4th International Seminar on ORC POWER SYSTEMS

clean energy ahead TURBODEN

a group company of MITSUBISHI HEAVY INDUSTRIES, LTD.

V International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

TECHNO-ECONOMIC ANALYSIS OF ORC IN GAS COMPRESSION STATIONS TAKING INTO ACCOUNT ACTUAL OPERATING CONDITIONS

M. Bianchi, L. Branchini, A. De Pascale, F. Melino, V. Orlandini, A. Peretto
Università di Bologna – DIN, Bologna, ITALY

D. Archetti, F. Campana, T. Ferrari, N. Rossetti
Turboden S.p.A, Brescia, ITALY

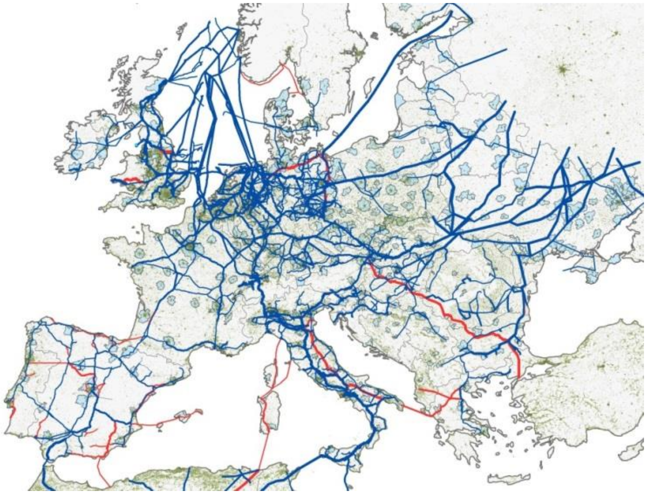
ALMA MATER STUDIORUM – UNIVERSITÀ DI BOLOGNA
IL PRESENTE MATERIALE È RISERVATO AL PERSONALE DELL'UNIVERSITÀ DI BOLOGNA E NON PUÒ ESSERE UTILIZZATO AI TERMINI DI LEGGE DA ALTRE PERSONE O PER FINI NON ISTITUZIONALI

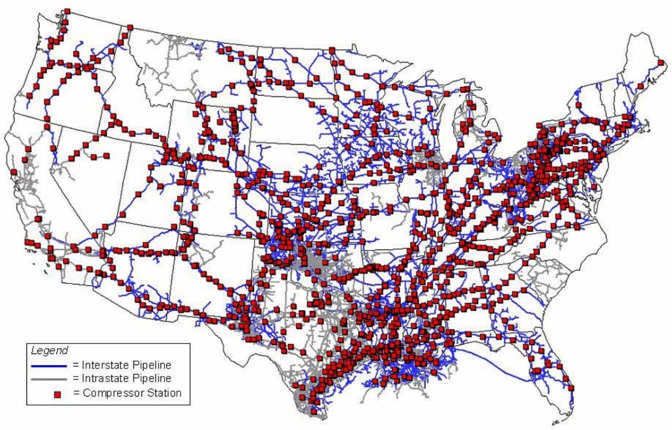
OUTLINES OF THE STUDY

- BACKGROUND & INTRODUCTION
- OBJECTIVES
- GTs-ORC CONFIGURATIONS: DIRECT EVA, WITH IHTF
- ASSUMPTIONS & BOUNDARY CONDITIONS FOR ORC DESIGN
- TECHNO-ECONOMIC PERFORMANCE RESULTS BASED ON YEARLY GTs 1 min. DATA OPERATION
- CONCLUSIONS

BACKGROUND & INTRODUCTION:

NG network potential

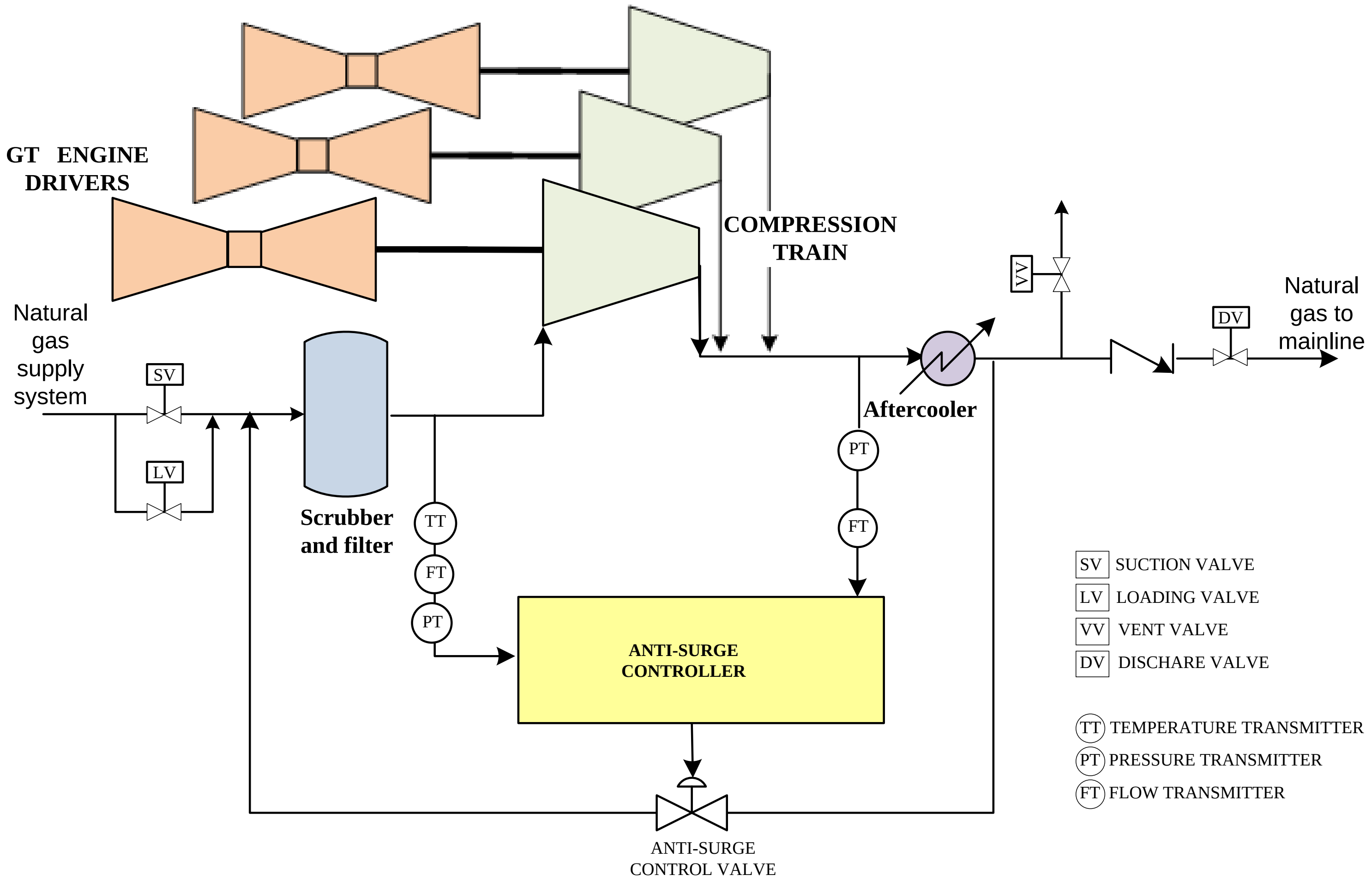




- **CSs** represent a **fundamental element of NG transport system: cost of compression** can reach **50 %** of total transmission cost [*Mercado et al. – Applied Energy, 2015];*
- in the decade (1996-2006), **+ 26 %** in **CSs installed power, + 19 %** in throughput **capacity** to reduce environmental footprint and accommodate higher volume of NG [*EIA-report*];
- **Huge energy recovery potential in the NG transmission sector**: **1300 MWe recoverable with ORC** applied to NG CSs (European market), energy generation up to 10.43 TWh/year, 3.7 million tons avoided GHG emissions and 934 million $/year of avoided energy costs [*Campana et al. - Energy Conversion and Management, 2013]*

BACKGROUND & INTRODUCTION

basic components of a NG CS facility



BACKGROUND & INTRODUCTION:

characteristics of GTs in O&G sector

GTs WIDELY USED IN O&G SECTOR FOR POWER GENERATION & MECHANICAL DRIVE APPLICATIONS: Why differentiate O&G Gas turbines from other applications?

