POLITECNICO MILANO 1863

11th International Gas Turbine Conference
Dispatchable technology & innovations for a carbon-neutral society

ETN Global

OPTIMIZATION OF FULLY RENEWABLE AND DISPATCHABLE GREEN-HYDROGEN POWER-TO-POWER PLANTS WITH SEASONAL STORAGES

Prof. Emanuele MARTELLI
MSc. Lorenzo PILOTTI
Dr. Alessandro Francesco CASTELLI
MSc. Cristina TAMPALINI

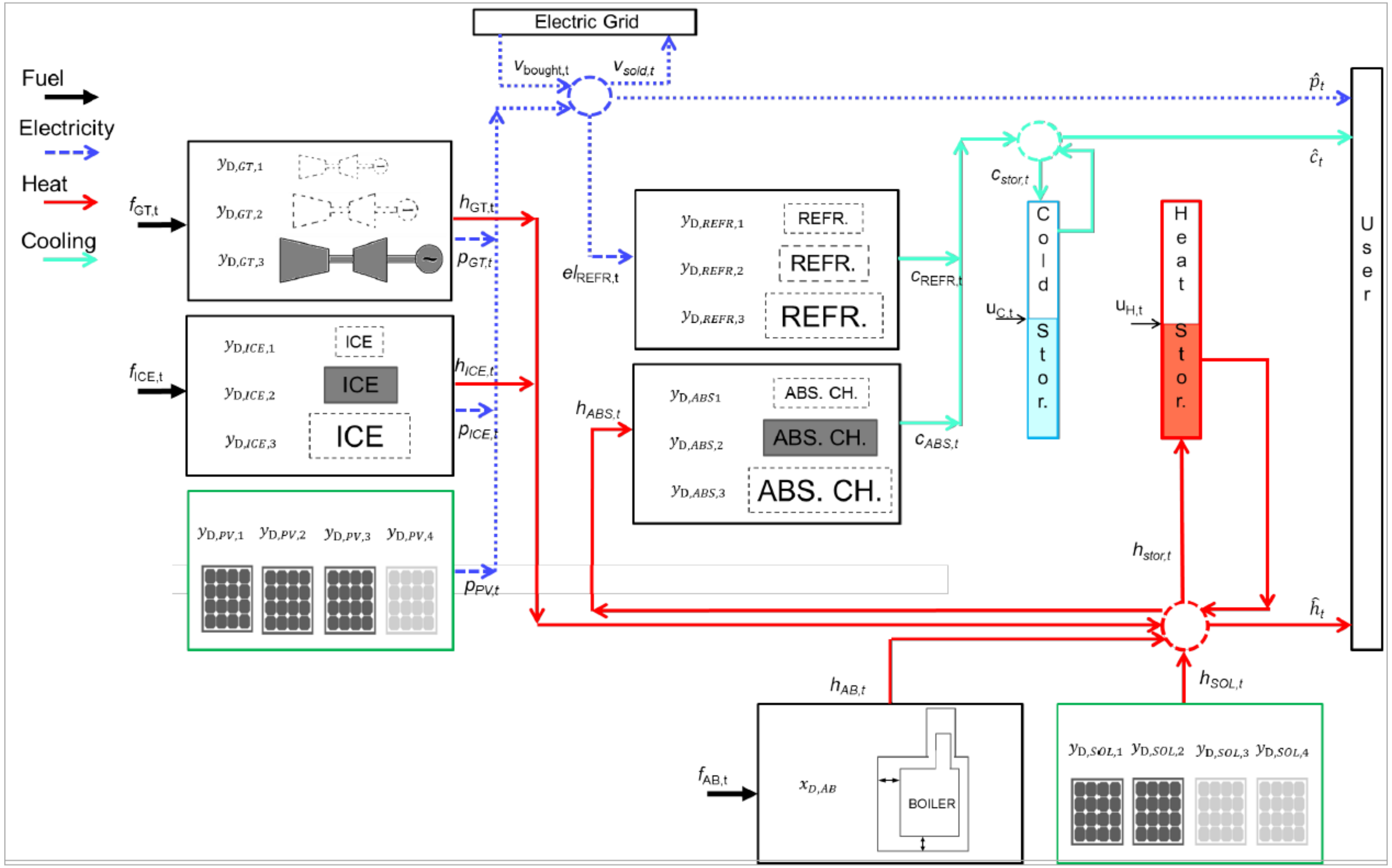
10-11 October 2023 | Brussels

11th IGTC Conference

The Department of Energy joins researchers in energy engineering, chemical engineering and electrical engineering (120 permanent researchers and professors).
The research of the ***GECOS*** group (12 professors) focuses on:

1. **CARBON CAPTURE TECHNOLOGIES**
2. **RENEWABLE ENERGY SOURCES AND WASTE-TO-ENERGY**
3. **ENERGY STORAGE, HYDROGEN AND FUEL CELLS**
4. **ORC, S-CO2 AND ADVANCED POWER CYCLES**
5. **MICROGRIDS, MULTI-ENERGY SYSTEMS, VPPs (AGGREGATED ENERGY SYSTEMS)**

OPTIMIZATION OF AGGREGATED SYSTEMS (Energy Districts, Microgrids, Virtual Power Plants)



Optimization tools for:

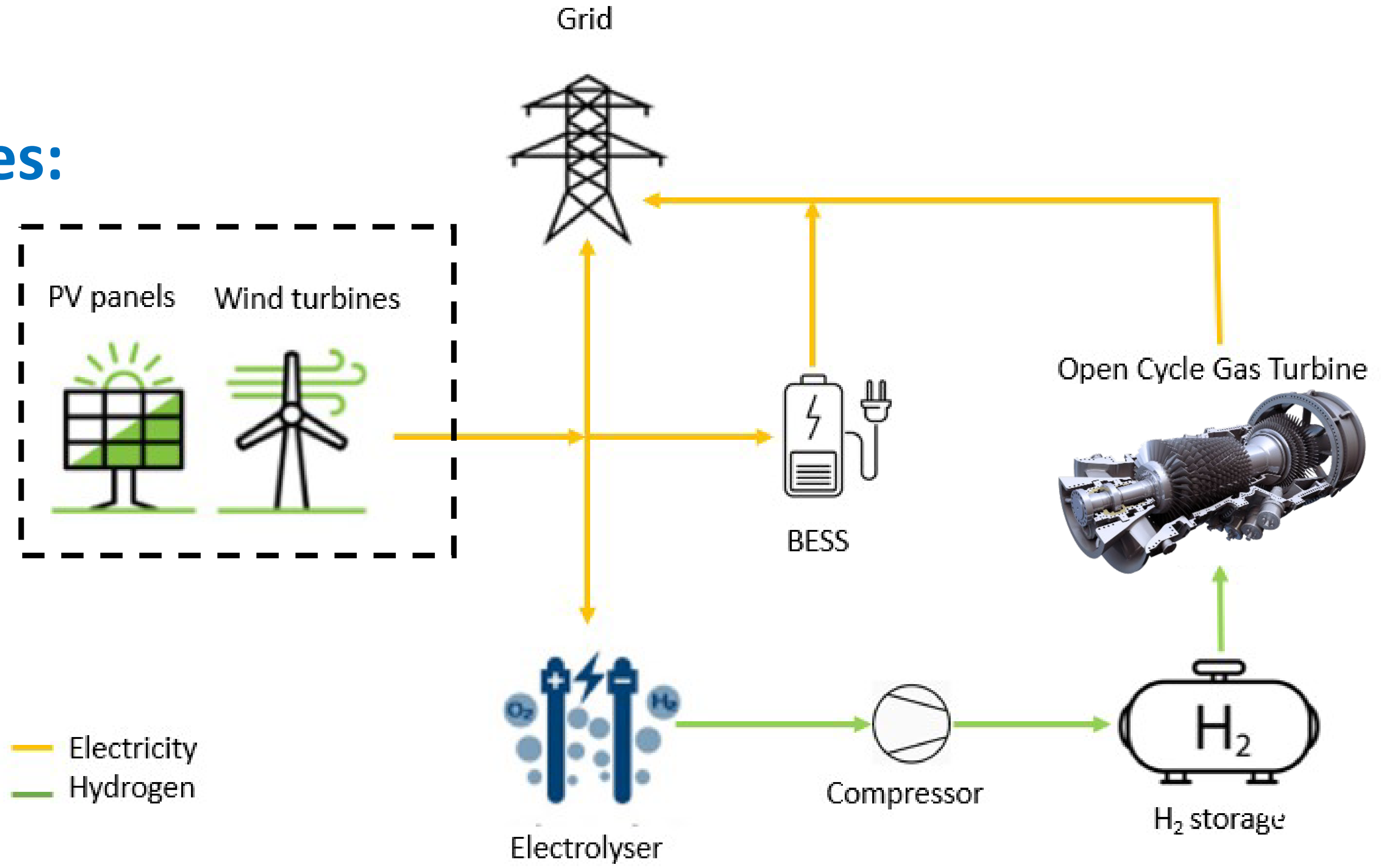
1. **Design and retrofit problems**
2. **Long-term operation planning (e.g., seasonal storage systems, yearly constraints)**
3. **24h-ahead short-term scheduling (unit commitment)**
4. **Intraday economic dispatch optimization (e.g., 15 min basis)**
5. **Optimal control**

Scope of work

*Determine the **optimal design** of a fully renewable AES capable of meeting a given fraction of the regional electricity demand for the whole year (24h-365days) with the **lowest Total Annual Costs (TAC)**.*

Catalogue of energy technologies:

- Hydrogen-fired Gas Turbines
- Long-term Hydrogen Storages
- Battery Storages (BESS)
- Electrolyzers
- PV fields
- Wind farms



Optimization problem statement

Given:

- Regional hourly profiles (for one or more years) of (i) PV and wind generation profiles, (ii) electricity load and (iii) forecasted electricity prices
- Catalogue of energy technologies (GTs, electrolyzers, BESS, H2 storages, etc) in the market
- Part-load performance maps and costs (capital and O&M) of each unit (GTs, electrolysers, PV, wind, H2 storages and BESSs)

Determine:

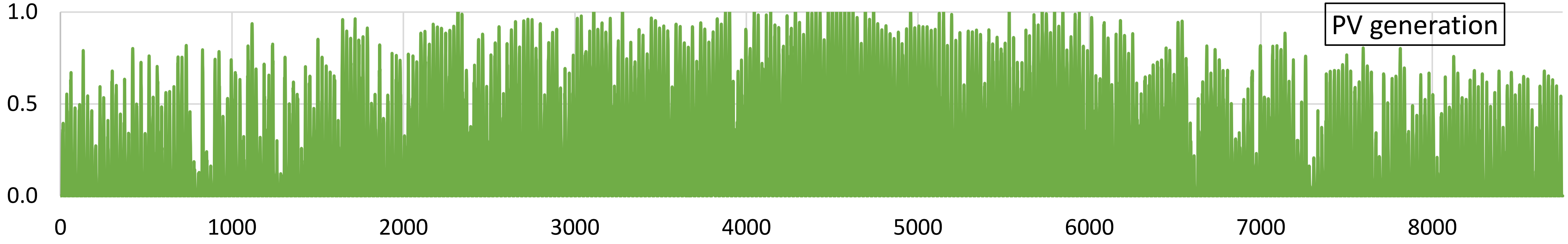
- the optimal number and sizes of GTs
- the sizes for PV, BESS, H2 storage, electrolyzer

