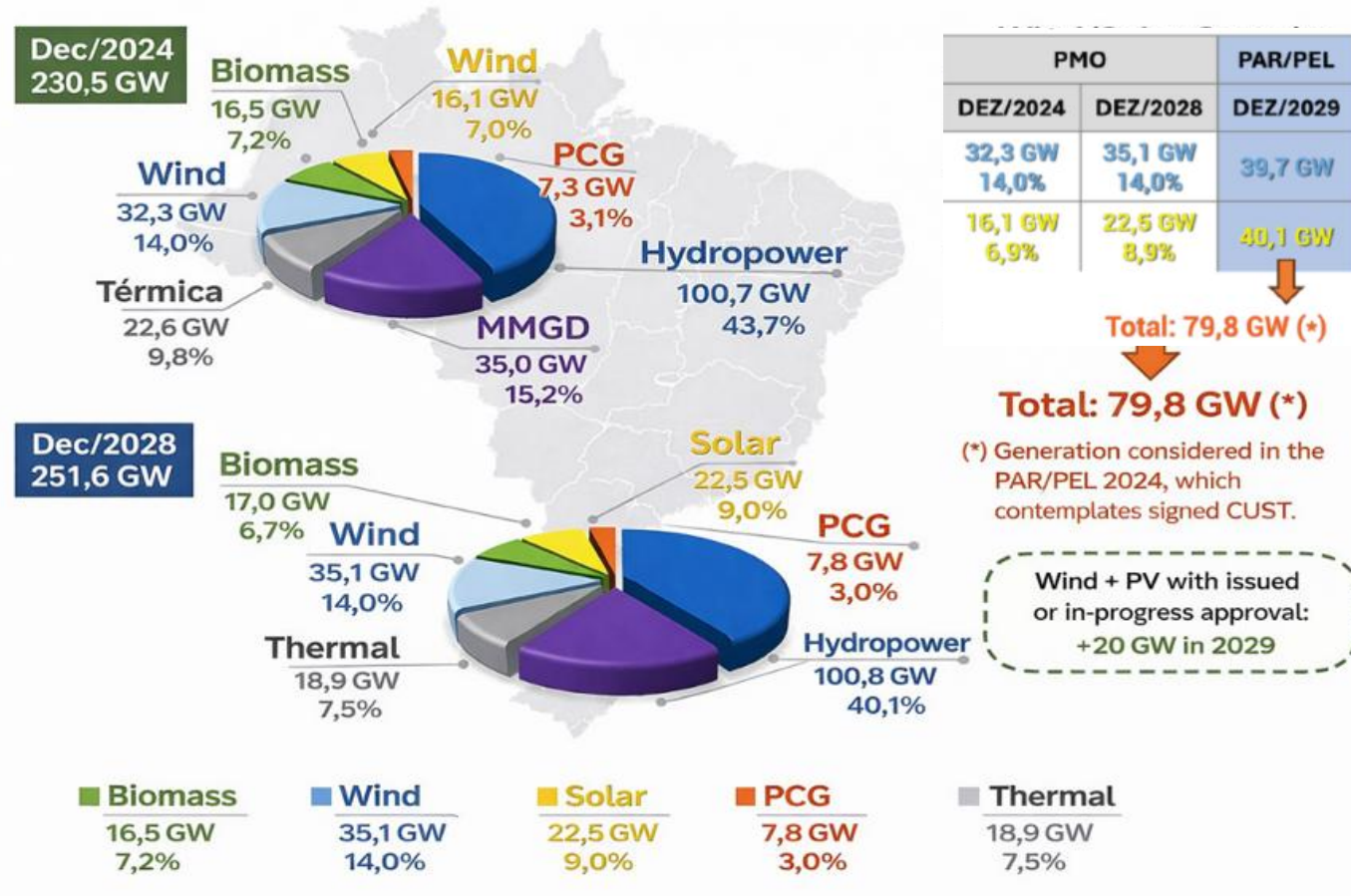
Northeast: 17,9%

Central: 8%

North: 7,8%

Source: EPE (Energy Research Office, Sept 2024)
 BRAZIL'S ACTION PLAN FOR RAPIDDECARBONIZATION OF POWER SECTORS

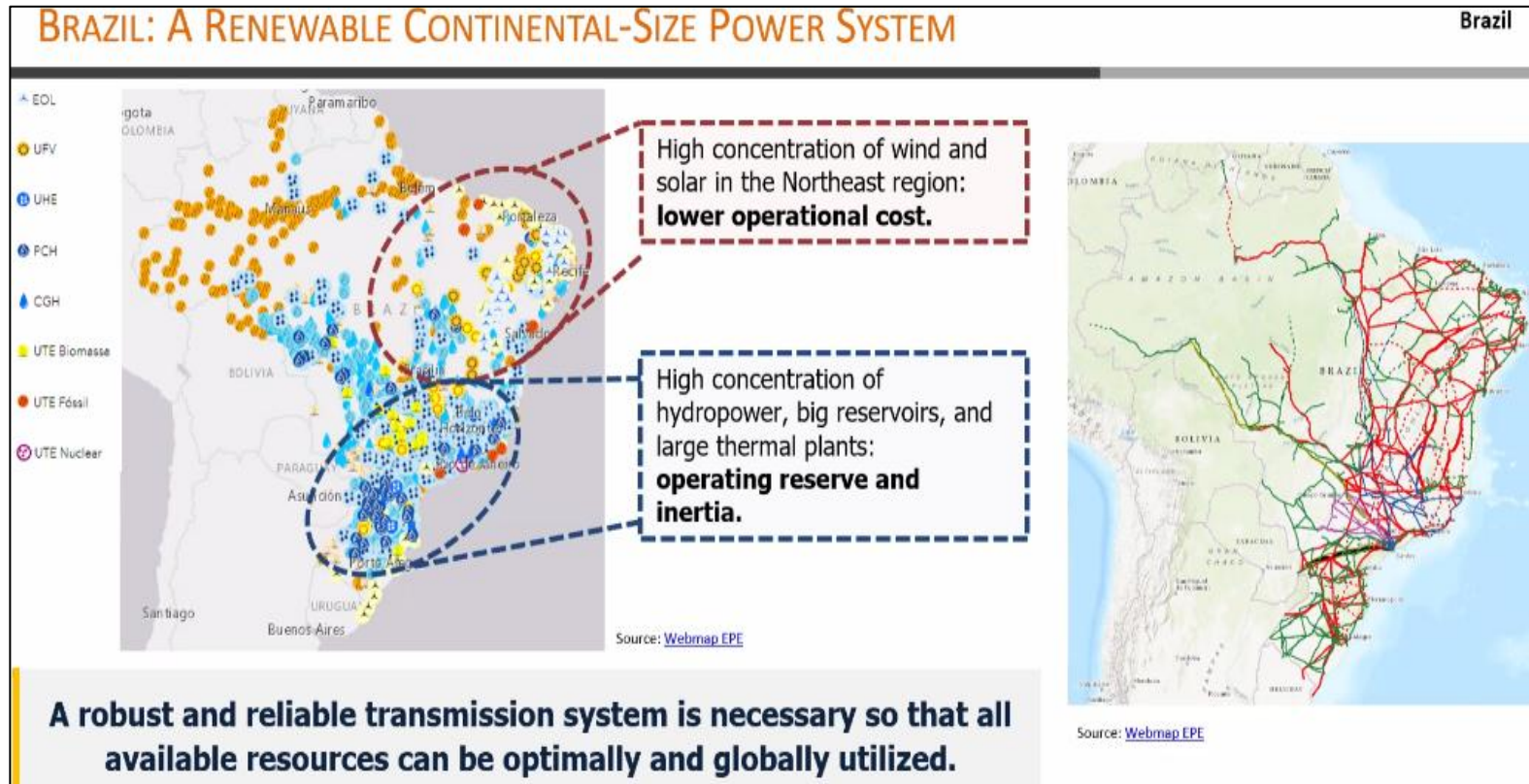
EXPANSION PLAN – 2024 - 2028



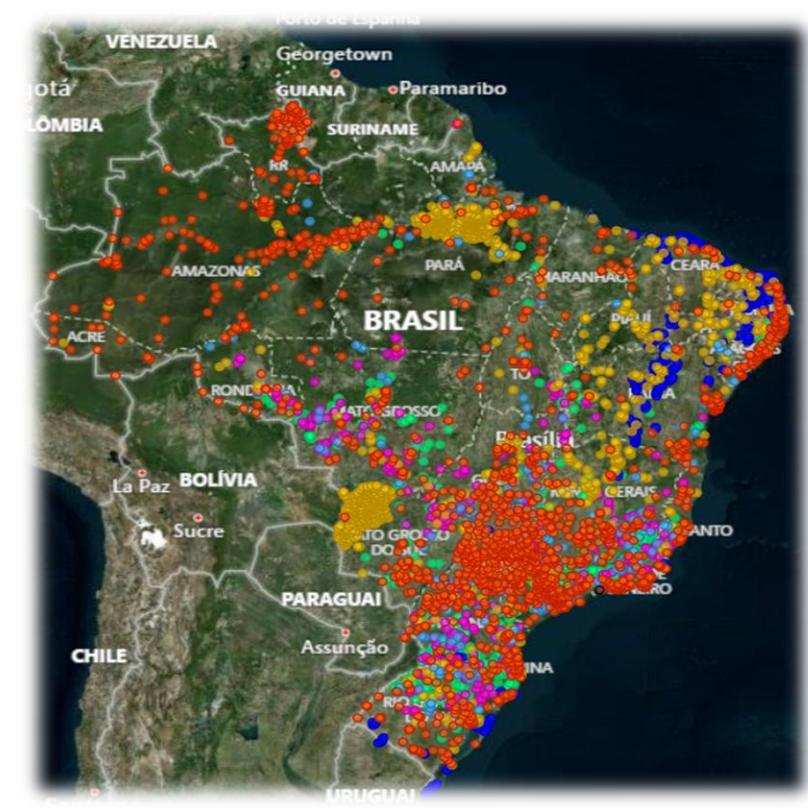
MMGD: Micro (<75 kW) and Mini Distributed Generation (<5MW) includes Solar, Small hydro, Biomass, Wind.

