INTEGRATION OF HEAT PUMP AND GAS TURBINE COMBINED CYCLE: LAYOUT AND MARKET OPPORTUNITY

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Motivations and Background

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MOTIVATIONS

- Improving power plant flexibility is a key change in the near-mid term energy environment
- The economic status is analyzed focusing on the Italian market
- The Pump-Heat Combined Cycle (PHCC) aims to improve flexibility of existing power plant by coupling the GTCC with a HP plus a thermal energy storage (TES)
- Constraint for the solution are:
  - Techninally feasible
  - Economically sustainable
  - OEM indipendent
  - For new and retrofit application
- A preliminary analysis is made focusing on CHP CC, basing on Turin DHN by IREN

Combined Cycle Actual Condition

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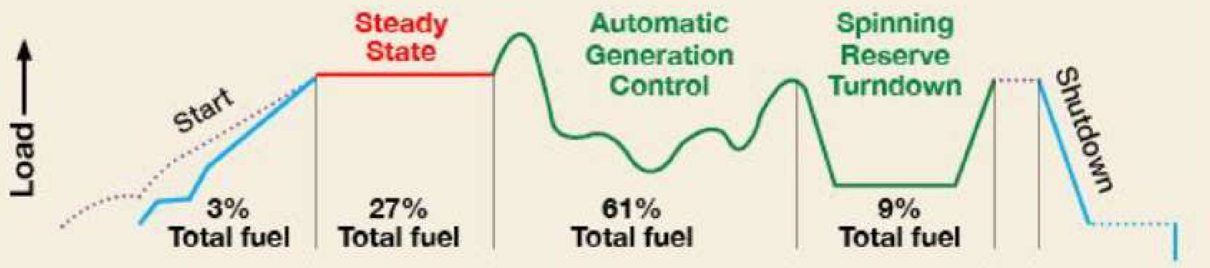
Combined Cycle Power Plant management have to take into account:

- the market price of the electricity
- the variability of the fuel cost,
- the cost of start-up maneuver
- the cost of maintenance

Operating profile for combined cycle gas turbines. Combined cycle gas turbines spend relatively little time in baseload steady state.



In particular nowadays, in Europe:

- More Renewables drives the need for CCPP flexibility
- CCPP's have to change load faster
- Daily start-up and even double daily start-ups
- Faster Start -up times Required

Main interest on:

- Increase the CC rangeability
- MEL reduction
- Increase yearly average efficiency (high off-design efficiency)

Combined Cycle Actual Condition

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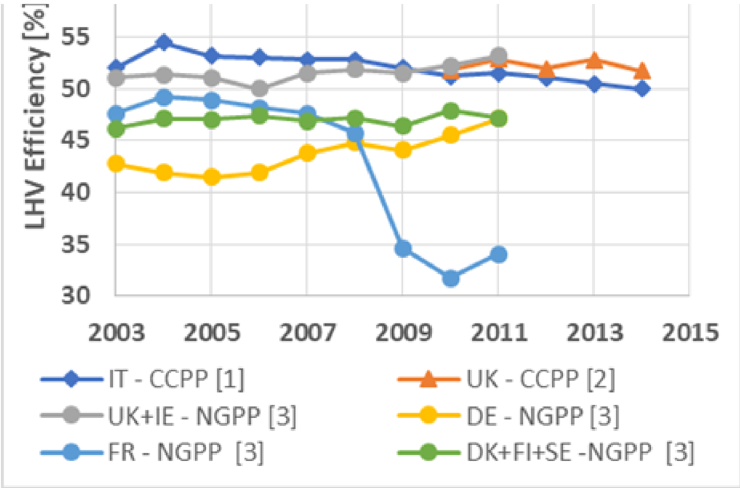
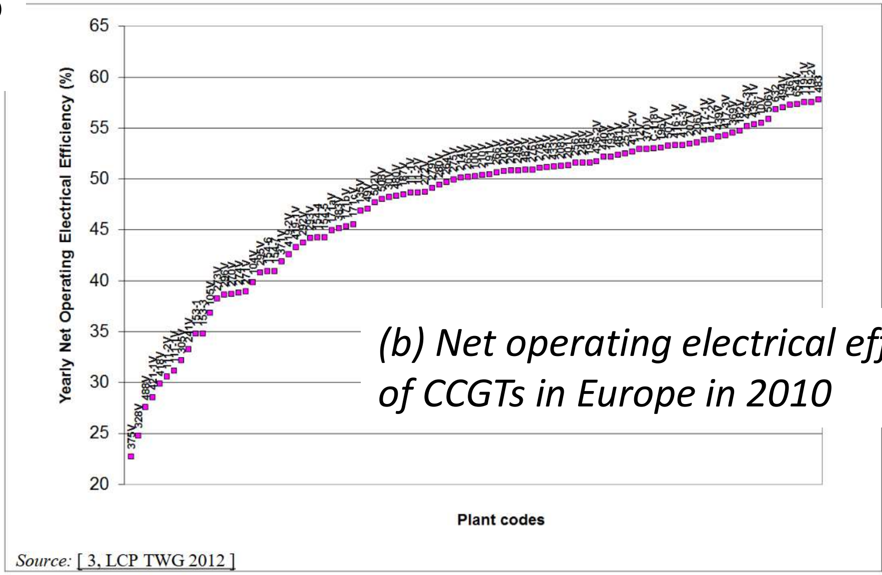
Italian average efficiency of the production CCGT portfolio dropped from 55% to 50% over 10 years (ARERA 2016)