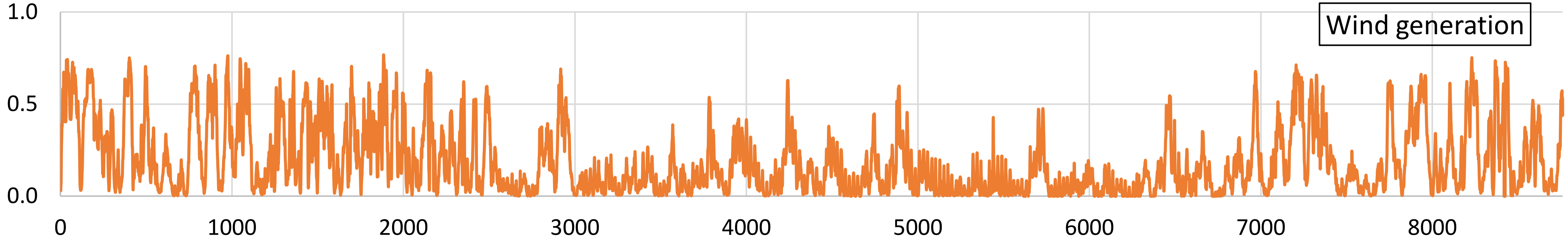
minimizing the Total Annual Cost (CAPEX+OPEX)

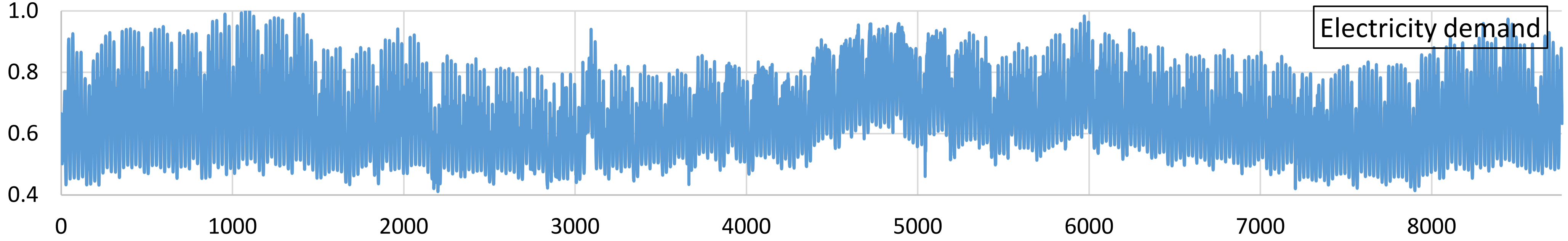
Taking into account:

- The optimal operation (on/off of units and loads)
- The operational constraints of the units (i.e., ramping limits, start-up/shut-down costs, part-load efficiency maps, storage management, storage losses, etc.)
- The need of meeting the energy demand in each hour of the year (100% dispatchability)

Regional profiles (normalized) of elec. Demand, PV and wind production







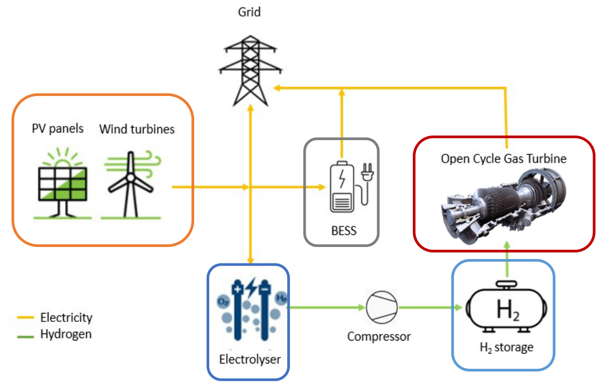
Optimization problem: MINLP model

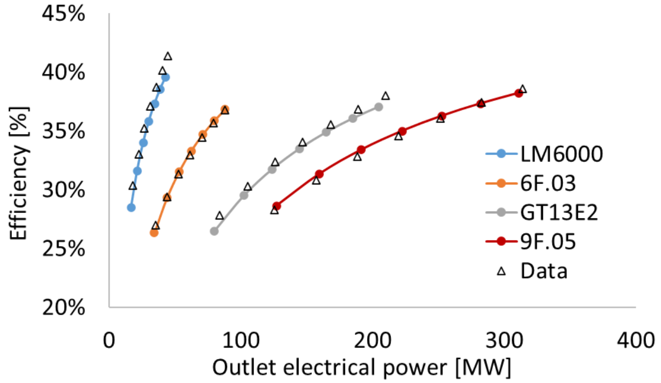
The problem is **Mixed-Integer NonLinear Programming (MINLP)** optimization problem

Design variables → **Selection (binary var.) and sizing (real var.) of the units**

Operational variables → **Optimal operation (on/off and loads) along the year**

Nonlinear Constraints → **Part-load performance maps of units**





However MINLP solvers (BARON, SCIP, etc) have difficulty in tackling large scale (> 10,000 binary variables, > 10,000 constraints) nonconvex problems

Linearization of the optimization problem: MILP

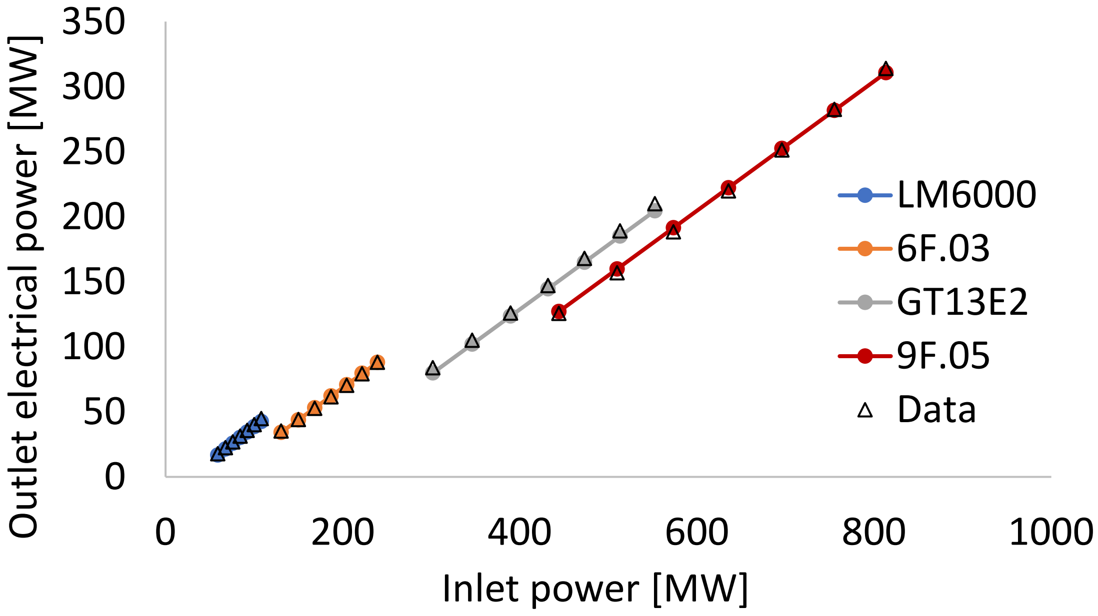
To make the problem solvable, the MINLP has been linearized into a Mixed Integer Linear Program (MILP) because MILP available solvers are far more efficient (e.g., Gurobi, CPLEX):