Source:
https://www.ons.org.br/AcervoDigital/DocumentosEPublicacoes/Revista%20PARPEL%20_2024_VF_27.12.24.pdf

BRAZILIAN POWER SECTOR



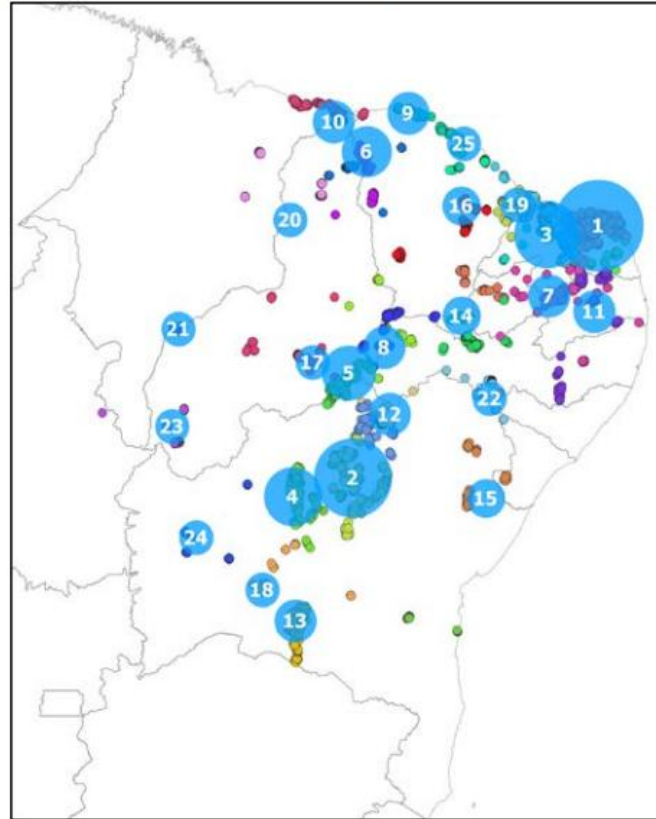
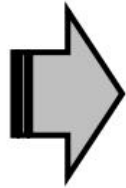
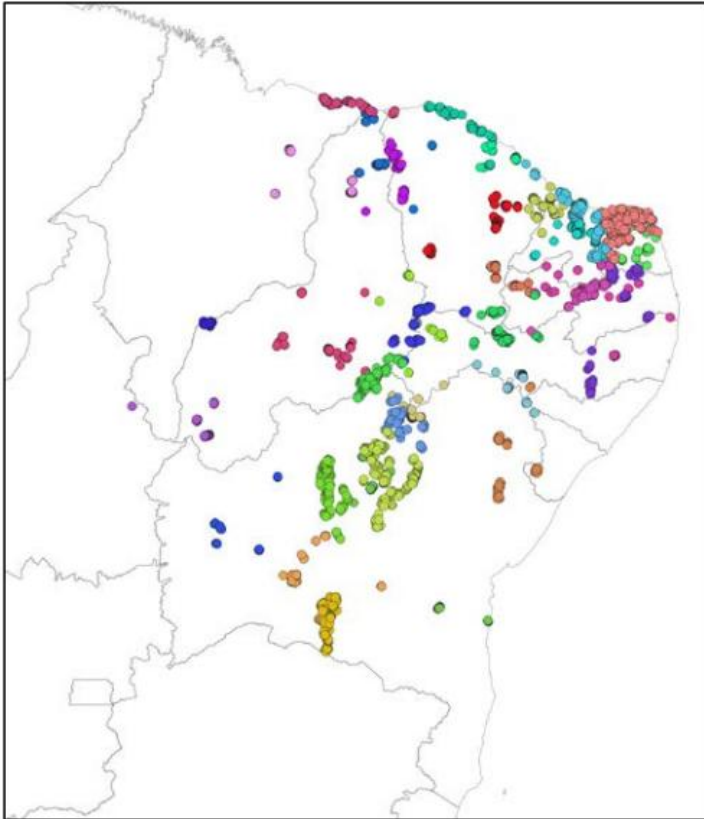
Source: EPE (Energy Research Office, Sept 2024)
 BRAZIL'S ACTION PLAN FOR RAPID DECARBONIZATION OF POWER SECTORS



CGH (Mini Hydro) | EOL (Wind) | PCH (Small Hydro) |
 UFV (Solar PV) | UHE (Large Hydro) | UTE (Thermal)
 | UTE (Nuclear)

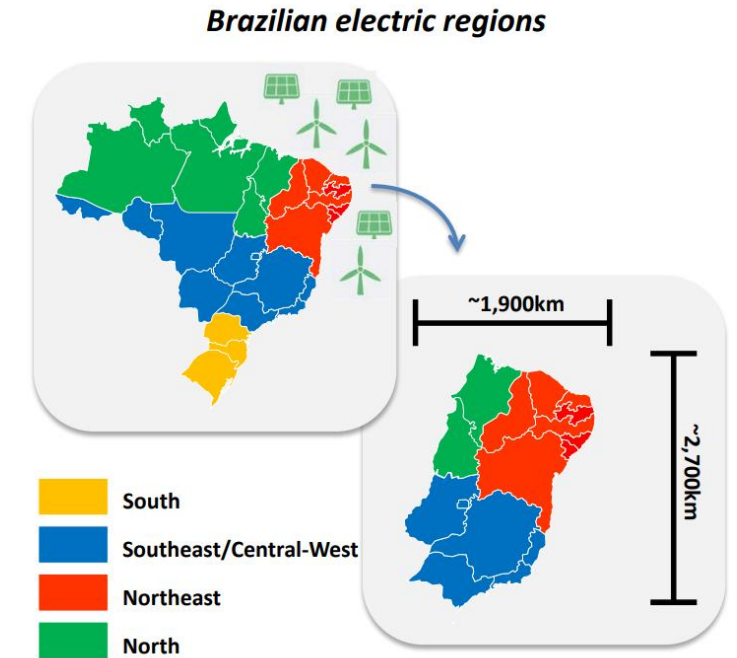
PROACTIVE TRANSMISSION PLANNING

Location of renewable projects (wind and solar)



Database: SIGEL (ANEEL), AEGE (EPE)
 1,845 projects; total installed capacity: 70 GW
 Reference: May 2021

Results from the clusterization process.
 Approx. 14-GW cluster size is proportional
 to the installed capacity.

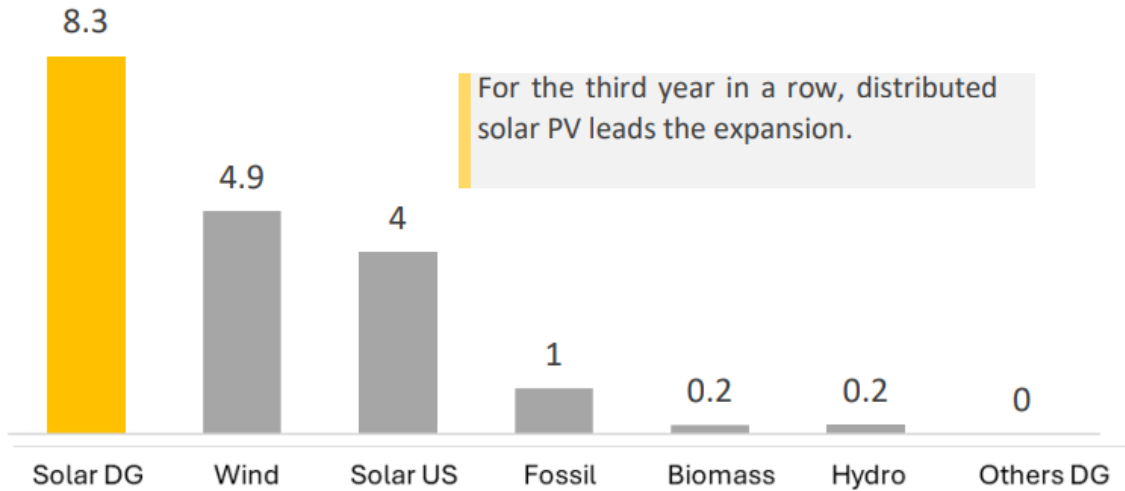


Source: EPE (Energy Research Office, Sept 2024)
BRAZIL'S ACTION
 PLANFORRAPIDDECARBONIZATI
 ONOF POWER SECTORS