OIL & GAS REQUIREMENTS:

- AVAILABILITY/RELIABILITY : redundant capacity installed to ensure the necessary reserve power
- RUGGEDNESS
- HIGH POWER/WEIGHT RATIO
- EFFICIENCY NOT VERY CRITICAL: significant portion of primary energy discharged into atmosphere

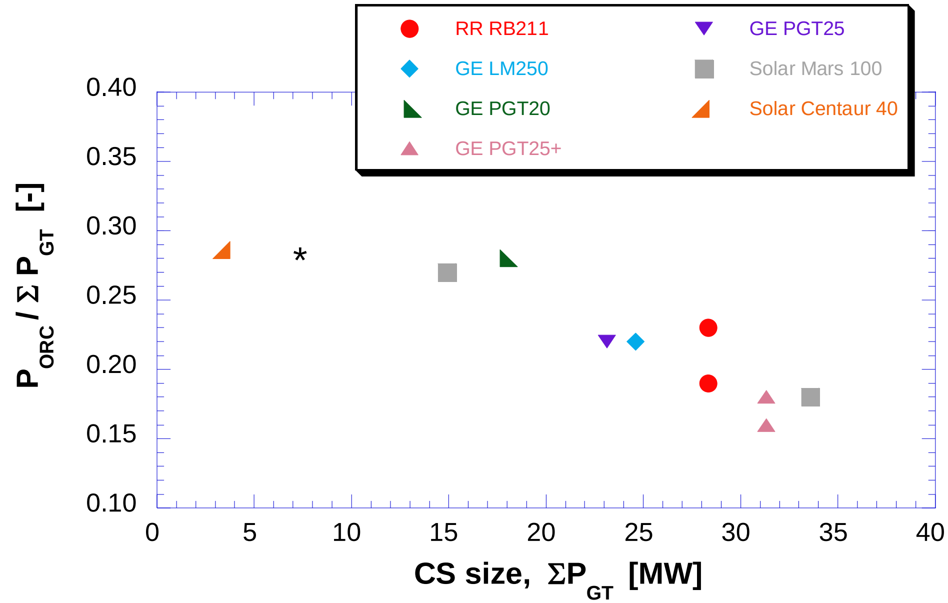
INDUSTRIAL POWER GENERATION REQUIREMENTS:

- COST OF ELECTRICITY
- EFFICIENCY
- COST OF O&M

BACKGROUND & INTRODUCTION:

Operative ORC in NG CS

Pipeline Name*	Location	GT model	GT/ORC Size [MW]
TransCanada	Gold Creek, Alberta	Rolls Royce RB211	**28.3 / 6.5**
Norther Border	St. Anthony, North Dakota		**28.3 / 5.5**
	Wetonka, South Dakota		
	Clark, South Dakota		
	Estelline, South Dakota		
	Manning, North Dakota		
	Zeeland, North Dakota		
	CS6, North Dakota		
	Culbertson, Montana		
	Garvin, Minnesota		
	CS 13, Minnesota		
Alliance	Kerrobert, Saskatchewan	GE LM2500	**24.6 / 5.5**
	Loreburn, Saskatchewan		
	Estlin, Saskatchewan		
	Alameda, Saskatchewan		
Spectra	Mile House, British Columbia	GE PGT 20	**17.9 / 5.0**
	Savona, British Columbia		
Alliance	Irma, Alberta	GE PGT 25+	**31.3 / 5.5**
Spectra	Australian, British Columbia		**31.3 / 5.0**
Spectra	Summit Lake, British Columbia	GE PGT 25	**23.1 / 5.0**
	Hixon, British Columbia		
Trailblazer	Peetz, Colorado	Solar Mars 100	**14.9 / 4.0**
Kern River	Goodspring, Nevada		**33.6 / 6.0**
Alliance	Windfall, Alberta		**- / 14**
	Morinville, Alberta		**- / 5.5**
TransGas**	Saskatchaewan	Solar Centaur 40	**3.4 / 1.0**



**E. Macchi, M. Astolfi, Organic Rankine Cycle (ORC) Power Systems- Technologies and Applications, Woodhead publishing series in Energy, Elsevier, 2017, ISBN: 978-0-08-100510-1*