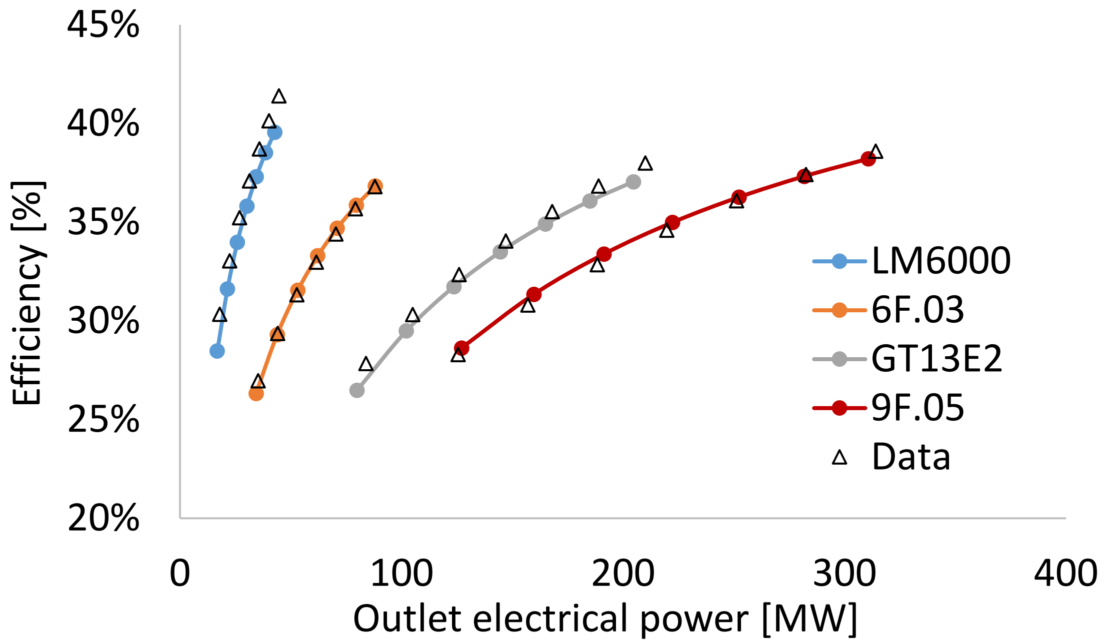
1) Formulation of all phenomena (ramp-up limits, on/off status, start-up/shut-down, etc) and costs as linear constraints involving binary and real variables
2) Linearization of the part-load performance maps of the units for each different ambient T
3) Definition of typical and extreme operating days via clustering algorithms

1. *Zatti et al., 2019. k-MILP: A novel clustering approach to select typical and extreme days for multi-energy systems design optimization. Energy Vol. 181*
2. *Gabrielli et al., 2018. Optimal design of multi-energy systems with seasonal storage. Applied Energy, Vol. 219*
3. *Elsido et al., 2017. Two-stage MINLP algorithm for the optimal synthesis and design of networks of CHP units. Energy, Vol. 121, pp. 403-426.*

Linearization of maps for catalogue units (fixed model and size)

Basic idea: linearize the **part-load performances** of the units with a **best-fit** linear curves giving the power output as a function of the fuel input





For a given GT model (e.g., LM6000):

$$P_{i,t}^{el} = \boldsymbol{K_{1,i}} \cdot F_{i,t}^{in} + \boldsymbol{K_{2,i}}$$

→

$$Eff_{i,t} = \frac{\boldsymbol{K_{1,i}} \cdot F_{i,t}^{in} + \boldsymbol{K_{2,i}}}{F_{i,t}^{in}} = \boldsymbol{K_{1,i}} + \frac{\boldsymbol{K_{2,i}}}{F_{i,t}^{in}}$$

$\boldsymbol{K_{2,i}} < 0$, efficiency increases with load

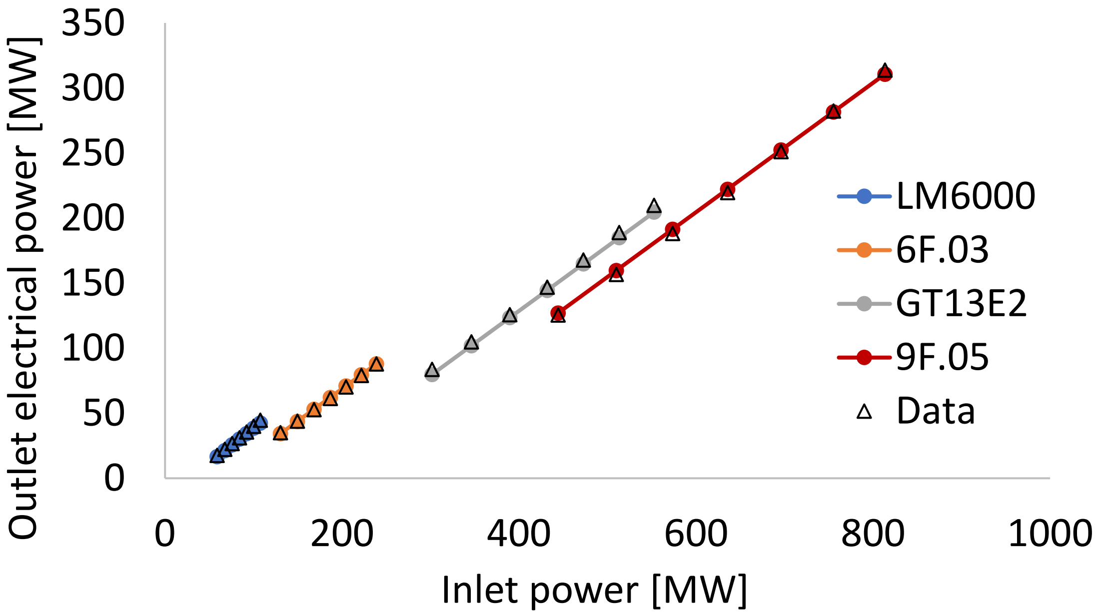
Linearization of units with variable sizes