(b) Net operating electrical efficiencies of CCGTs in Europe in 2010

(a) CC Efficiency: trend over the last years for specific European countries[1]

Expectation:

- Design efficiency over 55% (up to 62% for new installation) + NG fuel => Low Carbon Footprint
- High Operating Flexibility => Suitable for Ancillary Services

Reality:

- Low power prices have reduced the profitability of power generation
- Service factor reduction => less operative hours, reduced efficiency; not economically sustainable

1 AEEGSI, Relazione 24 Giugno 2016, 339/2016/I/efr; http://www.autorita.energia.it/it/docs/16/339-16.htm, Department of Energy & Climate Change, DIGEST OF UNITED KINGDOM ENERGY STATISTICS 2015, Ecofys, International comparison of fossil power efficiency and CO2 intensity - Update 2014 Final Report
2 European IPPC Bureau, BREF for LARGE Combustion Plant, Final Draft (June 2016)

Market Scenario «forecast»

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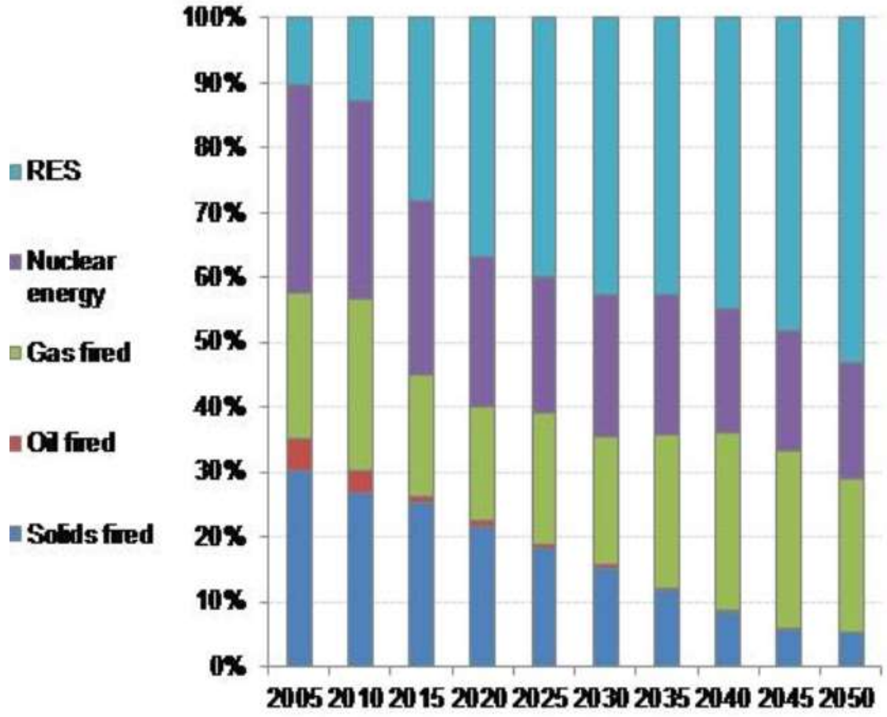

EU power generation (net) by fuel (EU commission, 2016)

European Power Generation share by fuel

- The EU power generation mix changes considerably over the projected period in favour of renewables
- Before 2020, this occurs to the detriment of gas, as strong renewables policy to meet 2020 targets, very low coal prices compared to gas prices. In addition, low CO2 prices do not help the shift from coal to gas.
- After 2020, further renewables deployment, larger coal to gas shift, driven mainly in anticipation of increasing CO2 prices

The Analysis will focus expecially over Italian market conditon since Italian electrical production for 35% of the total rely on gas (vs provisional 25% of the EU average)