*** Turboden data*

OBJECTIVES

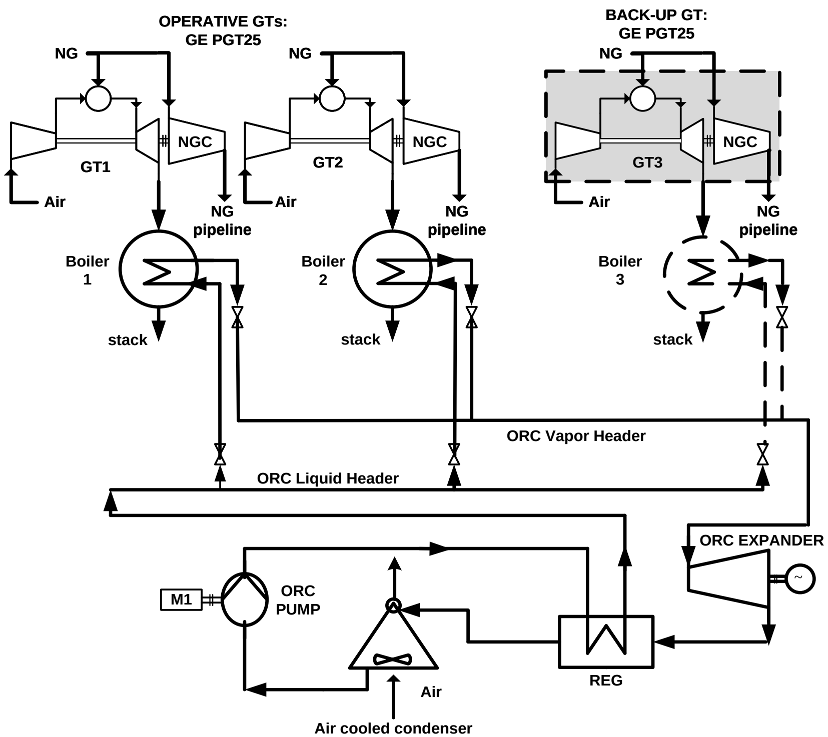
ANALYZE THE ENERGETIC-ECONOMIC POTENTIAL OF ORC AS BOTTOMER CYCLE OF A 50 MW NG COMPRESSION STATION, UNDER ACTUAL GTs OPERATION.

- TWO DIFFERENT GTs-ORC CONFIGURATIONS (WITH/WITHOUT INTERMEDIATE FLUID) DESIGNED AND THERMODYNAMIC PERFORMANCE IDENTIFIED.
- TAKING INTO ACCOUNT GTs PART-LOAD BEHAVIOR DURING THE YEAR, ORC OFF-DESIGN OPERATION ARE ESTIMATED.
- ENERGETIC, ECONOMIC AND ENVIRONMENTAL ANALYSIS, YEARLY BASE, IS CARRIED OUT TO SHOW THE FEASIBILITY OF ORC.

GTs-ORC CONFIGURATIONS

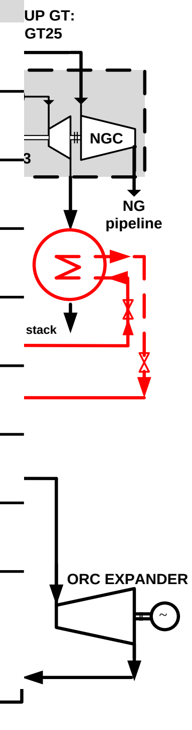
DIRECT HEAT EXCHANGE

GTs SELECTED



NT

GE PGT25	
Shaft power [kW]	**23684**
Electric power [kW]	23109
GT shaft/electric efficiency [%]	**37.1 / 36.2**
Fuel input power [kW]	63810
Pressure ratio [-]	**18**
Exhaust gas temperature [°C]	**542**
Exhaust gas mass flow [kg/s]	**69**
Specific work [kJ/kg]	340
Available heat in exhaust Q_{AVA} (@ 15°C) [kW]	**46102**