BRAZIL AND THE RISE OF DISTRIBUTED GENERATION

In recent years

New capacity of power generation in 2023 [GW]



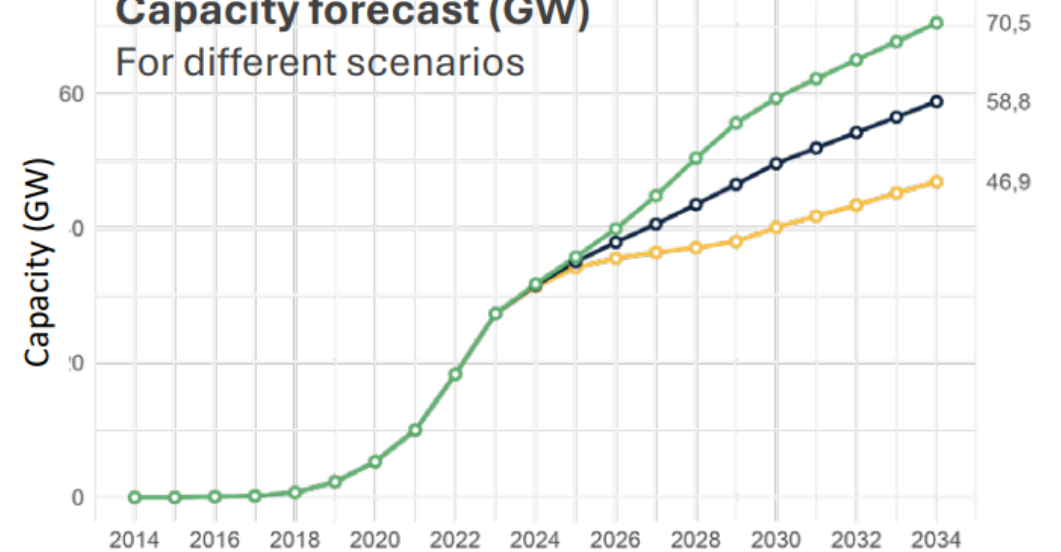
Source: EPE (Energy Research Office, Sept 2024)

BRAZIL'S ACTION PLAN FOR RAPID DECARBONIZATION OF POWER SECTORS

In the future

Capacity forecast (GW)

For different scenarios

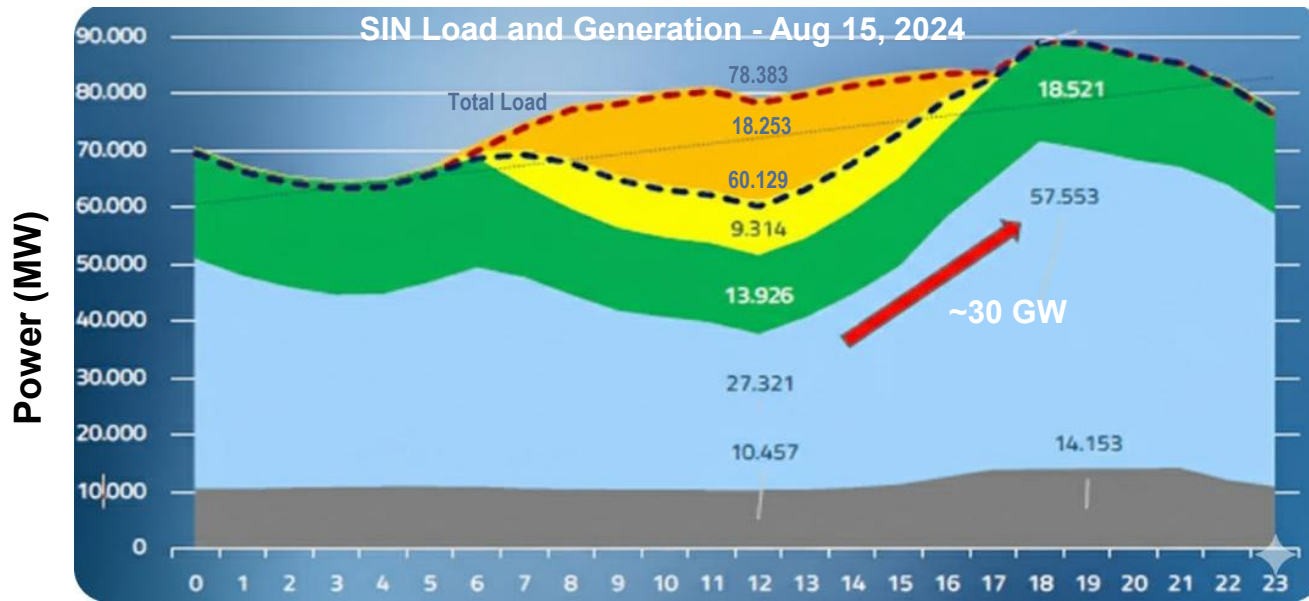


Scenarios
○ Lower ○ Reference ○ Upper

OPERATIONAL CHALLENGES OF SIN WITH VARIABLE GENERATION

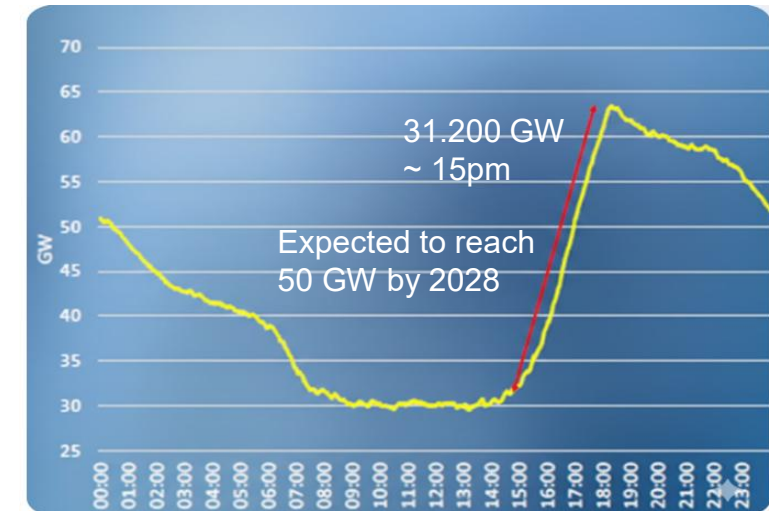


Challenges for SIN Operation



Thermal | Hydro | Wind | Centralized Solar PV | Distributed Generation | Global SIN Load | Net SIN Load | Net Load Linear

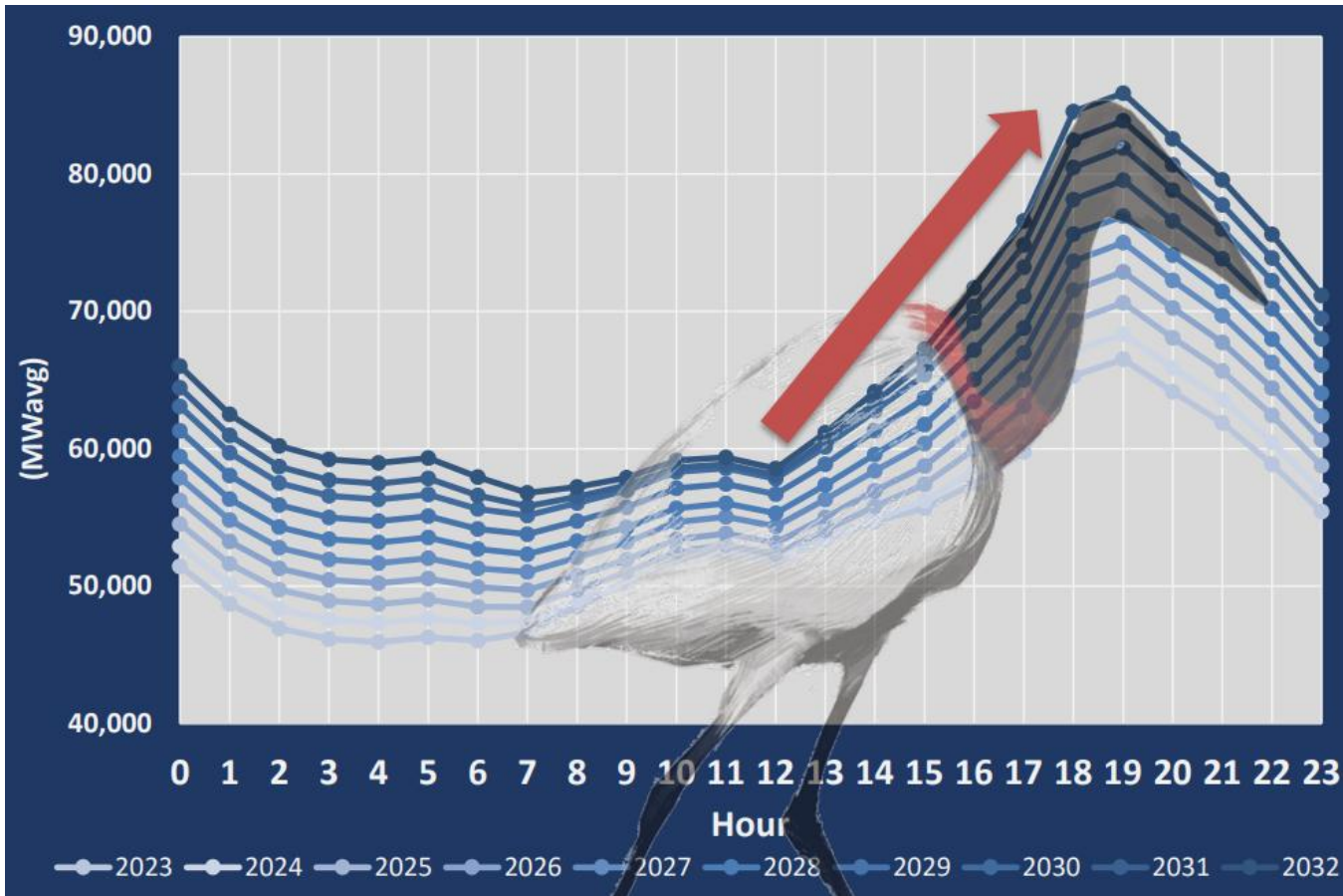
Largest Hydro Ramp on May 5, 2024



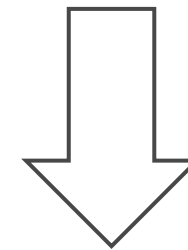
New Challenges to Operation Planning of SIN

