

Optimal Sizing of Storage Systems for Hybrid RES-BESS Projects

Parametric analysis for optimal size of BESS component

Athens, November 2023

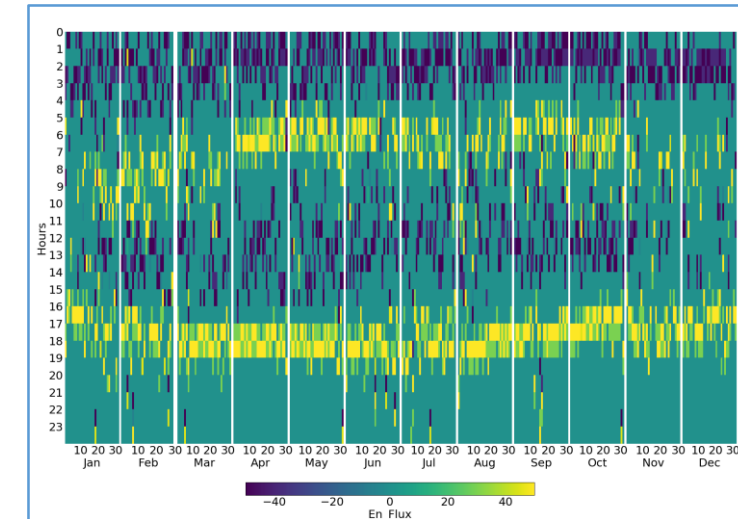
BESS operation optimization tool

- Stand-alone BESS or Hybrid RES-BESS plants
- BESS can charge from the RES units or both from RES and the grid
- Charge/discharge throughput on hourly basis
- Charge/discharge cycles limit
- Battery roundtrip efficiency and degradation

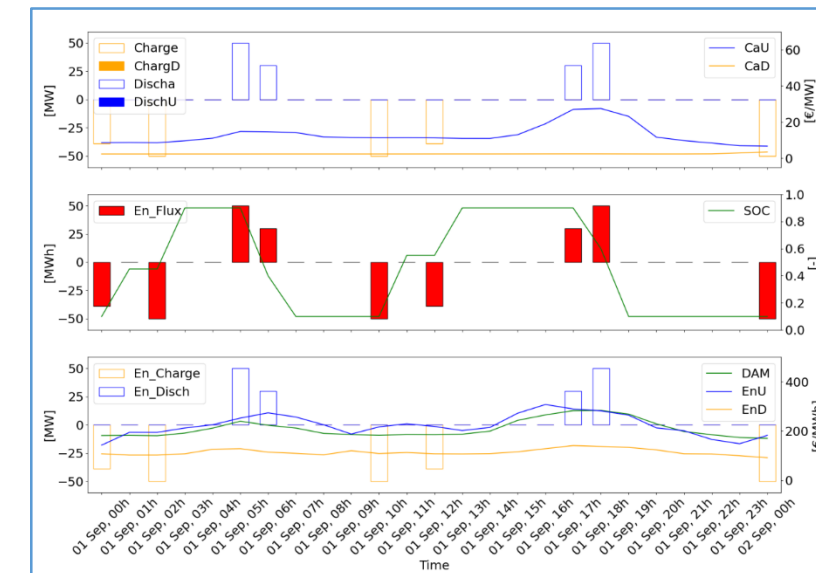
- Revenues from
 - Fixed electricity selling price
 - Participation in the free market (day-ahead)
 - Auxiliary services to the grid (balancing market)

- Implementation of actual price time-series of the capacity and energy markets
- Revenue maximization for given time-series of capacity and energy markets prices, based on historical prices or scenarios prices

- Optimization of BESS power and capacity sizing



Full year energy flux heatmap in (MWh)



Optimized daily power/energy throughput and market prices

Simulations

- Various WF/PV locations in Greece
- 100MW_p Wind farm, 100MW_p PV plant
- BESS: 2.5MW step for useful BESS power output, 2-hour storage, 0.85 useful/nominal ratio, 85% RTE

Category D1 projects

- Hybrid RES-ESS plants
- Total RES units installed power $\geq 100\text{MW}$
- ESS unit not allowed to charge from the grid but only from the RES units
- 15' mean power injection of the hybrid RES-ESS system to the grid cannot exceed the nominal capacity of the ESS component
- Minimum 2-hour storage

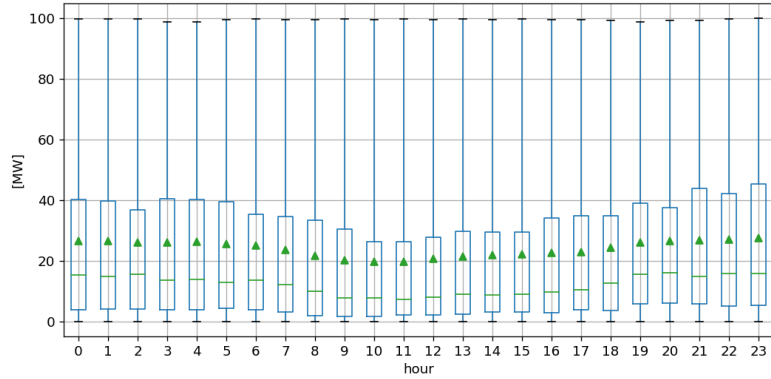
Financial

- Simplified IRR calculations for 20 year projects
- Fixed electricity selling price 60€/MWh
- Sub-station (SS) capacity considered equal to BESS useful power output for hybrid plants, or equal to RES installed power for RES-only plants
- WF: 900 k€/MW, annual OPEX 2.9% of CAPEX
- PV: 580 k€/MW, annual OPEX 1.5% of CAPEX
- BESS: 690 k€/MW (useful storage), annual OPEX 1.4% of CAPEX
- SS: 60 k€/MW
- No BESS augmentation costs considered

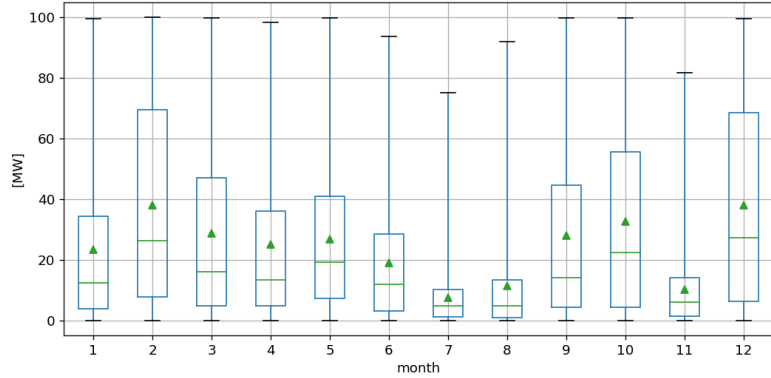
WF - BESS configurations

Makedonia

Boxplot grouped by hour
WF_Power [MW]