Assuming that GTs have continuos sizes, it is possible to find an accurate linear best fit correlation taking into account both load and the size effects on efficiency:

$$P_{i,t}^{el} = \boldsymbol{K_{1,i}} \cdot F_{i,t}^{in} + \boldsymbol{K_{2,i}} \cdot F_{i}^{nom} + \boldsymbol{K_{3,i}}$$

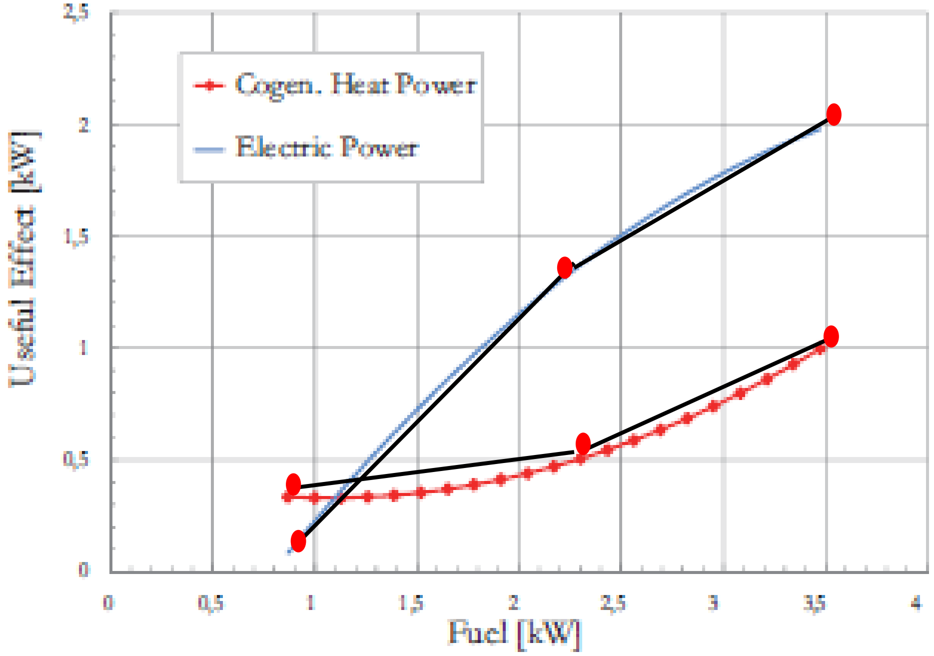
$$Eff_{i,t} = \frac{\boldsymbol{K_{1,i}} \cdot F_{i,t}^{in} + \boldsymbol{K_{2,i}} F_{i}^{nom} + \boldsymbol{K_{3,i}}}{F_{i,t}^{in}} = \boldsymbol{K_{1,i}} + \frac{\boldsymbol{K_{2,i}}}{\%load_{i,t}^{in}} + \frac{\boldsymbol{K_{3,i}}}{F_{i,t}^{in}}$$

OCGT category	Power range MW_{el}	$K_{1,i}$ [MW_{el}/MW_{fuel}]	$K_{2,i}$ [MW_{el}/MW_{fuel}]	$K_{3,i}$ [MW_e]
OCGT1	30-80	0.529	-0.105	-3.010
OCGT2	80-116	0.495	-0.081	-10.890
OCGT3	116-314	0.497	-0.091	-20.055

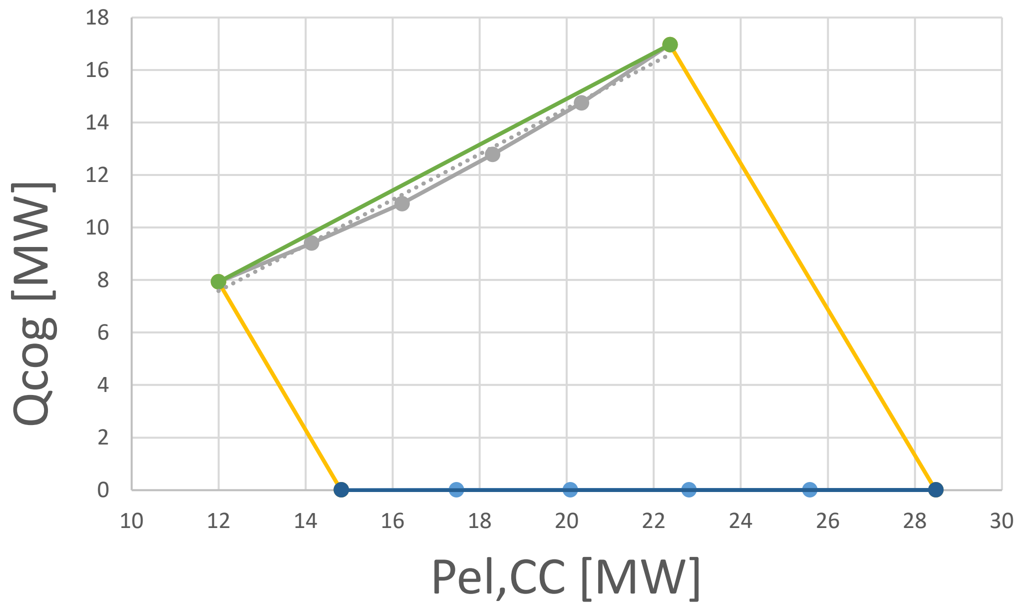


Piece-wise linearization

PWL approximation of performance maps



Extension to CHP cycles with «convex-hull»