- When Load < Non Dispatching Renewable Generation (Solar & Wind): **Curtailement**
- When Load Flow in Transmission Lines are Low (0-5 am and along the day): **Problems of Voltage Control**
- Ramps at the end of afternoon period: **Requires Flexible Sources**

FLEXIBILITY REQUIREMENTS ASSESSMENT



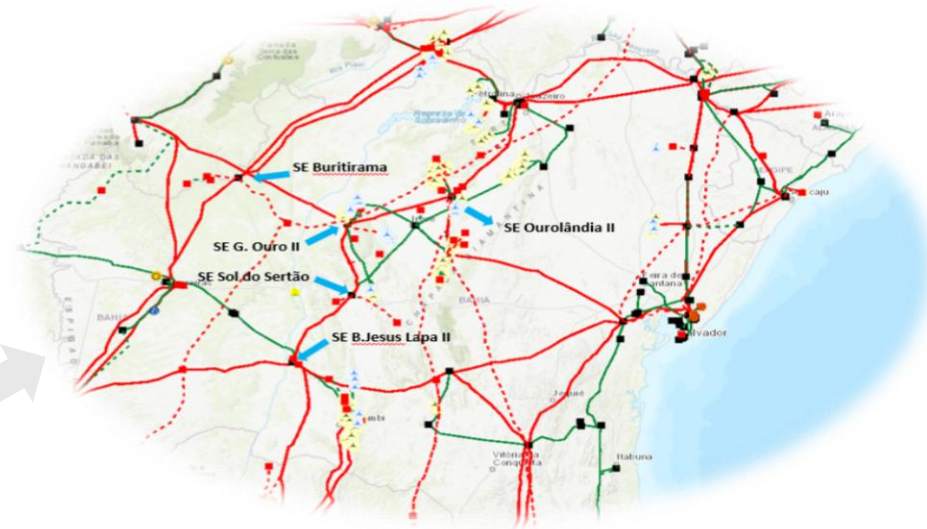
As the energy mix increasingly incorporates variable renewable sources, it becomes essential to track not just the average energy and capacity, but also the fluctuations in system demand



Energy Storage Systems

Source: EPE (Energy Research Office, Sept 2024)
 BRAZIL'S ACTION PLAN FOR RAPID DECARBONIZATION OF POWER SECTORS

WIND ENERGY COMPLEX



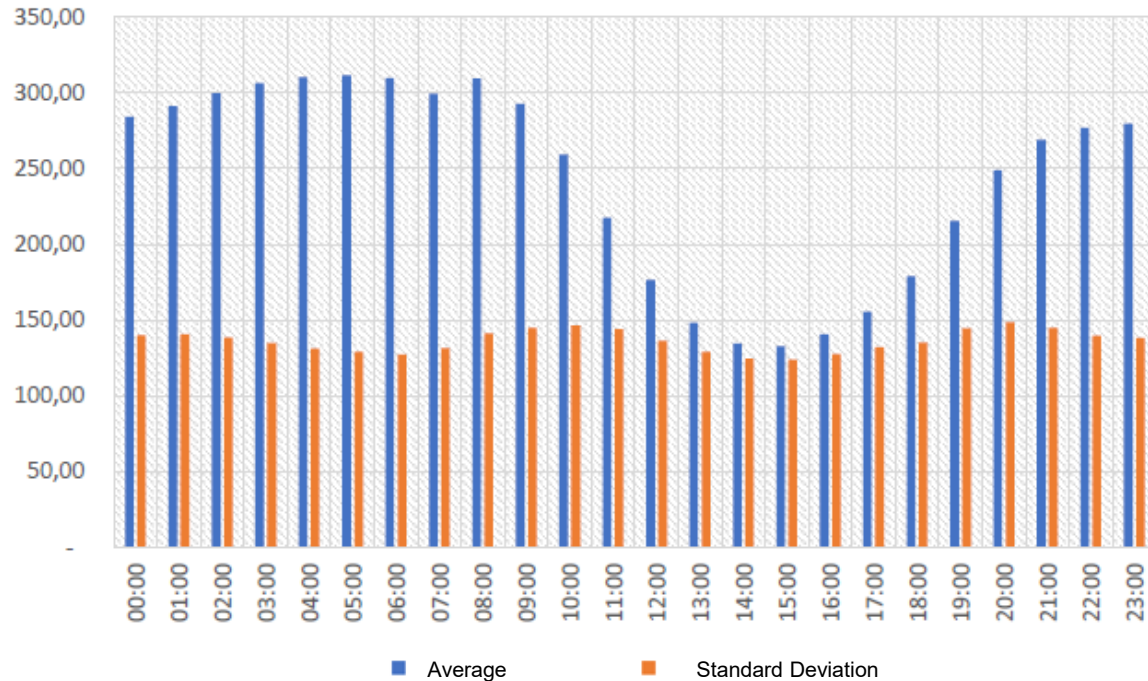
- Located in the interior of Bahia, Brazil
- Region that has attracted wind and solar renewable projects

Wind Complex

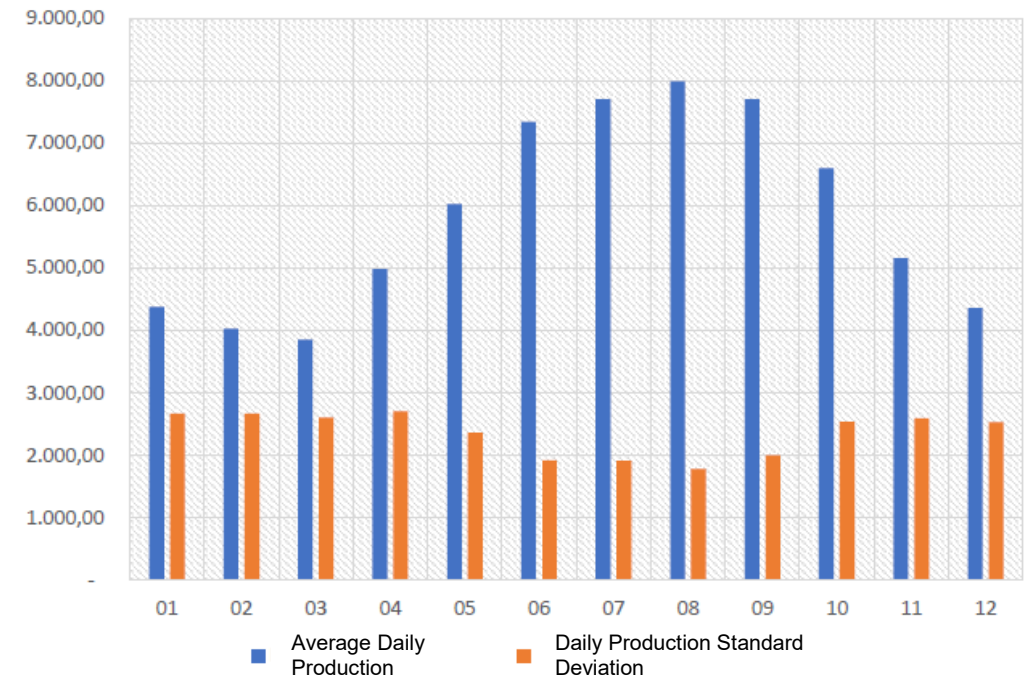
- Installed capacity: 465 MW
- Total of 75 wind turbines
- Initial capacity per turbine: 6.2 MW
- Operational analysis: 186 MW installed

WIND ENERGY COMPLEX

Hourly Variation of Simulated Average Wind Power Generation (MWh)