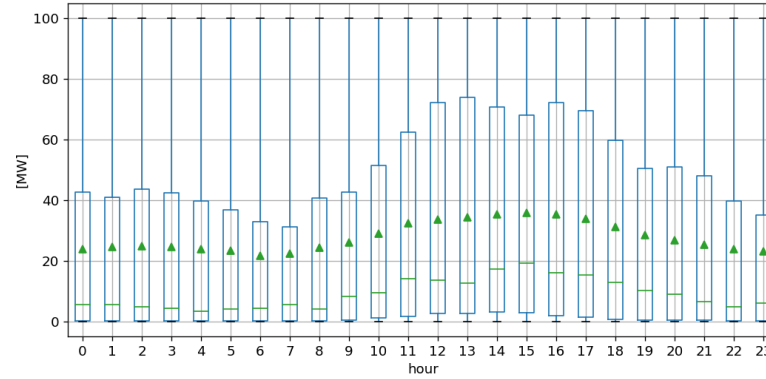


Boxplot grouped by month
WF_Power [MW]

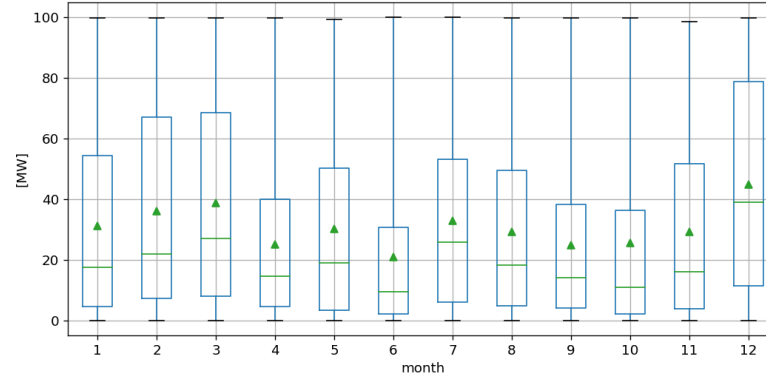


Fokida

Boxplot grouped by hour
WF_Power [MW]

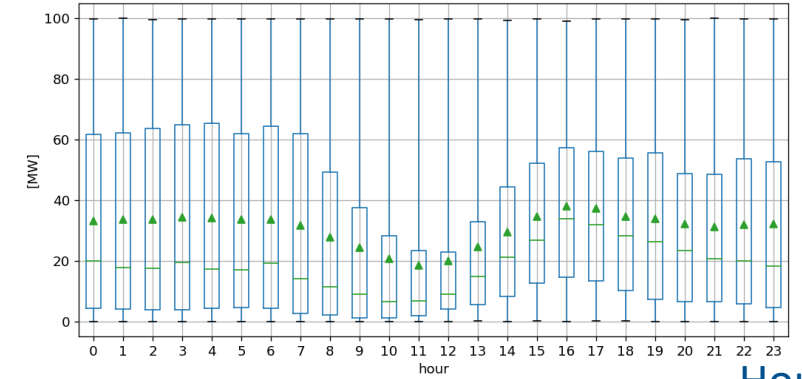


Boxplot grouped by month
WF_Power [MW]

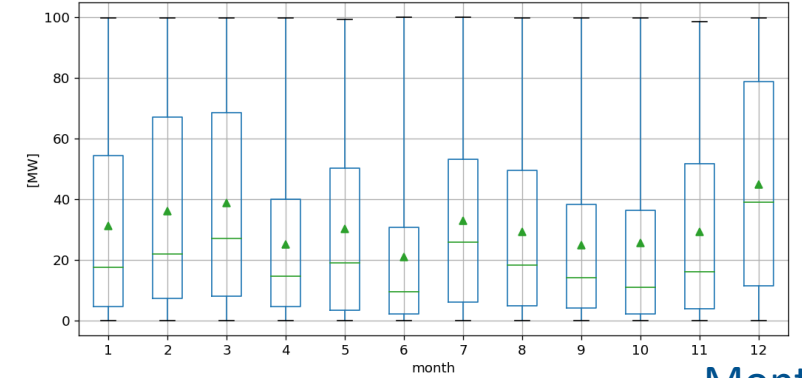


Ioannina

Boxplot grouped by hour
WF_Power [MW]



Boxplot grouped by month
WF_Power [MW]



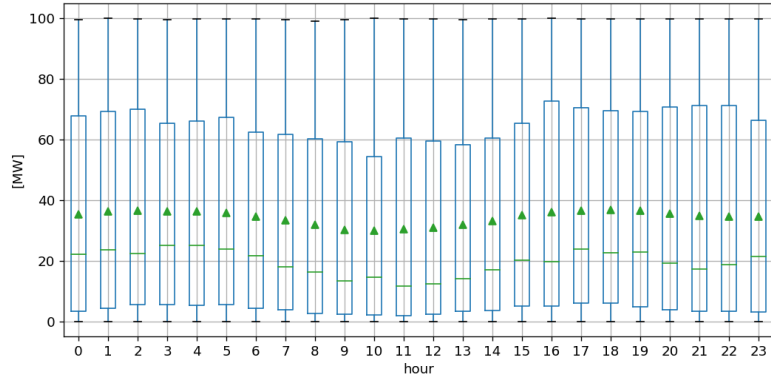
Hourly

Monthly

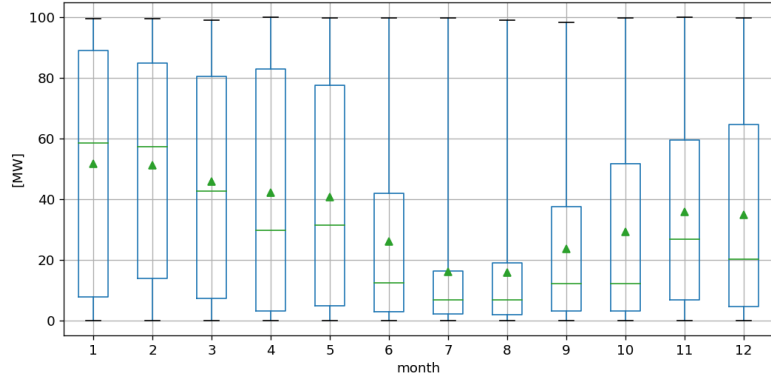
Location	WF CF	WF var [%]
Makedonia	24.0%	27.8%
Fokida	27.8%	34.7%
Ioannina	30.8%	31.0%
Mani	34.3%	34.6%
Rodopi	37.8%	39.2%
Kafireas	40.4%	36.5%