Optimization problem: assumptions

Electrolyser

- PEM electrolyzer
- H2 compressor work is included in electrolyzer efficiency

OCGT

- GTs have continuous sizes in the range 30 to 300 MWel
- Divided in 3 size ranges

Hydrogen storage

- Pressure variations not considered (constant pressure storage)
- Negligible self-discharge

Batteries

- 3 Li-ion BESS, with different discharge durations (4 h, 12 h and 20 h)
- Constant charging/discharging and self-discharge efficiencies

Optimization problem: techno-economic assumptions

	OCGT technologies		
OCGT category	OCGT1 (Farmer, 2021)	OCGT2 (Farmer, 2021)	OCGT3 (Farmer, 2021)
Power range [MW_{el}]	30.8 - 57.0	80 - 116.5	144.1 - 314.0
Efficiency range [%]	37.2 - 40.1	36.4 - 38.3	34.8 - 38.6
Inv. Cost [€/kW_{el}]	376.5 - 261.0	276.3 - 202.9	227.7 – 154.3

	PEM Electrolyzer (IRENA, 2019c)	
Power range [MW_{el}]	0-1500	
	Current value	Future value (2050)
Efficiency (EE-to-LHV)	60%	75%
Inv. Cost [€/kW_{el}]	800	400
PV OM fix [€/kW-year]	32	16

	Non-dispatchable technologies (IRENA, 2019a) (IRENA, 2019b)	
PV power range [MW_{el}]	0-1300	
Wind power range [MW_{el}]	0-740	
	Current value	Future value (2050)
PV Inv. Cost [€/kW_{el}]	800	282
Wind Inv. Cost [€/kW_{el}]	1500	721
PV OM fix [€/kW-year]	16	6
Wind OM fix [€/kW-year]	45	22

	Storage technologies					
	Current value			Future value (2050)		
BESS category (Kebede et al., 2021)	BESS1	BESS2	BESS3	BESS1	BESS2	BESS 3
Discharge time [h]	4	12	20	4	12	20
Round-trip efficiency [%]	88.4	90.3	94.1	88.4	90.3	94.1
Self-discharge efficiency [%/month]	3	3	3	3	3	3
Inv. Cost [€/kWh_{el}]	463	368	349	350	278	264
OM fix [€/kWh-year]	10.8	5.2	3.8	8.2	3.9	2.9
H_2 storage (R.K. Ahluwalia et al., 2010) (Landinger, 2013)	Pipes storage	Line rock cavern		Pipes storage	Line rock cavern	
Inv. Cost [€/$kWh_{H2,LHV}$]	13.5	1.20		13.5	1.20	

Case study

The AES should supply **10%** of the regional electricity demand of Sicily → approx. 300 MW peak

The optimal design and operation management of the VPP are analysed for **three configurations** with a **different seasonal storage solution** for the **current** and **future (2050) scenarios**

1) BESS only available (“**pure BESS**” case)

2) H2 storage only available (“**P2P**” case):

- pipes vessels as H2 storage (high cost) → “**P2P-pipes**”
- line rock cavern as H2 storage (low cost) → “**P2P-cavern**”

3) BESS and H2 storage both available (“**hybrid**” case):

- pipes vessels as H2 storage (high cost) → “**hybrid-pipes**”
- line rock cavern as H2 storage (low cost) → “**hybrid-cavern**”