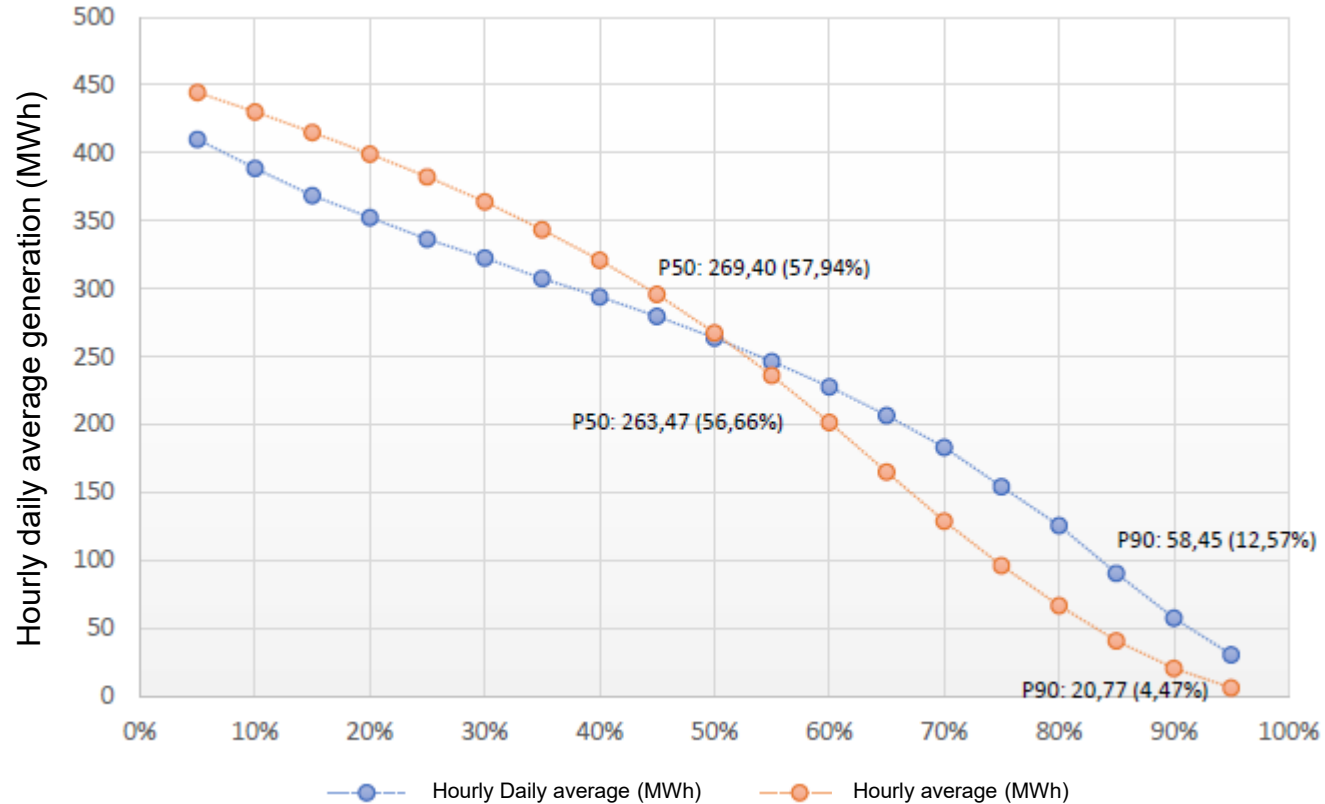
Variation of Simulated Daily Average Wind Power Generation over the Months (MWh)



•The analysis uses a **22-year simulated dataset (2000–2021)**, including losses from wake effect (7%), unavailability (2%), electrical efficiency (2.5%) and turbine performance (4.3%).

WIND ENERGY PARK

Duration curves for hourly production over the entire time series



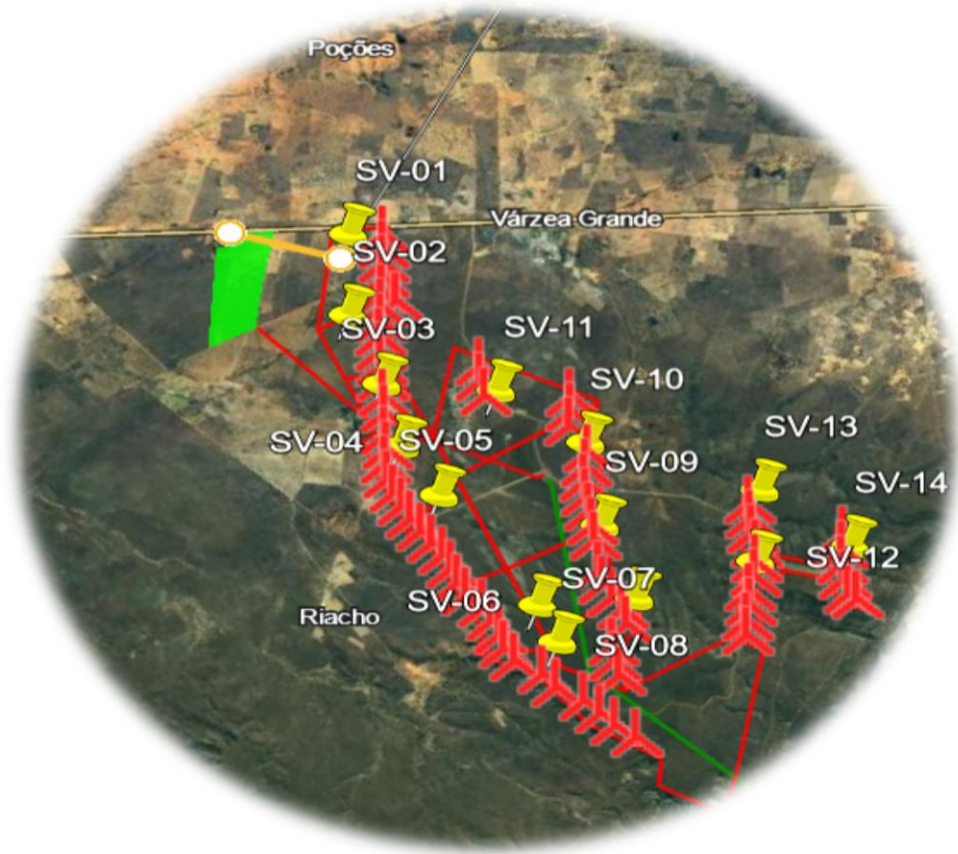
- Duration curves are widely used to assess the probabilistic availability of a resource in relation to demand.

- For wind power generation, they allow the identification of the minimum expected production for a given probability level.

$$PHD = \frac{PD}{24}$$

$$PMHD = \frac{\sum PHD}{n}$$

SOLAR ENERGY PARK



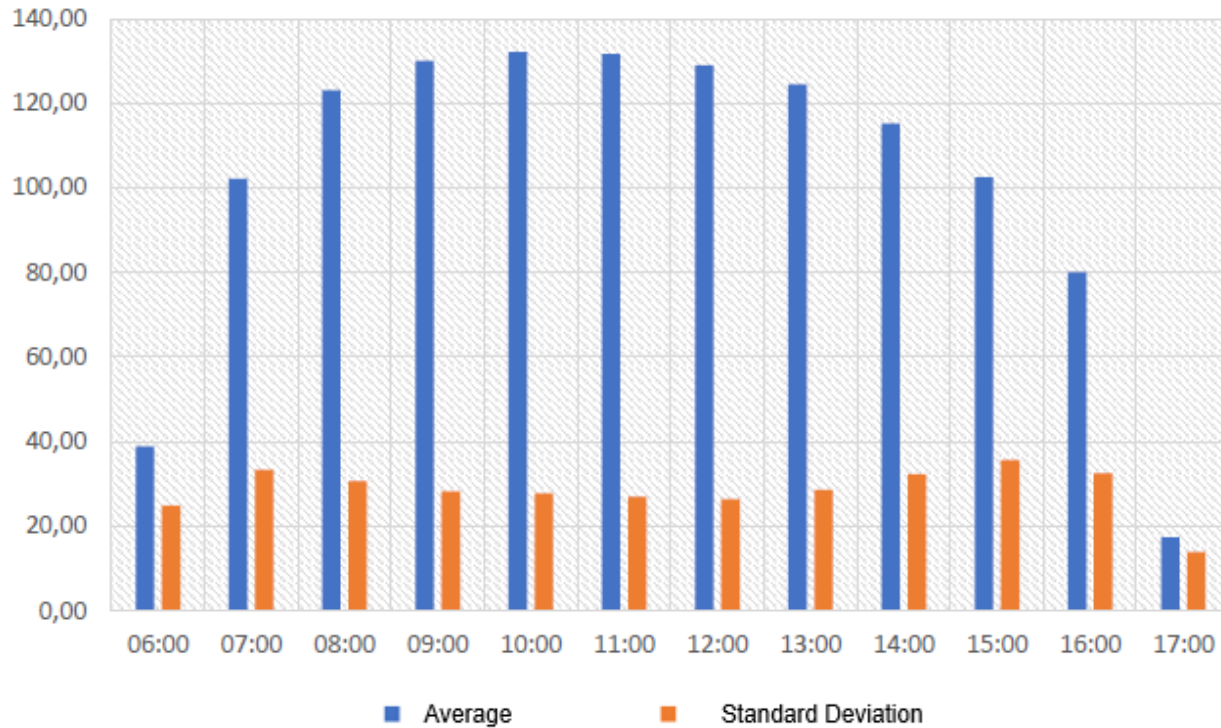
Power at Connection Point	kW	150,000.00
Installed Power (Inverter Limitation)	kW	155,633.76
Peak Power	kWp	179,452.80
DC-AC (Nominal)	%	13.29%
DC-AC (Actual)	%	15.30%
Strings – Number of Modules	units	31.00
Strings – Number of Strings	units	8,640