Mani

Boxplot grouped by hour
WF_Power [MW]

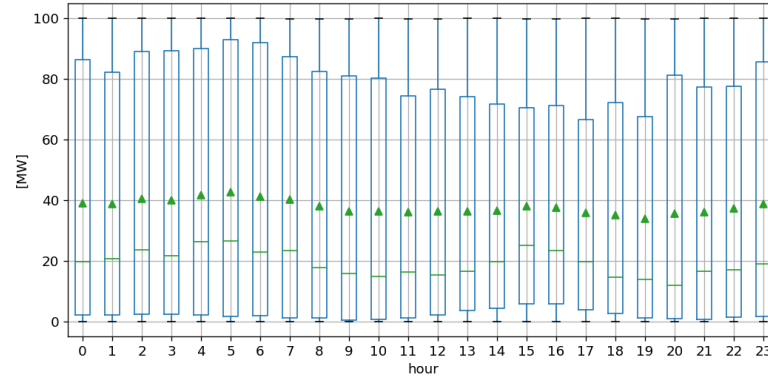


Boxplot grouped by month
WF_Power [MW]

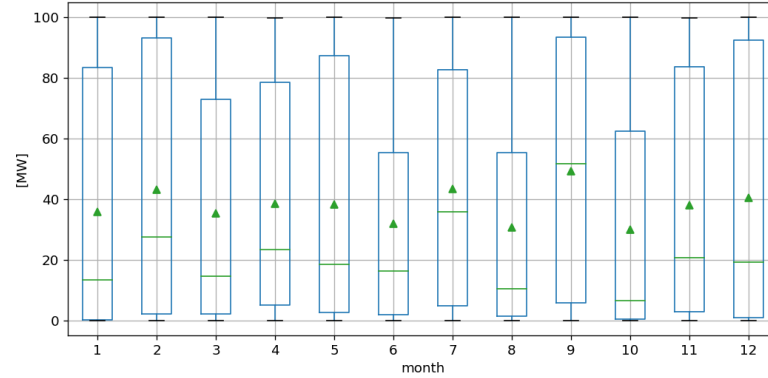


Rodopi

Boxplot grouped by hour
WF_Power [MW]

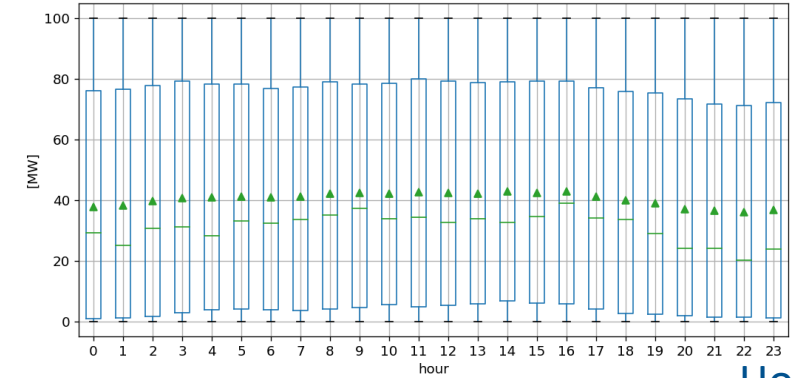


Boxplot grouped by month
WF_Power [MW]

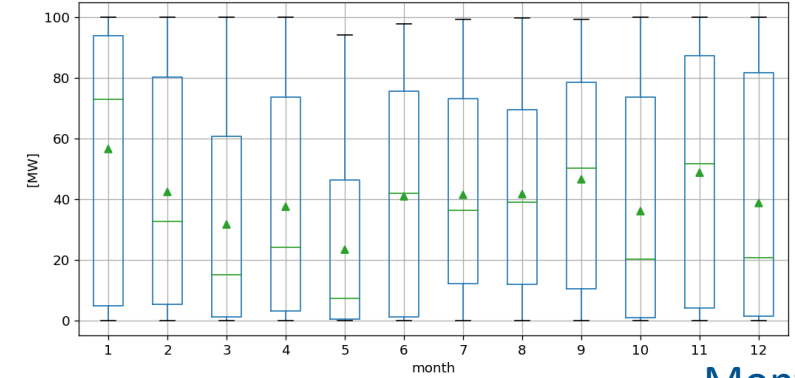


Kafireas

Boxplot grouped by hour
WF_Power [MW]



Boxplot grouped by month
WF_Power [MW]



Hourly

Monthly

Location	WF CF	WF var [%]
Macedonia	24.0%	27.8%
Fokida	27.8%	34.7%
Ioannina	30.8%	31.0%
Mani	34.3%	34.6%
Rodopi	37.8%	39.2%
Kafireas	40.4%	36.5%

Results

- Optimal BESS size increases with CF and production variability
- Min 67.5MW/135MWh
- Max 85.0MW/170MWh
- BESS useful power output 67.5% to 85.0% of WF
- 2% to 6% of production discarded
- 0.2 to 0.3 average daily charge/discharge cycles