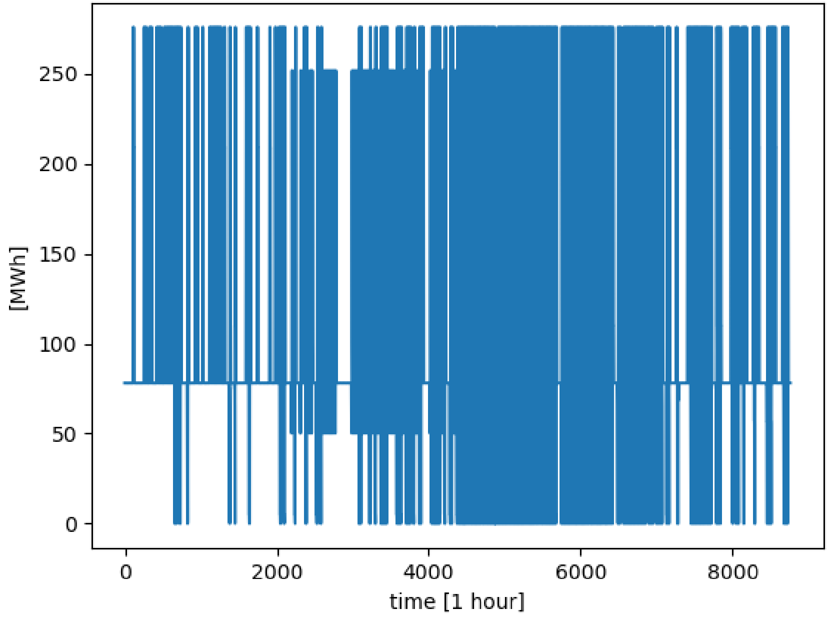
Results – current scenario

Configuration	BESS only	P2P - pipes	P2P - cavern	Hybrid - pipes	Hybrid - cavern
PV [MW]	1265.6	1300.0	1300.0	1207.7	969.9
Wind [MW]	332.1	740.0	723.3	365.6	379.7
Electrolyzer [MW]	-	978.2	804.3	68.2	196.2
GT [MW] – s1	-	53.5	54.5	33.6	57.2
GT [MW] – s2	-	57.1	56.2	0.0	0.0
GT [MW] – s3	-	57.2	57.2	0.0	0.0
GT [MW] – s4	-	95.3	88.4	0.0	0.0
BESS1 – 4 h [GWh]	1.36	-	-	1.38	0.62
BESS2 – 12 h [GWh]	1.98	-	-	1.49	1.71
H_2 pipes [GWh]	-	182.7	-	5.8	-
H_2 cavern [GWh]	-	-	205.1	-	106.4
Demand/PV/wind [GWh]	1757/2390/522	1757/2455/1163	1757/2455/1137	1757/2281/574	1757/1832/597
Ren. Curtailed [%]	36.8%	4.5%	4.8%	32.1%	8.9%
CAPEX [M€]	2871	5486	3097	2850	2567
OPEX [M€/y]	89.9	85.7	84.6	89.5	80.7
TAC [M€/y]	377.0	634.3	394.3	374.5	337.4
LCOE [€/MWh]	**214.6**	**361.0**	**224.4**	**213.2**	**192.0**

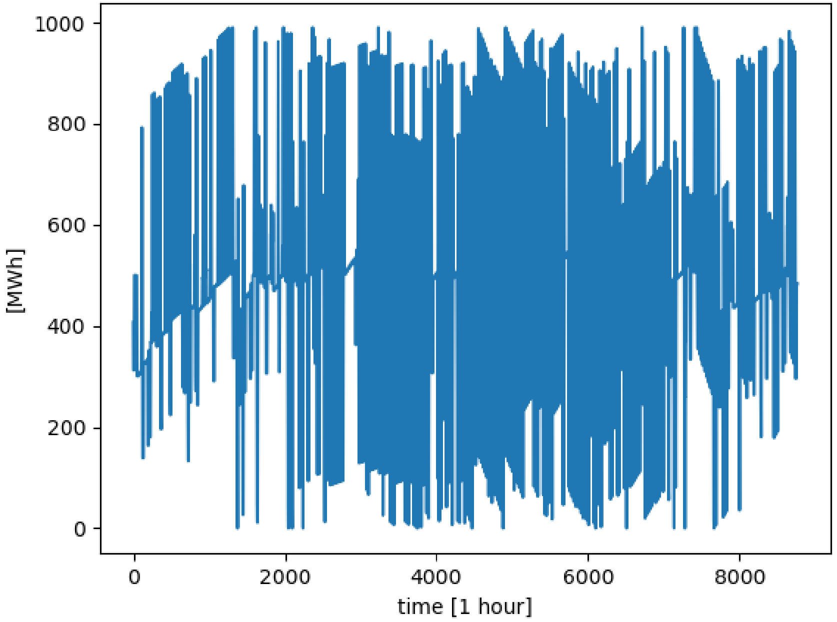
- Optimal PV capacity equal or close to maximum limit (chepest renewable)
- BESS only features large curtailment (36.8%) of renewables because of limited storage capacity
- P2P systems saturates PV capacity and requires larger Wind capacity due to the lower round-trip efficiency (22%)
- P2P-cavern is economically competitive with BESS while P2P-pipes is penalized by the large H2 storage cost.
- Hybrid solutions require a smaller renewable capacity and features lowest LCOE, specially for cavern.
- Optimal GT sizes are in the range 30-90 MW

Results – Hybrid cavern configuration

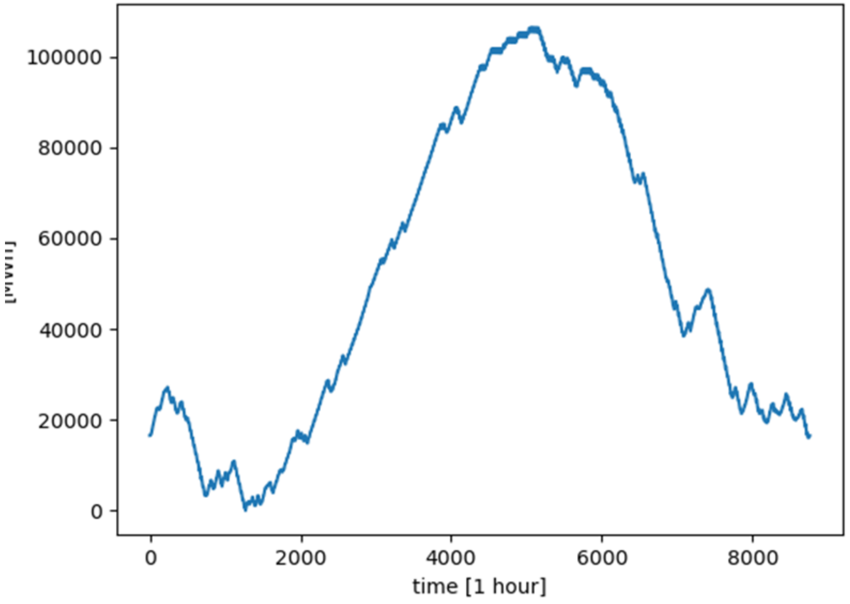
- **Batteries work as short-term** storage systems
- **H2 rock cavern operates as long-term** storage solution