•Data Overview

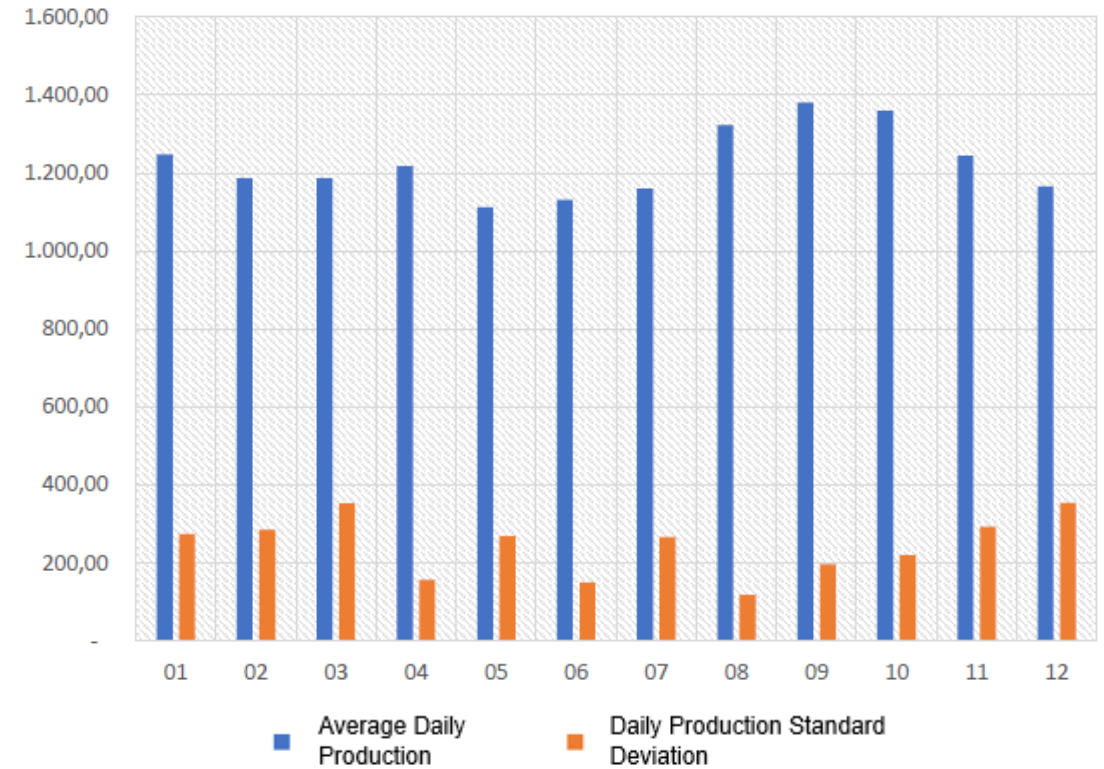
- 20-year PVsyst time series including panel degradation.
- Production only during daytime (06:00–17:00 for analysis).

SOLAR ENERGY PARK

Hourly Variation of Simulated Average Solar Power Generation (MWh)

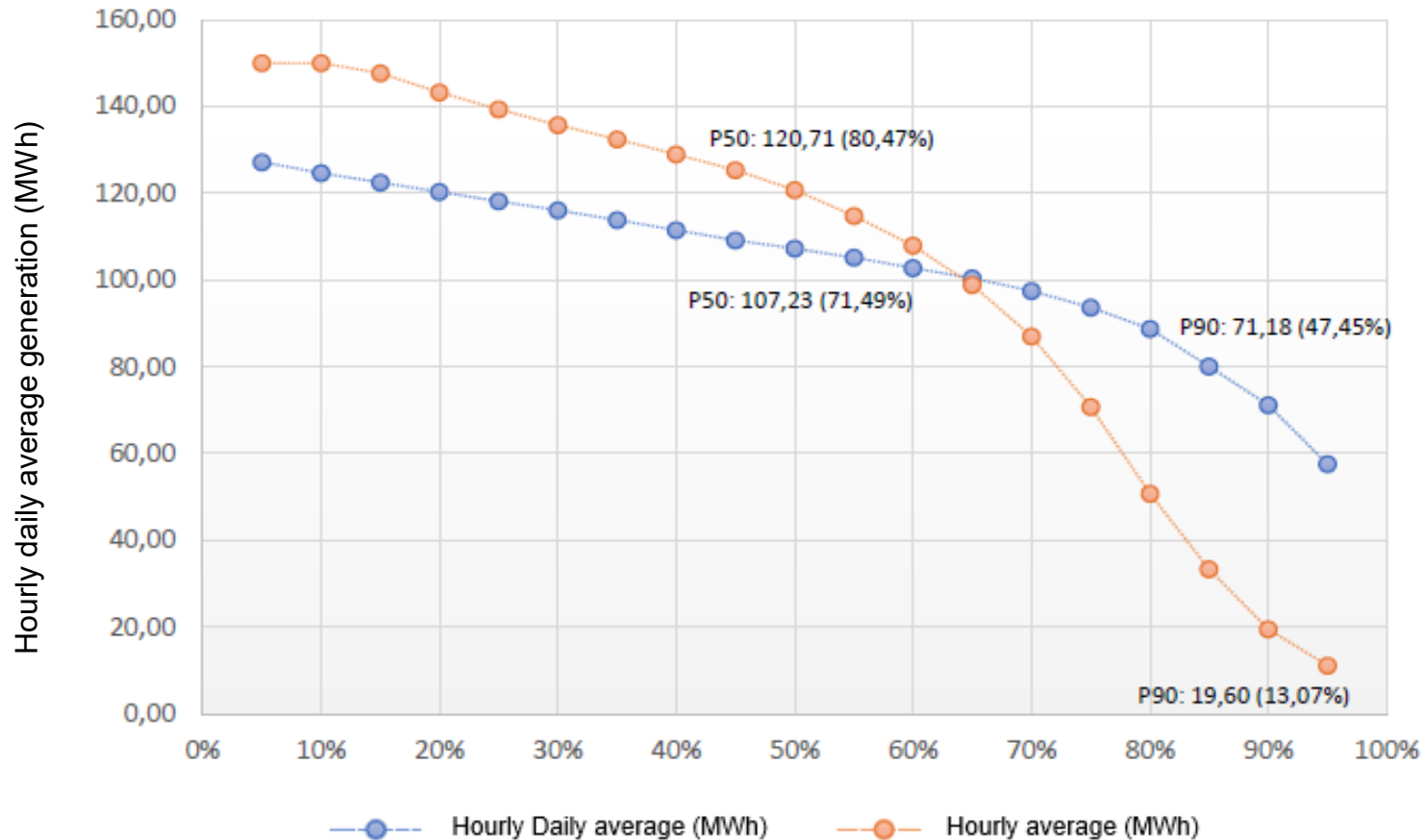


Variation of Simulated Daily Average Solar Power Generation over the Months (MWh)



SOLAR ENERGY PARK

Hourly Average Duration Curve for Solar Generation



- Duration Curve: shows the fraction of time generation stays above specific levels
→ helps assess variability and plant performance
- P50 (Median): typical generation level (50% of the time generation \geq P50)
- P90 (Conservative): low-end generation level (90% of the time generation \geq P90)
→ supports risk assessment and reliable planning

Analysis of hourly solar generation during operating hours (6:00–17:00)

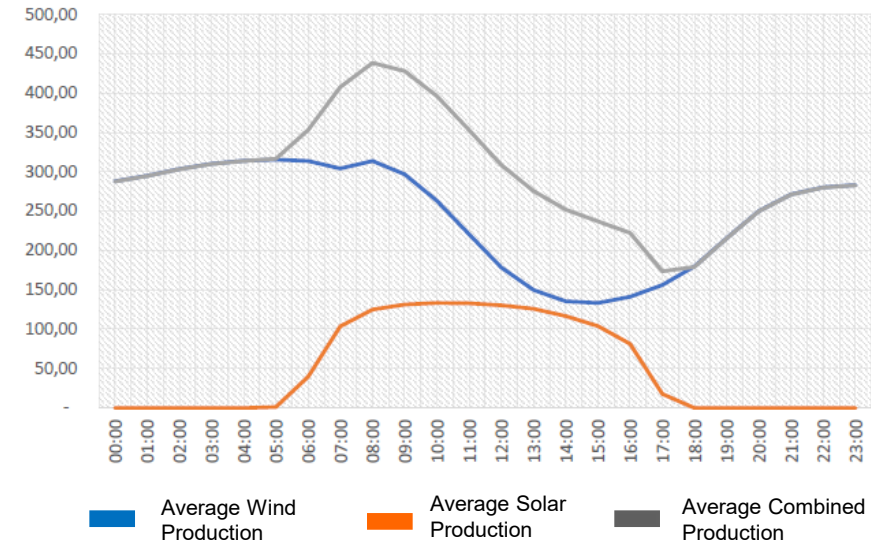
In 50% of the cases, generation \geq 120.71 MWh
→ equivalent to 80.47% of installed capacity