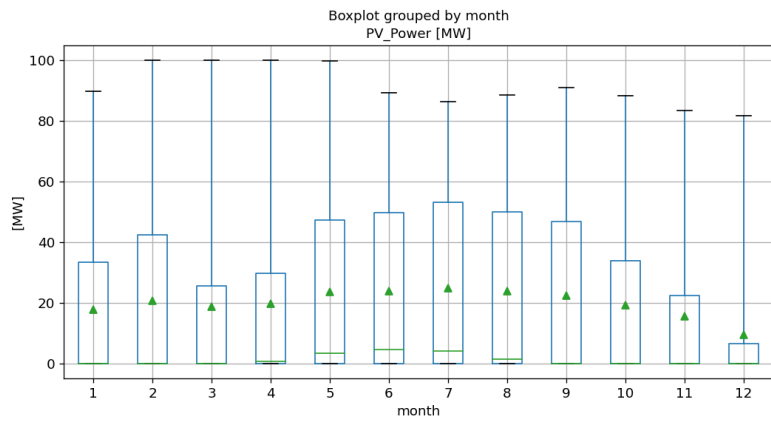
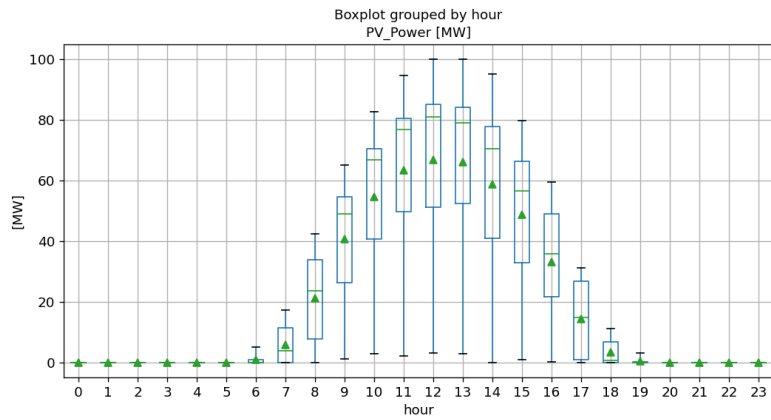
No curtailment schedule applied

Location	WF (no BESS)		
	Annual Revenue [M€]	IRR [%]	CAPEX [M€]
Makedonia	12.7	8.2	96.0
Fokida	14.6	10.8	
Ioannina	16.2	12.8	
Mani	18.1	15.1	
Rodopi	19.9	17.2	
Kafireas	21.3	18.8	

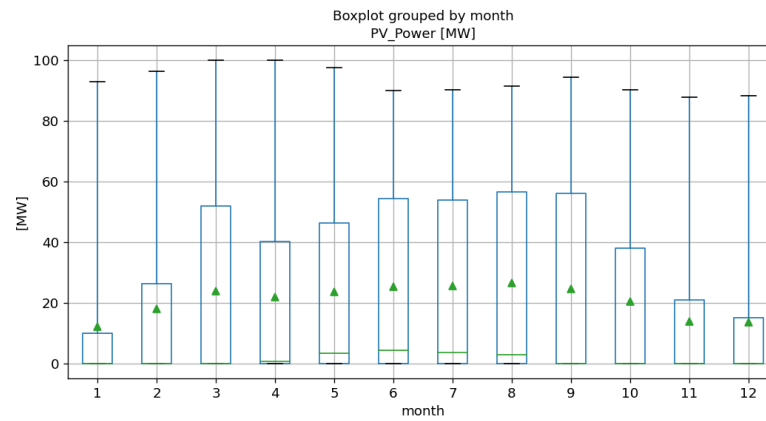
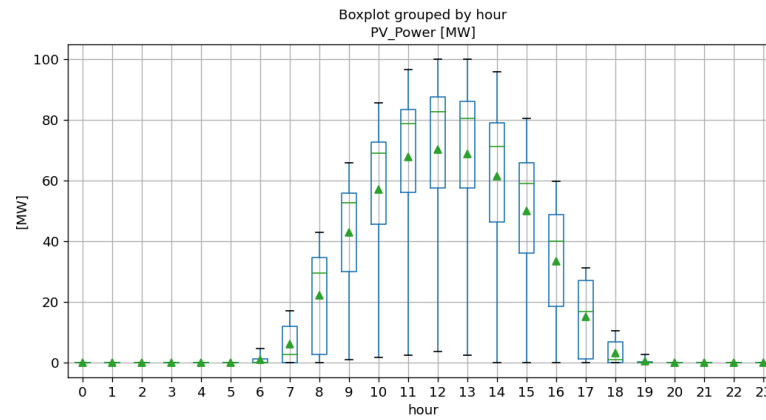
Location	WF CF ↑	WF var [%]	Opt BESS [MW]	RES to Grid [%]	RES to BESS [%]	Discarded [%]	Ave. daily cycles	Annual Revenue [M€]	IRR [%]	CAPEX [M€]
Makedonia	24.0%	27.8%	67.5	89.1	5.2	5.7	0.19	11.8	1.9	140.6
Fokida	27.8%	34.7%	80.0	90.8	6.0	3.2	0.21	14.0	3.5	150.0
Ioannina	30.8%	31.0%	67.5	87.6	6.8	5.6	0.32	15.1	5.5	140.6
Mani	34.3%	34.6%	80.0	91.4	5.3	3.3	0.23	17.3	6.8	150.0
Rodopi	37.8%	39.2%	85.0	90.9	7.0	2.2	0.32	19.2	8.1	153.8
Kafireas	40.4%	36.5%	80.0	91.2	5.2	3.6	0.27	20.4	9.4	150.0

PV - BESS configurations

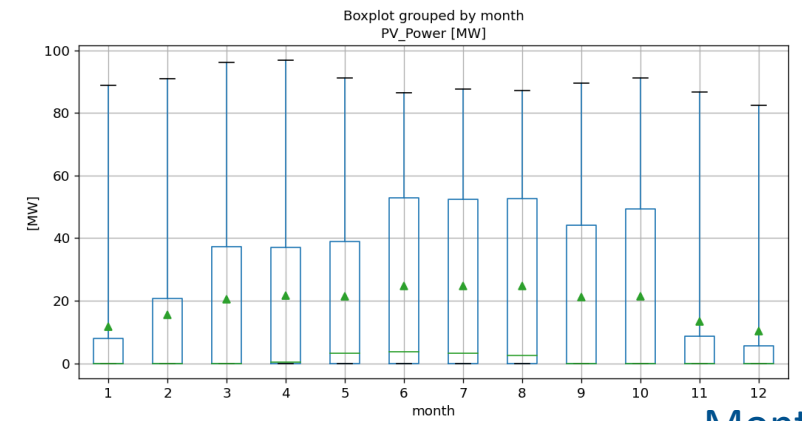
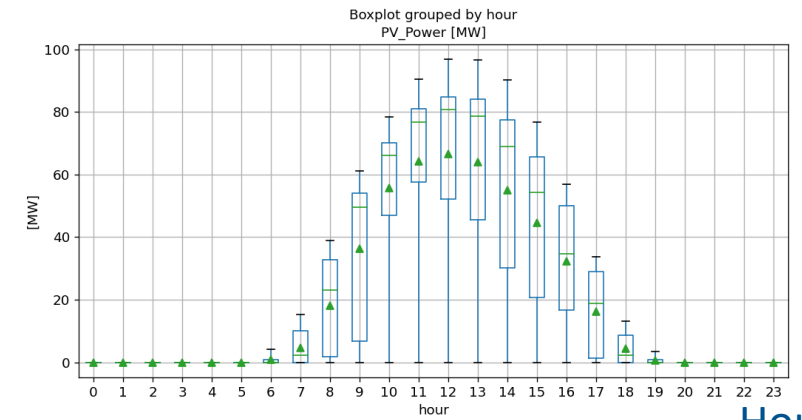
Makedonia