PO and CHP Combined Cycle COE

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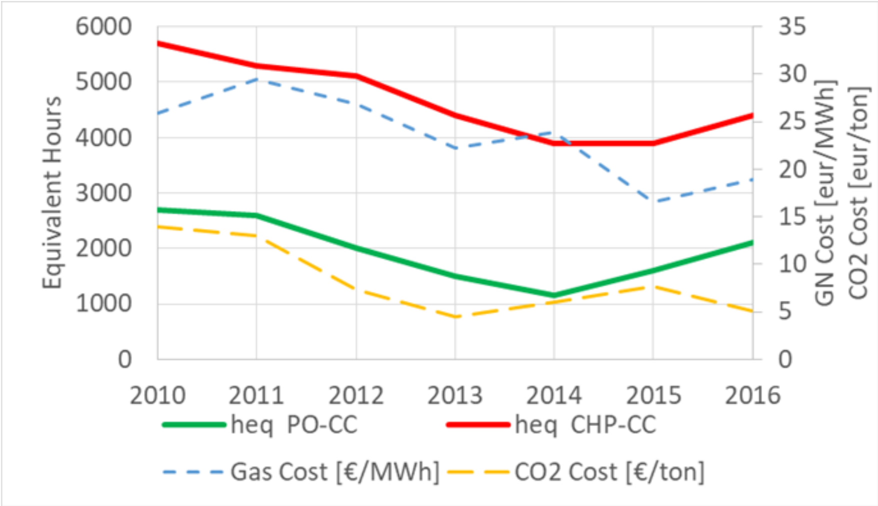
$$COE_{year,i} = \frac{C_{gas,i}}{\eta_{plant,i}} + C_{O\&M,fix} + \\ + \left(C_{O\&M,var} + C_{O\&M,year}\right)\frac{P_{CC}}{h_{eq,i}} + \\ + \left(\theta_{gas}^{CO_2} * \frac{3600}{\eta_{plant,i} * 10^6} * C_{CO2,i}\right)$$

$COE_{year,i}$	Cost of Electricity referred to i-th year [€/MWh]
C_{gas}	Natural Gas Cost [€/MW]
C_{CO2}	CO_2 Cost [€/ton]
$C_{O\&M,fix}$	Fix O&M costs [k€/MW-year]
$C_{O\&M,var}$	Variable O&M costs [€/MWh]
$C_{O\&M,year}$	Annual total O&M cost [k€/MW]
h_{eq}	Equivalent hours [hours]
P_{CC}	Net Nominal Combined Cycle Power [MWe]
η_{plant}	Plant efficiency [%]
$\theta_{gas}^{CO_2}$	NG CO_2 emission factor [$kgCO_2$/GJ]

	Unit of measure	*Value*
Net Nominal Power	MWe	400
Investment Costs	k€/MW	650
Annual total O&M	% of investment costs	3.5
Fix O&M costs	k€/MW-year	10.5
Variable O&M costs	€/MWh	3.15
Construction time	Years	3
Useful lifespan	Years	20



Ricerca sul Sistema Energetico – RSE SpA, 2016. Energia Elettrica, Anatomia dei Costi ISBN 978-88-907527-7-3