In 90% of the days, average hourly production \geq 71.18 MWh
→ capacity factor of 47.45%

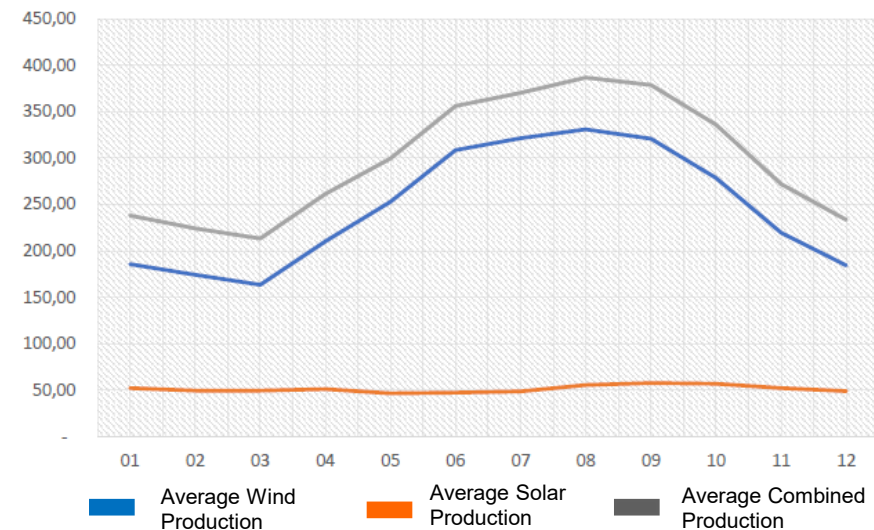
HYBRID ENERGY PARK (SOLAR + WIND)

Installed Capacity (MW)	615 MW
Average Hourly Production (kWh)	297,829.47
Average Capacity Factor (%)	48.43%
Minimum Hourly Production (kWh)	-512.72
Maximum Hourly Production (kWh)	617,926.46
Hourly Production Standard Deviation (kWh)	154,405.48
Hourly Coefficient of Variation (%)	51.84%
Average Daily Production (kWh)	7,147,825.66
Minimum Daily Production (kWh)	538,827.26
Maximum Daily Production (kWh)	12,429,075.62
Daily Production Standard Deviation (kWh)	2,817,828.51
Daily Coefficient of Variation (%)	39.42%

Variation of the Simulated Average Hourly Generation (MWh)

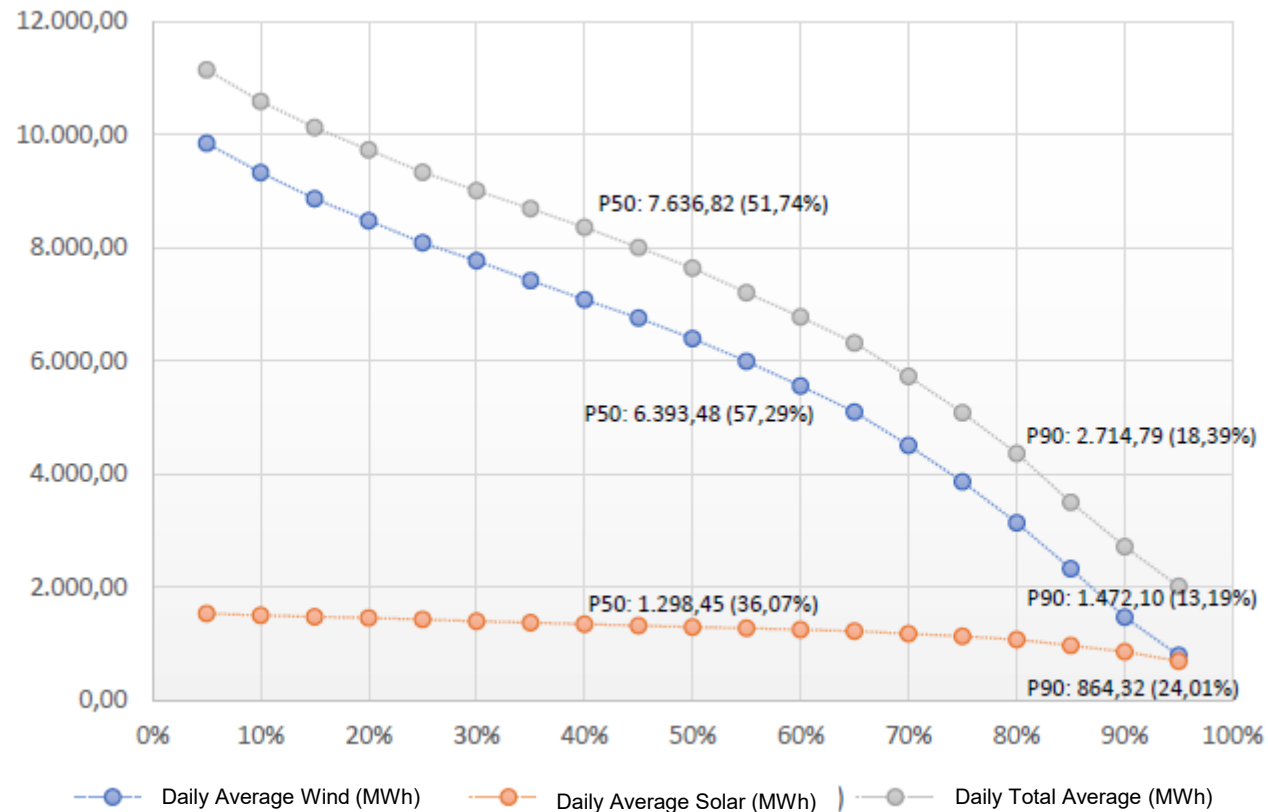


Variation of Simulated Combined Generation over the Months (MWh)



HYBRID ENERGY PARK (SOLAR + WIND)

Daily Average Duration Curve of the Combined Plant



•Generation Duration Curve

•Similar to the analysis of wind and solar generation, the generation duration curve of the associated plant is presented.

•It is visually evident that wind generation has a strong influence on the total generation of the associated plant.

•This is expected, as the main objective of the associated generation in this case was to exploit the complementarity of solar generation with wind, optimizing the use of the contracted MUST.

•Daily Average Generation Probabilities

•**50% probability:** Total daily average generation $\geq 7,621$ MWh (≈ 318 MWh hourly).

•**90% probability:** Total daily average generation $\geq 2,698$ MWh (≈ 112 MWh hourly).

•Implications for Optimization

- Detailed analysis of this graph provides important insights for:
 - Optimizing the use of MUST.
 - Sizing and planning energy storage (batteries)

COMPUTATIONAL IMPLEMENTATION: OPTIMIZATION

Input Parameters

- **Time-Dependent Variables**
 - Any parameter or decision variable with a temporal reference (suffix **[t]**) varies at each time step.
- **Associated Generation**
 - Hourly wind and solar generation over a 20-year period.
 - Determines the size of the temporal series.
- **Series Size**
 - **Full series:** 175,200 hourly records.
 - **Sample series:** 240 weeks → 40,320 records (~23% of total).

Key Variables

- $ger[t]$ – Total net generation of the associated plant at time t [MWh].
- $cbessmax[t]$ – Maximum battery charge at time t [MW]
 - Calculated as excess energy: $ger[t] - MUST$.
- $dbessmax[t]$ – Maximum battery discharge at time t [MW]
 - Calculated as $MUST - ger[t]$.

Decision Variables

- $bess_cap$: BESS storage capacity [MWh]
- $bess_pmax$: Battery installed power [MW]
- $bess_duration$: Battery duration [h] (simulated for 1h, 2h, and 4h Set to 0 if the battery cannot be discharged).
- $charge[t]$ and $discharge[t]$: Battery power flow [MW]
- $storage[t]$: Energy stored at time t [MWh]
- $curtailment[t]$: Energy discarded after battery usage [MWh]

Applied Constraints

- **Battery Capacity Constraint**
 $bess_cap = bess_pmax \times bess_duration$ → Battery capacity equals installed power times duration

COMPUTATIONAL IMPLEMENTATION: VALIDATION

Objective Function

$$\sum_{t=0}^T \text{curtailment}[t] \times \text{prob}[t]$$

•Key Input Parameter

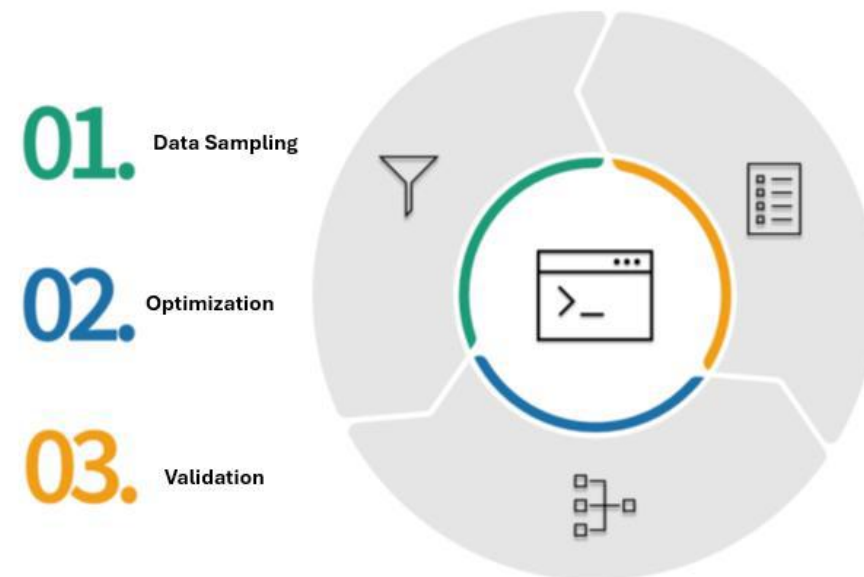
- Hourly series of renewable generation (wind/solar).
- Used in both full and reduced forms.