4 hours BESS storage level
→ 143 equivalent cycles



12 hours BESS storage level
→ 116 equivalent cycles



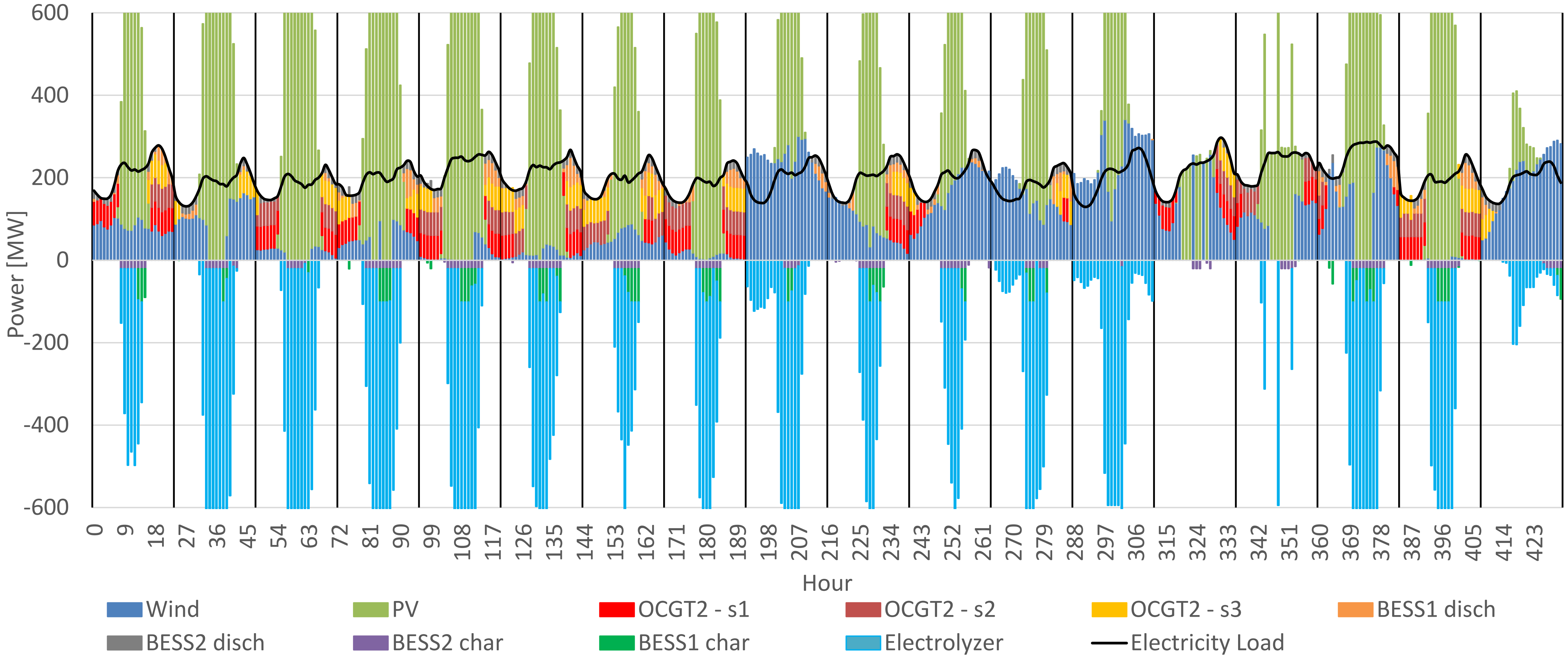
H2 rock cavern storage level
→ 1.4 equivalent cycles

Results – future scenario (2050)

Configuration	BESS only	P2P - pipes	P2P - cavern	Hybrid - pipes	Hybrid - cavern
PV [MW]	1257.6	1300.0	1300.0	1300.0	1300.0
Wind [MW]	344.5	740.0	601.4	521.0	459.1
Electrolyzer [MW]	-	978.2	684.5	329.1	594.6
GT [MW] – s1	-	32.0	54.4	57.2	57.2
GT [MW] – s2	-	54.9	57.2	0.0	57.2
GT [MW] – s3	-	56.5	57.2	0.0	57.2
GT [MW] – s4	-	112.8	89.4	0.0	0.0
BESS1 – 4 h [GWh]	1.37	-	-	0.69	0.30
BESS2 – 12 h [GWh]	1.96	-	-	1.50	0.23
H_2 pipes [GWh]	-	101.9	-	6.9	-
H_2 cavern [GWh]	-	-	184.6	-	120.4
Demand/PV/wind [GWh]	1757/2375/ 541	1757/2455/ 1163	1757/2455/945	1757/2455/819	1757/2455/721
Ren. Curtailed [%]	37.0%	13.4%	8.1%	32.3%	9.2%
CAPEX [M€]	1627	2749	1379	1642	1307
OPEX [M€/y]	62.4	38.6	36.0	51.2	40.2
TAC [M€/y]	225.1	313.6	173.9	215.4	170.9
LCOE [€/MWh]	**128.1**	**178.5**	**99.0**	**122.6**	**97.3**

- Similar considerations as the current scenarios
- PV is preferred to wind
- BESS only features large curtailment of renewables because of limited storage capacity
- P2P-cavern becomes very competitive w.r.t. BESS while P2P-pipes is penalized by the large H2 storage cost.
- Hybrid solutions require a smaller wind and GT capacities and features lowest LCOE, specially for cavern.
- Optimal GT sizes for the hybrid solution is about 60 MW

Results – Hybrid cavern optimized dispatch (2050 scenario)



Conclusions and future works

Conclusions

- **The economic KPI of H2 based storage solutions strongly depend on the cost of the H2 storage system (using a cavern is economically competitive already now, using pipes is not)**
- **P2P system using only pipes for long-term H2 storage turns out to be too expensive, today as well as in 2050**
- **Hybrid solutions with H2 storage and BESS allow a more competitive LCOEs compared to BESS only solutions, with an economic advantage expected to increase over the years**
- **For a peak electricity demand of 300 MW, the optimal GT size turns out to be in the range 30-110 MW and about 60 MW in most cases.**

Future works

- **Repeating the optimization considering a region located in Nothern Italy with also heating demand (e.g., DHNs)**

Thank you for your attention!

Back up slides

Results – Pure BESS

- **Only batteries** used **as storage** system
- **No benifit in terms of efficiency improvement and no economy of scale** due to «modularity» of tecnologies involved

Components	Current	Future
PV [MW_{el}]	1265.6	1257.6
Wind [MW_{el}]	332.1	344.5
BESS1 – 4 h [MWh_{el}]	1364.4	1368.1
BESS2 – 12 h [MWh_{el}]	1980.6	1960.0
BESS3 – 20 h [MWh_{el}]	0.0	0.0

Economic KPIs	Current	Future
CAPEX [M€]	2871	1627
OPEX [M€/year]	89.9	62.4
TAC [M€/year]	377.0	225.1
LCOE [€/MWh_{el}]	**214.6**	**128.1**