Status of the Italian CC

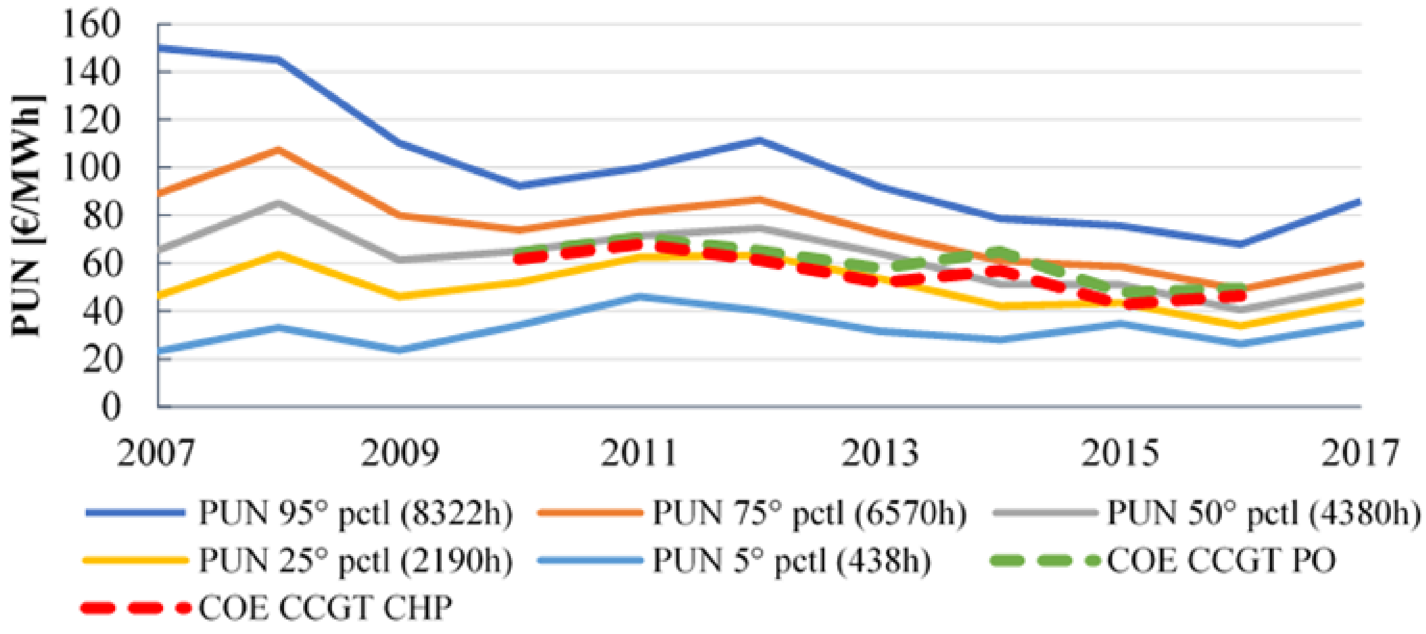


Fig. 1: CHP and PO CC COE and PUN variation along the years (2007-2017)

Since 2009 Low power prices have reduced the profitability of power generation **=> CCGT Cycling**

CCGT due to high marginal costs, have been pushed out from the system**, decreasing their running hours**

Last 2 years increase is mainly due to low gas cost

MSD (ancillary services) became more attractive

PUN is globally reducing with also a reduction of the yearly variability.

Reduction in daily spread makes **Electricity Arbitrage** via **Electric Energy Storage less favourable**.

2017 Daily Spread Opportunity [euro]				
pctl		50°	75°	95°
EES charge /discharge	1h	27,9	37,5	67,2
	2h	24,5	31,6	59,9
	3h	20,5	26,7	51,3

Which Future for Large Scale Thermal Power Plant? Market Opportunity: Power 2 Process

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- ✓ Electricity Price is globally reducing with some experience of zero and negative price (e.g. Germany) due to over-generation from Not Dispatchable RES.
- ✓ Energy Intensive Process should become Grid Stabilizer increasing the electricity consumption capacity during low or negative price periods (Smart Load).
- ✓ The process should create a product sold by-itself without come back to electricity (no-round trip efficiency)

- ✓ Power 2 Heat => cold and heat production for DHN/industrial CHP integration
  - i) absorbing electricity during high RES production and low price periods,
  - ii) using the TES for Thermal and equivalent electric arbitrage,
  - iii) reducing economic and environmental costs to fulfill thermal demand;

PUMPHEAT

- ✓ Power 2 Chemical => green Chemical production (e.g. Carbon fuel or reactant)
  - i)Global CO2 emissions reduction
  - ii)Fossil fuel consumption reduction
  - iii)Production of innovative fuel with low carbon-footprint

MefCO$_2$
Methanol fuel from CO$_2$

PUMP-HEAT Project

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Performance Untapped Modulation for Power and Heat via Energy Accumulation Technologies

Project Objective

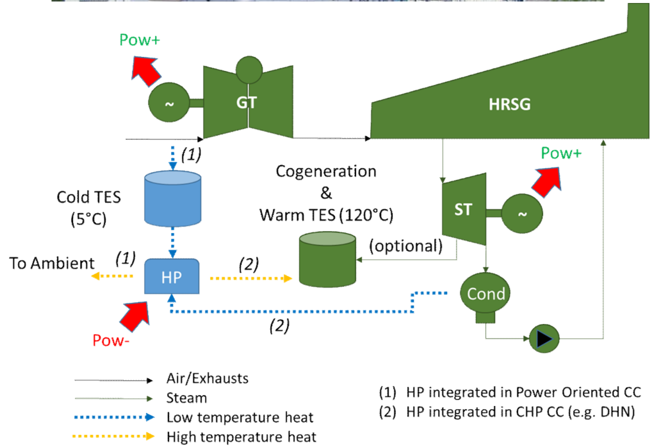
To enhance Combined Cycle (CC) power flexibility, the PUMP-HEAT project proposes an innovative concept based on the coupling of a fast-cycling highly efficient Heat Pump (HP) with CCs. The integrated system features Thermal Storage and predictive control for smart scheduling.