Fokida



Ioannina

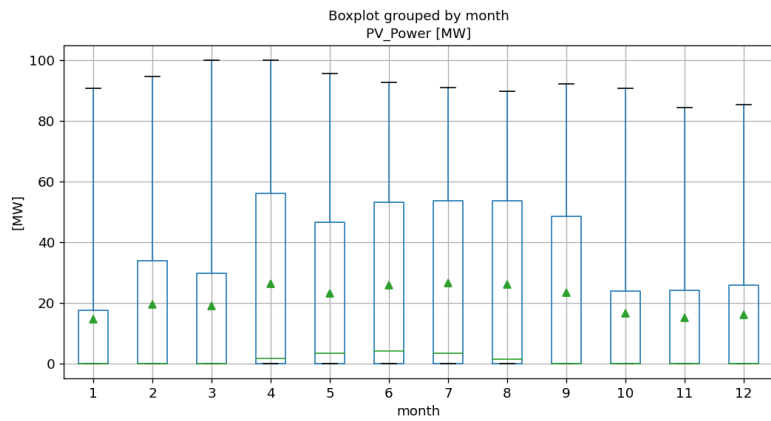
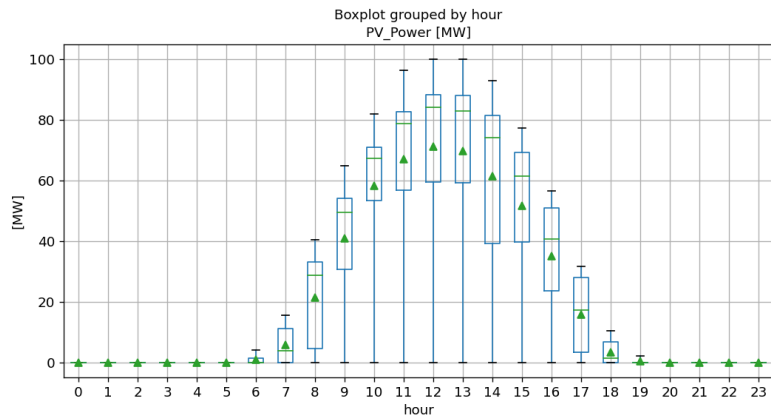


Hourly

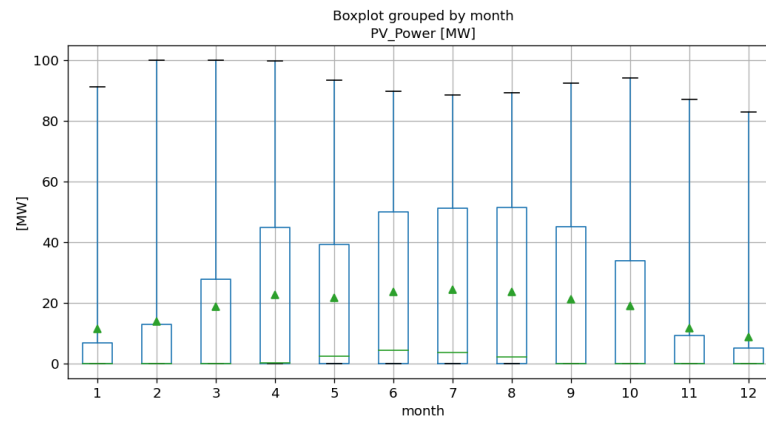
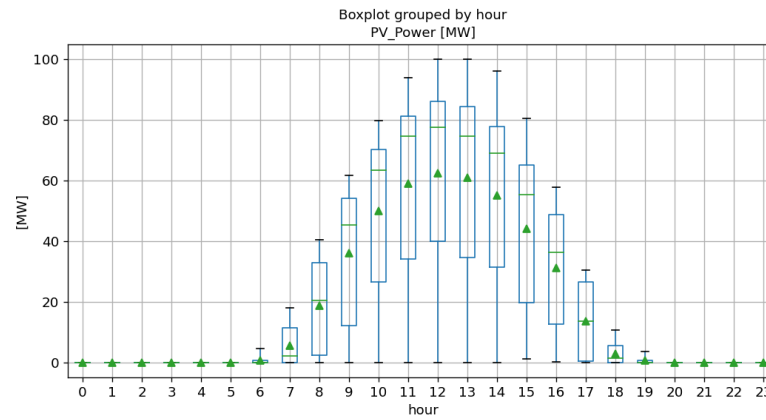
Monthly

Location	PV CF	PV var [%]
Makedonia	19.9%	29.3%
Fokida	20.8%	30.2%
Ioannina	19.3%	28.9%
Mani	21.0%	30.4%
Rodopi	18.4%	28.4%
Kafireas	20.2%	30.4%