•Phase I Objective

- Minimize curtailment.

•Scenario Probabilities

- Each reduced observation has an associated probability from the scenario reduction algorithm.
- Probabilities are used to weight each scenario appropriately in the optimization.



RESULTS & DISCUSSION

Parameters Evaluated

- **MUST** (minimum generation requirement, MW): 465 and 480 MW
- **Battery Duration (h)**: 1, 2, and 4 hours
- **Maximum Investment (M USD)**: 20, 50, 100 M USD

Experimental Design

- Optimizer initially developed and calibrated using only reduced time series.

• Performance Metric

Lowest investment cost per discharged MW

Best Results

- **MUST**: 465 MW
- **Maximum Investment**: 20 M USD
- **Battery Duration**: 2–4 hours
- **Costs**: 95.38 and 93.72 USD/MW

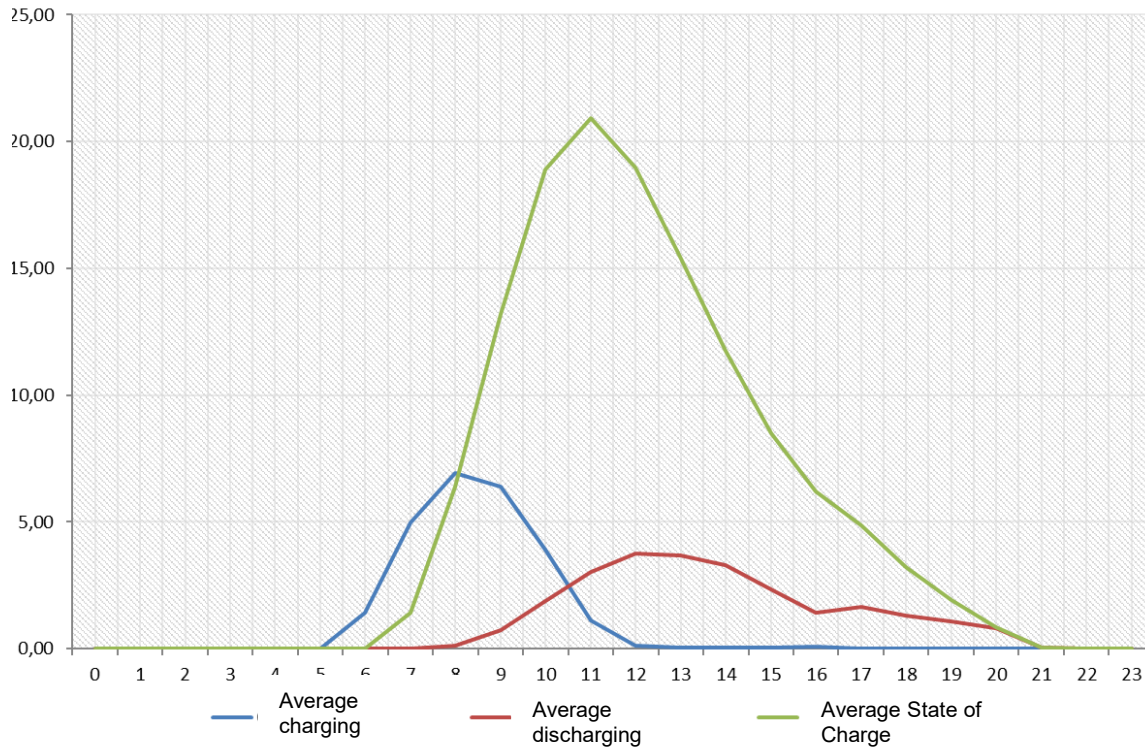


CONCLUSION AND OUTLOOK

Must (MW)	Duration (h)	Max Investment (M USD)	Capacity (MWh)	Installed Power (MW)	Total Cost (1M USD)	Total Discharged Energy (GW)	Cost per Discharged MW (USD/MW)	Charge/Discharge Cycles)
465	1	20	41	41	19,93	171,05	116,49	4.672
465	1	50	102	102	49,57	390,78	126,85	4.672
465	1	100	205	205	99,63	695,54	143,24	4.672
465	2	20	50	25	19,25	201,83	95,38	4.672
465	2	50	128	64	49,28	473,66	104,04	4.672
465	2	100	258	129	99,33	823,24	120,66	4.672
465	4	20	56	14	18,82	200,76	93,72	4.672
465	4	50	148	37	49,73	495,57	100,35	4.672
465	4	100	296	74	99,46	875,64	113,58	4.672
480	1	20	41	41	19,93	159,24	125,13	4.318
480	1	50	102	102	49,57	359,38	137,94	4.318
480	1	100	205	205	99,63	625,72	159,22	4.318
480	2	20	50	25	19,25	187,14	102,86	4.318
480	2	50	128	64	49,28	433,21	113,76	4.318
480	2	100	258	129	99,33	733,10	135,49	4.318
480	4	20	56	14	18,82	183,48	102,55	4.318
480	4	50	148	37	49,73	449,14	110,72	4.318
480	4	100	296	74	99,46	778,70	127,72	4.318

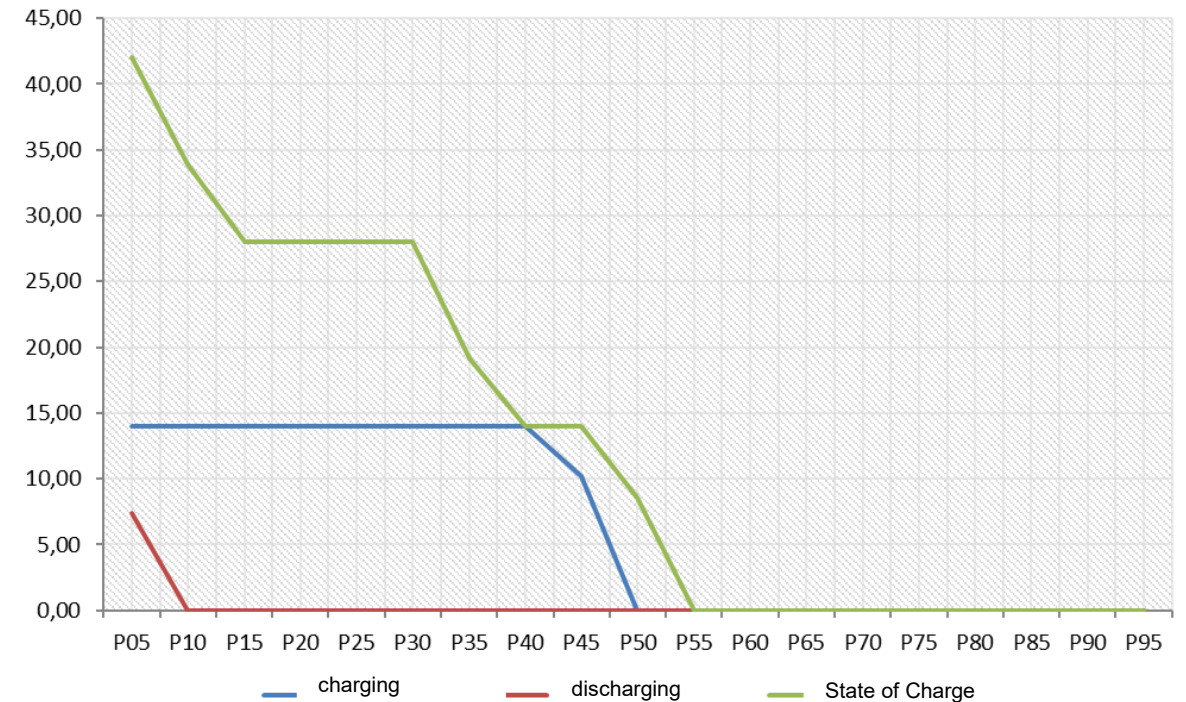
COMPUTATIONAL IMPLEMENTATION: VALIDATION

General Validation Results – Hourly Average Values Chart



- MUST (MW): 480.00
- Duration (h): 4.00
- Maximum Cost (USD million): 20.00
- Energy Capacity (MWh): 56.00
- Installed Power (MW): 14.00
- Total Cost (USD million): 18.82

Validation Results – Hourly Duration Curve



- Total Discharge (GWh): 183.48
- **Cost per Discharge (USD/MWh): 102.55**
- Charge/Discharge Cycles: 4,318



IZABELLA CARNEIRO BASTOS

LEHRSTUHL FÜR ENERGIEVERBUNDTECHNIK
MONTANUNIVERSITÄT LEOBEN



www.evt-unileoben.at



evt@unileoben.ac.at



03842 402 5400