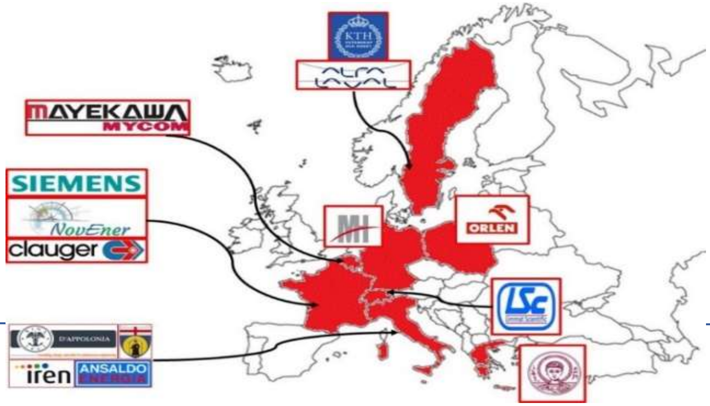
The CC integration with a HP and a cold/hot thermal storage brings to a reduction of the Minimum Environmental Load (MEL) and to an increase in power ramp rates, while enabling power augmentation at full load and increasing electrical grid resilience and flexibility.

Approach

In the PUMP-HEAT Combined Cycle (PHCC), demonstrated at TRL 6:

- the HP is controlled to modulate power in order to cope with the CC primary reserve market constraints;
- the high-T heat can be exploited in district heating network;
- HP cooling can be used for gas turbine power boost
- the HP will include an innovative bi-phase expander to increase the overall efficiency.





Impact and Expected Results

The PHCC will reach maturity in 2023, with 5 revamped plants and 1 new plant (600MW) per year, targeting an initial market of around 800 M€/yr. A single PHCC plant will allow an yearly saving of 5000t of natural gas, 72320 tCO_2 eq. emissions. PH-CC aims to become a new paradigm for GT and CC power plants, for both **retrofit and new applications**, paving the way for further renewable sources.

PHCC Layouts

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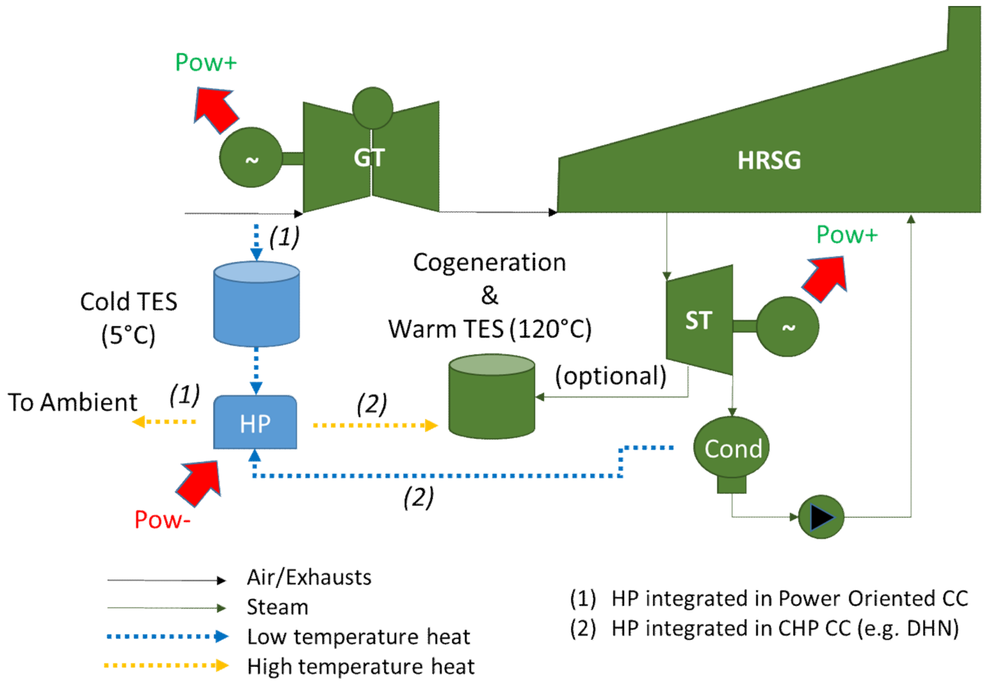
- Two main application have been targeted: Power Oriented (PO) and Cogenerative (CHP)

POWER ORIENTED

COGENERATIVE

- Low Temperature HP => DHN
- High temeperature HP => steam for industrial demand