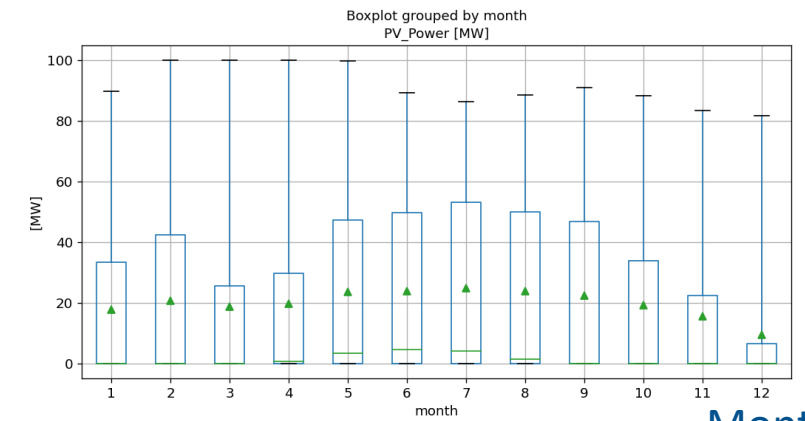
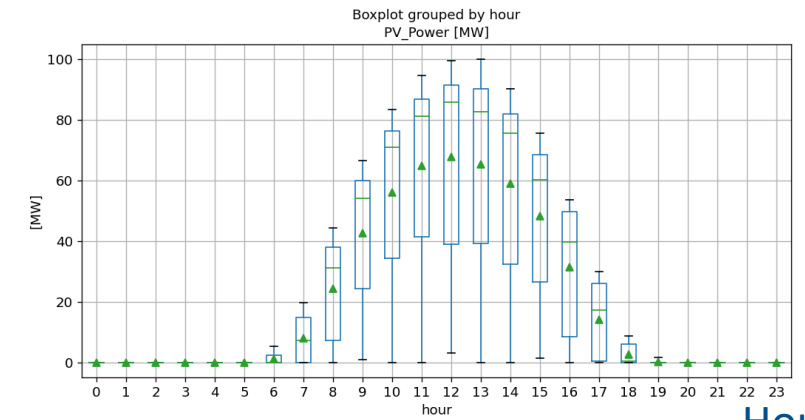
Mani



Rodopi



Kafireas



Hourly

Monthly

Location	PV CF	PV var [%]
Makedonia	19.9%	29.3%
Fokida	20.8%	30.2%
Ioannina	19.3%	28.9%
Mani	21.0%	30.4%
Rodopi	18.4%	28.4%
Kafireas	20.2%	30.4%

Results

- Optimal BESS size increases with CF and production variability
- Min 52.5MW/105MWh
- Max 57.5MW/115MWh
- BESS useful power output 52.5% to 57.5% of PV
- 2% to 3% of production discarded
- 0.6 to 0.7 average daily charge/discharge cycles

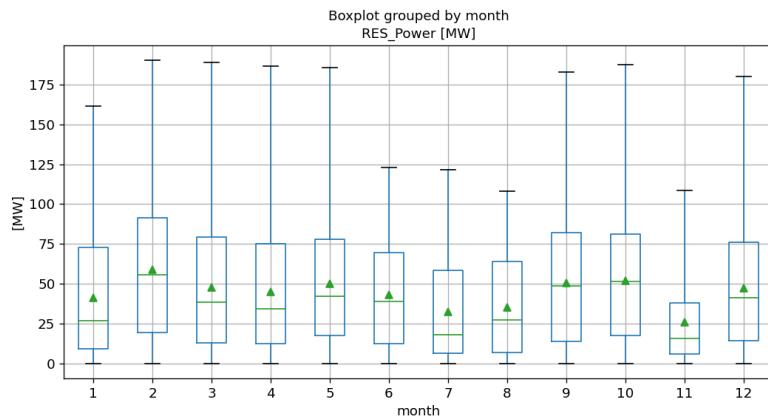
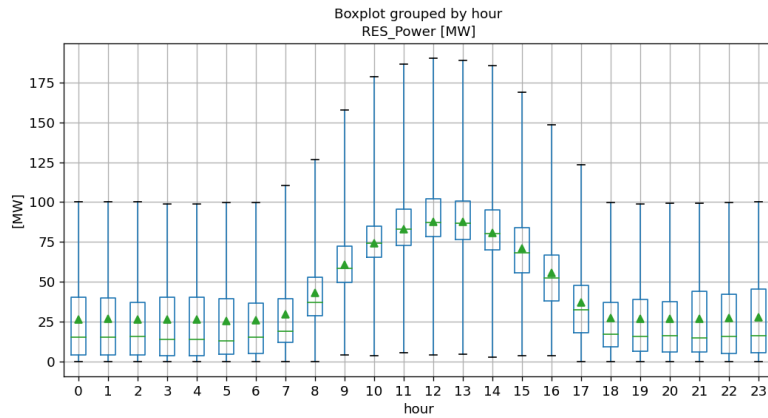
No curtailment schedule applied

Location	PV (no BESS)		
	Annual Revenue [M€]	IRR [%]	CAPEX [M€]
Rodopi	9.7	12.2	64.0
Ioannina	10.2	13.8	
Makedonia	10.5	13.8	
Kafireas	10.7	14.1	
Fokida	10.9	14.6	
Mani	11.0	14.8	

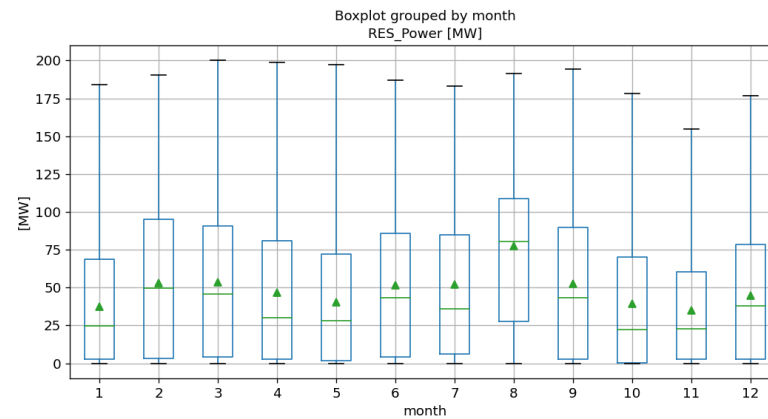
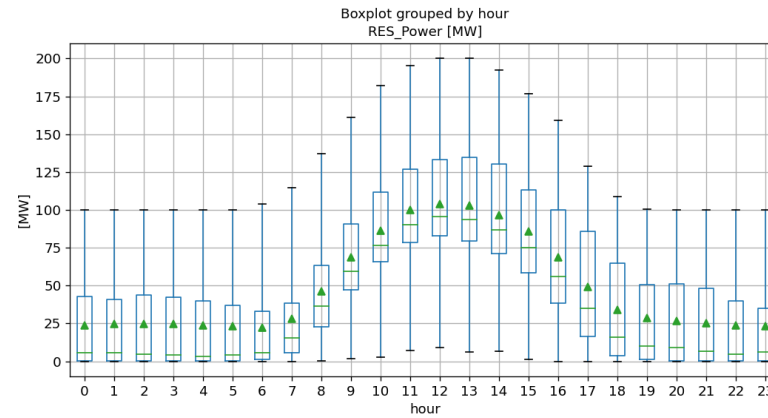
Location	PV CF ↑	PV var [%]	Opt BESS [MW]	RES to Grid [%]	RES to BESS [%]	Discarded [%]	Ave. daily cycles	Annual Revenue [M€]	IRR [%]	CAPEX [M€]
Rodopi	18.4%	28.4%	52.5	80.3	17.0	2.8	0.61	9.10	4.9	97.4
Ioannina	19.3%	28.9%	52.5	79.9	17.7	2.4	0.66	9.60	5.9	97.4
Makedonia	19.9%	29.3%	52.5	79.6	17.3	3.1	0.67	9.90	6.0	97.4
Kafireas	20.2%	30.4%	57.5	81.8	16.5	1.7	0.59	10.20	5.9	101.1
Fokida	20.8%	30.2%	55.0	80.8	17.3	1.9	0.67	10.50	6.5	99.3
Mani	21.0%	30.4%	55.0	80.5	17.3	2.3	0.67	10.50	6.6	99.3