Background analysis PHCC - PO

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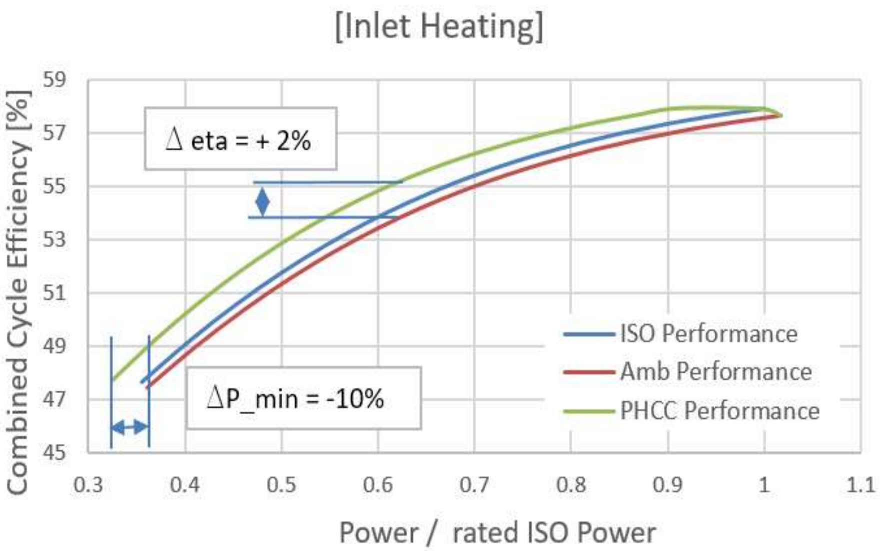
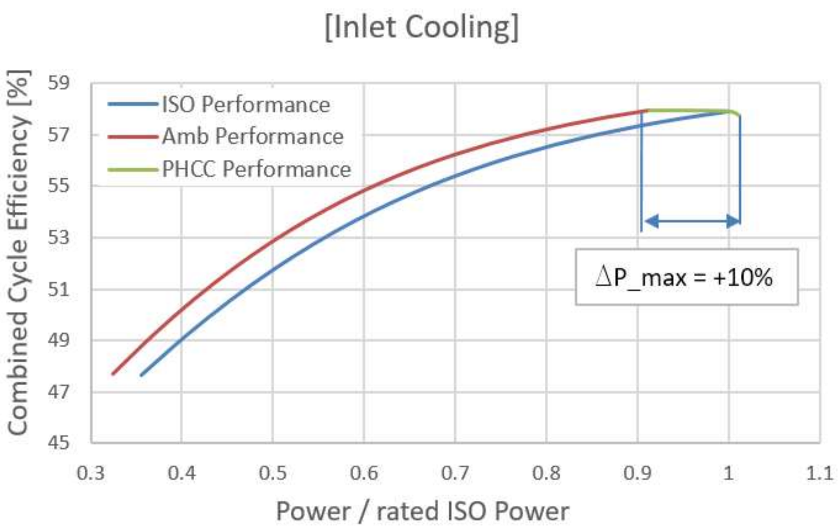
- PO is devoted to production of electric energy and heat pump is used to influence compressor intake temperature (Integret Inlet Conditioning)
- IIC acts as a closed systems, without waste energy conveyed to the external environment:
  - during off-peak hours while the HP charges the cold TES, the heat released by the HP is used for inlet heating (average increasing the efficiency of 2%) and decreasing the MEL (-10%).
  - during peak hours the HP shut off and the TES is discharged to the inlet coil increasing the maximum power output, P_max (+10%).





Background analysis PHCC - CHP

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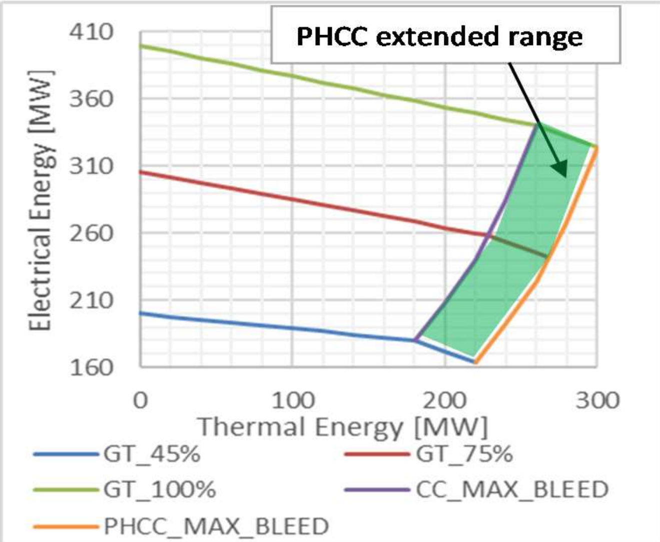
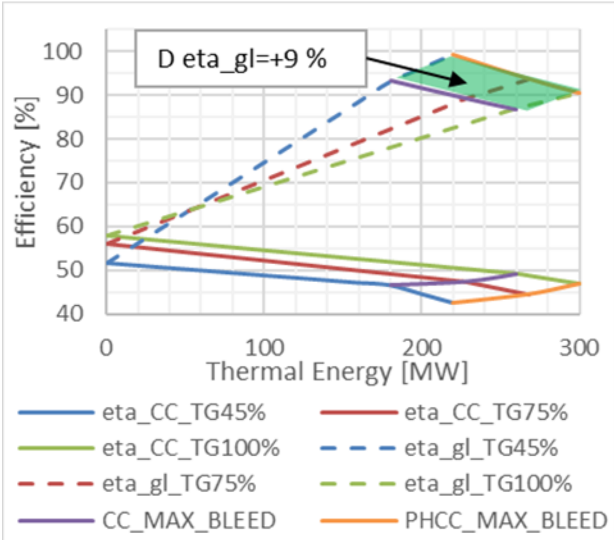
- CHP is devoted to production of electrical and thermal energy,
- the energy required is drained form the Bottoming Cycle and the effect over the cycle is described by the Z Factor