WF - PV - BESS configurations

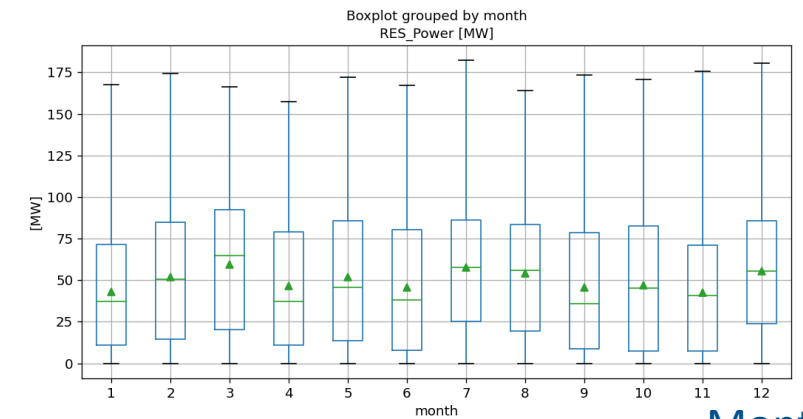
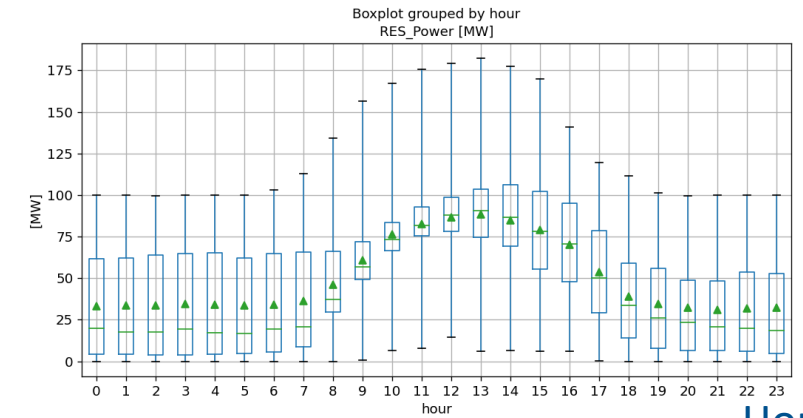
Makedonia



Fokida



Ioannina



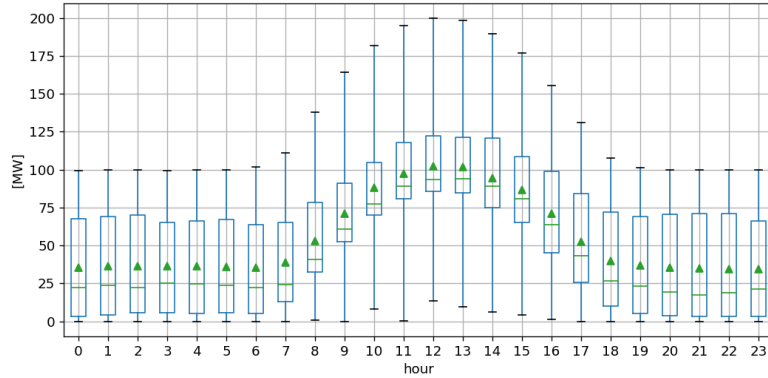
Hourly

Monthly

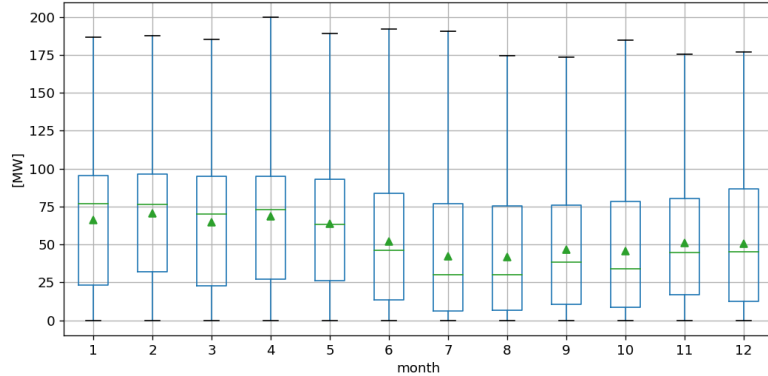
Location	Comb. CF	Comb. var [%]
Makedonia	22.0%	18.7%
Fokida	24.3%	24.0%
Ioannina	25.0%	19.1%
Mani	27.6%	21.9%
Rodopi	28.1%	23.7%
Kafireas	30.3%	23.4%

Mani

Boxplot grouped by hour
RES_Power [MW]

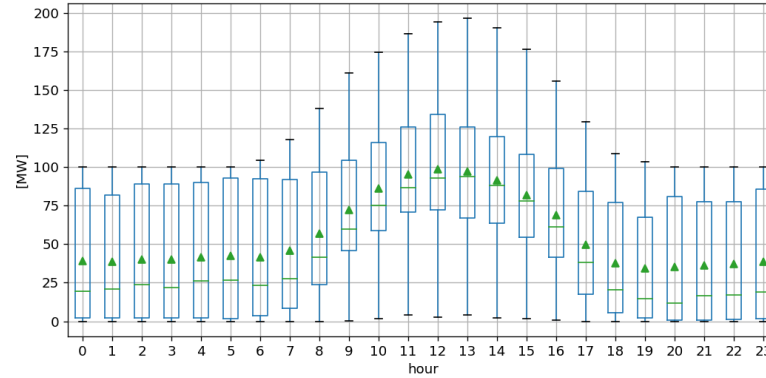


Boxplot grouped by month
RES_Power [MW]