$$Z_{factor} = \frac{P_{th,CC}}{\Delta P_{el,CC}} = 4.7$$

- Here the heat pump is used to enhance the flexibility of GTCC by improving heat prediction
- Iren Energia Moncalieri GTCC 370MW power plant will be the demo site for the CHP configuration





PHCC – CHP: integration of the HP

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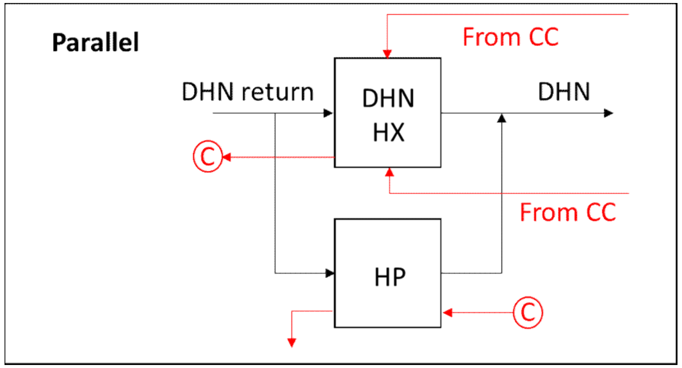

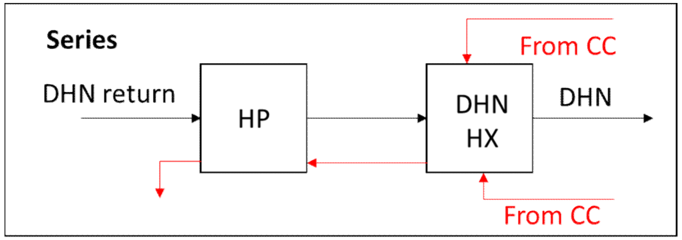

- HP1: in parallel with the DHN return pipeline, delivering thermal energy at the DHN temperature level, working with a fraction of the DHN mass.
- HP2 and HP3: in series with the DHN return pipeline, working with higher mass flows these pumps require more complex pipeline connections and bigger heat exchangers

CC CHP	Series	Parallel
Pro	High COP (partial temperature lift)	By –pass of a % of DHN mass flow rate Chance to operate with CC off
Cons	Operating on the whole DHN mass flow rate (larger size)	Low COP (complete temperature lift)

Equipment	specific cost
Electric Motor [k€/MWe]	64
Heat Pump [k€/MWth]	166
Piping [k€/MWth]	170

→

Equipment	HP1	HP2	HP3
Electric Motor [k€]	160	117	100
Heat Pump [k€]	1660	1660	1660
Piping [k€]	680	1360	2040
Total Cost [k€]	2500	3137	3800

PHCC – CHP: integration of the HP

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As preliminary calculation, the heat pumps have been considered to have the same thermal power of 10 MWth.

	HP1	HP2	HP3
DHN Temp. [°C]	120	120	120
DHN return Temp. [°C]	70	70	70
HP delivery Temp. [°C]	120	95	80
HP Condenser Temp. [°C]	125	100	85
HP Evaporator Temp. [°C]	60	60	60
COP	4.00	5.48	6.41
HP thermal energy [MWth]	10	10	10
CC thermal energy [MWth]	0	10	40
CC share [0-1]	0	1/2	4/5
Critical PUN [€/MWh]	39.3	53.9	63.1

$$C_{th_{j,k}} = \frac{PUN_j}{COP_k} * \left(1 - CC_{sh,k}\right) + \frac{COE}{Z_{factor}} * CC_{sh,k}$$

$$Save_k = \sum_{j=1}^{n} \left(\frac{COE}{Z_{factor}} - \frac{PUN_j}{COP_k} \right) * H_j * P_{th,HP}$$