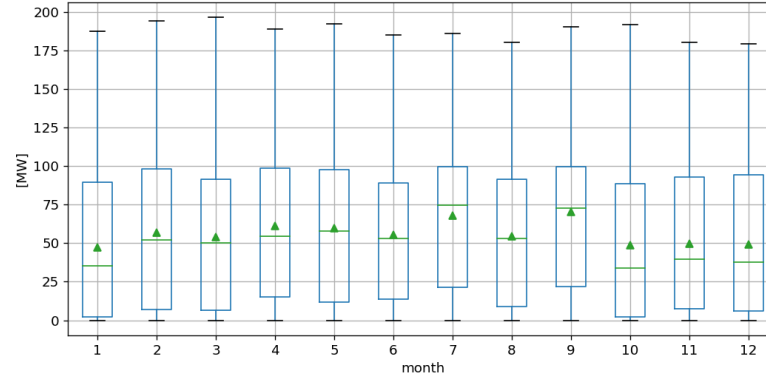


Rodopi

Boxplot grouped by hour
RES_Power [MW]

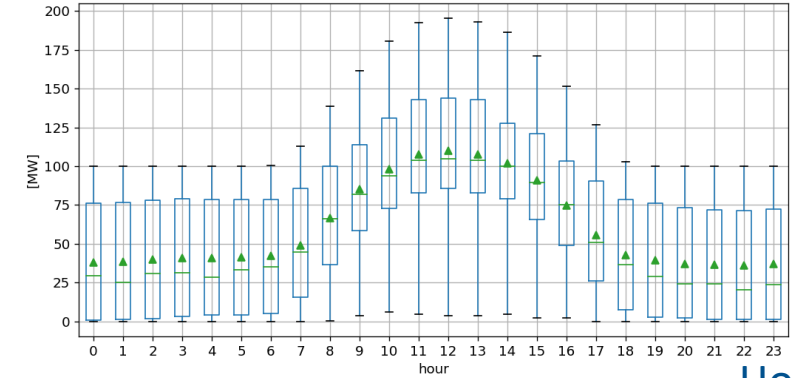


Boxplot grouped by month
RES_Power [MW]

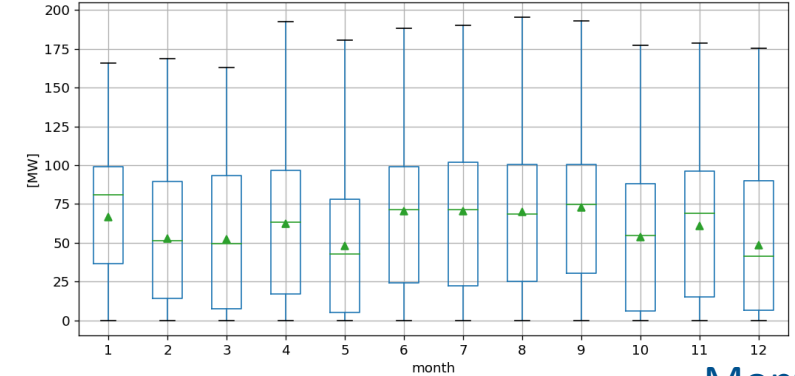


Kafireas

Boxplot grouped by hour
RES_Power [MW]



Boxplot grouped by month
RES_Power [MW]



Hourly

Monthly

Location	Comb. CF	Comb. var [%]
Macedonia	22.0%	18.7%
Fokida	24.3%	24.0%
Ioannina	25.0%	19.1%
Mani	27.6%	21.9%
Rodopi	28.1%	23.7%
Kafireas	30.3%	23.4%

Results

- Optimal BESS size increases with CF and production variability
- Min 80.0MW/160MWh
- Max 100.0MW/200MWh
- BESS useful power output 40.0% to 50.0% of combined WF - PV
- 3% to 5% of production discarded
- 0.3 to 0.4 average daily charge/discharge cycles
- Up to 33% reduction of BESS size compared to total BESS of separate WF-BESS and PV-BESS plants

No curtailment schedule applied

Location	WF/PV (no BESS)		
	Annual Revenue [M€]	IRR [%]	CAPEX [M€]
Makedonia	23.2	10.5	160.0
Fokida	25.5	12.3	
Ioannina	26.3	13.2	
Mani	29.1	14.9	
Rodopi	29.5	15.2	
Kafireas	32.0	16.9	

Location	Comb. CF ↑	Comb. var [%]	Opt BESS [MW]	(*)	RES to Grid [%]	RES to BESS [%]	Discarded [%]	Ave. daily cycles	Annual Revenue [M€]	IRR [%]	CAPEX [M€]
Makedonia	22.0%	18.7%	80.0	0.67	89.5	5.8	4.7	0.33	21.9	5.6	208.0
Fokida	24.3%	24.0%	97.5	0.72	88.6	6.4	5.0	0.33	24.0	6.2	221.1
Ioannina	25.0%	19.1%	82.5	0.69	90.1	7.0	3.0	0.43	25.3	7.8	209.9
Mani	27.6%	21.9%	95.0	0.70	90.2	5.5	4.2	0.33	27.6	8.5	219.1
Rodopi	28.1%	23.7%	100.0	0.73	90.6	5.8	3.6	0.33	28.2	8.6	223.0
Kafireas	30.3%	23.4%	100.0	0.73	90.6	6.1	3.3	0.38	30.6	9.9	223.0

(*) ratio of BESS size to total BESS of separate WF-BESS and PV-BESS plants

Summary

- WF-BESS
 - BESS useful power output 67.5% to 85.0% of WF
- PV-BESS
 - BESS useful power output 52.5% to 57.5% of PV
- WF-PV-BESS
 - BESS useful power output 40.0% to 50.0% of combined WF-PV
 - Up to 33% reduction of BESS size compared to total BESS of separate WF-BESS and PV-BESS plants
 - Gains from RES combination are even higher when WF production is complimentary to PV production (lower in noon and summer)
- Low BESS utilization in all cases (0.2 to 0.7 average daily charge/discharge cycles)
- 2% to 6% of RES production discarded