CHP production cost

HP production cost

$$PUN_{critical} = \frac{COE}{Z_{factor}} COP$$

PHCC – CHP: integration of the HP

Frequency 2016 [hours]	PUN [€/MWh]	HP1 C_{th} [€/MWh]	HP2 C_{th} [€/MWh]	HP3 C_{th} [€/MWh]
8	12.5	3.13	6.06	8.25
46	17.5	4.38	6.51	8.41
233	22.5	5.63	6.97	8.57
772	27.5	6.88	7.42	8.72
1527	32.5	8.13	7.88	8.88
1667	37.5	9.38	8.34	9.03
1422	42.5	10.63	8.79	9.19
1079	47.5	11.88	9.25	9.34
705	52.5	13.13	9.71	9.50
444	57.5	14.38	10.16	9.66
302	62.5	15.63	10.62	9.81
225	67.5	16.88	11.07	9.97
130	72.5	18.13	11.53	10.12
80	77.5	19.38	11.99	10.28

CC thermal production cost

2016 ($COE/Z_{factor} = 9.83$ €$/MWh$)

2017 ($COE/Z_{factor} = 10.87$ €$/MWh$)

Savings and payback period for heat pump integrated system

	HP1	HP2	HP3
Savings 2016 [k€]	69.267	207.259	287.969
PBP 2016 [years]	>20	15.1	13.2
Savings 2017 [k€]	28.212	153.888	246.119
PBP 2017 [years]	>20	>20	15.4

the actual market condition is not suitable for this kind of integrated system, if they are used only to substitute combined cycle thermal energy production during low price periods

PHCC – CHP: Heat Only Boiler substitution

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2016 HOB heat production cost (25.77 €/MWh), sum of three contributions:

- The ratio between the Gas Cost (Tab. 3) and the boiler efficiency (85%))
- Maintenance costs: 10% of the Gas Cost
- CO2 Cost in €/MWh.

Savings and payback period for heat pump integrated system – HOB energy replacement

	HP1	HP2	HP3
Savings [k€/year]	129.472	163.268	176.549
PBP [years]	19.3	19.21	>20

real case scenario IREN: peak hours with HOB on during 2016 in Turin Power Plant Complex

all the HP present saving which are proportional to their installation cost leading to a PBP around the HP lifespan (HP3 has PBP of 21.5 years), so even this solution alone is not meaningful

PHCC – CHP: CC + HOB substitution

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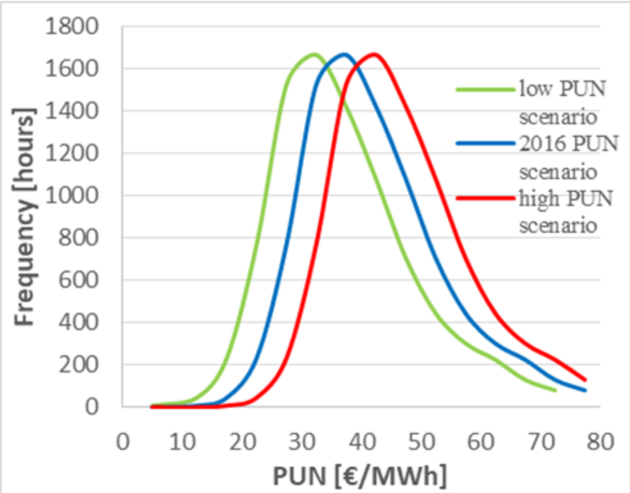
real case scenario IREN: operating CC hours + peak hours with HOB on during 2016 in Turin Power Plant Complex

The payback period can be considered acceptable

Sensitivity analysis on average Electricity price variation
- Same distribution of price
- 5 eur/MWh shift



Savings and payback period for heat pump integrated system - CC+boiler

	HP1	HP2	HP3
Savings [k€/year]	179.607	313.853	385.284
PBP [years]	13.81	9.99	9.86

		HP1	HP2	HP3
Low PUN scenario	*Savings [k€/year]*	228.894	371.325	438.483
	PBP [years]	10.92	8.45	8.66
High PUN scenario	*Savings [k€/year]*	130.319	256.380	332.086
	PBP [years]	19.18	12.24	11.44

Conclusions

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- After an preliminary market analysis three scenarios have been analyzed to evaluate benefit of CC CHP + HP :

a) HP energy is used to substitute part of the thermal energy produced by the combined cycle using 2016 and 2017 energy prices.

b) HP energy is used to substitute part of HOB energy during heat demand peak, based on IREN data of 2016.

c) A combination of the two previous strategy on the 2016 operating condition and considering:

- 2016 Electricity cost

- 5 €/MWh shift sensitivity for a low and high energy price scenario.

- Despite the higher capital costs, the heat pump with the lower temperature difference between condenser and evaporator presented a lower payback period thanks to a higher COP
- Actual market conditions are still not completely favorable to this kind of innovative plant layout (CHP HP + CC) leading however to interesting economic results, exploiting low electricity prices
- The CC and HP integration, shifting the heat production to the most convenient source can be envisaged as key-technology to reducing both generation cost and fuel consumption

Acknowledgments

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http://www.pumpheat.eu/

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Thank you for your time

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