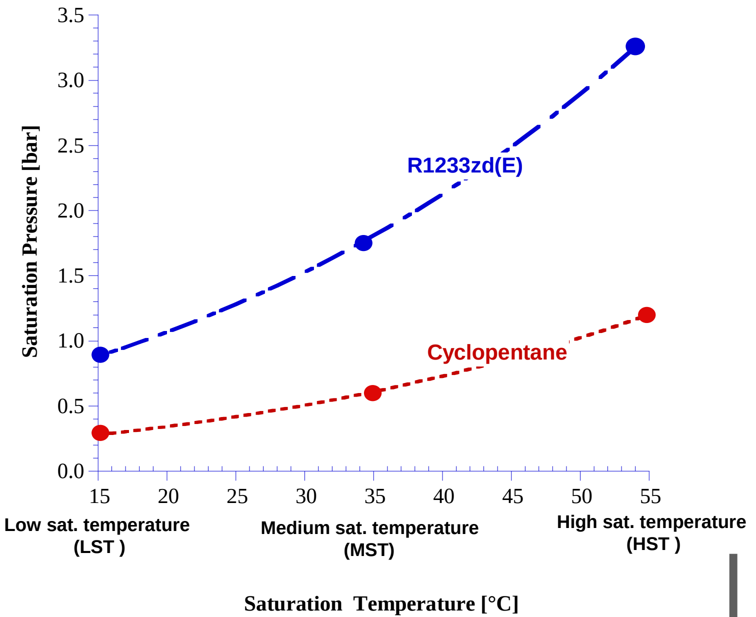


GTs-ORC DESIGN ANALYSIS: preliminary investigations for optimum

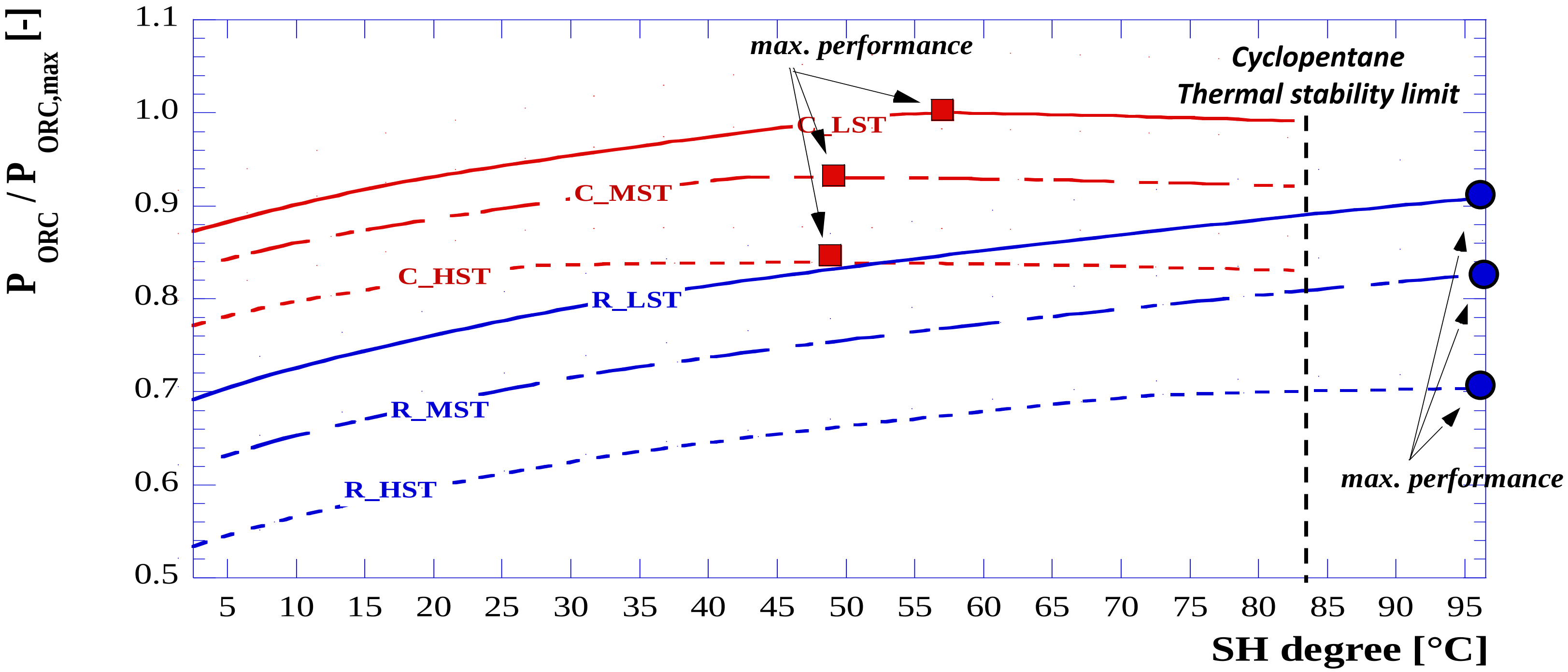
Preliminary parametric investigation on ORC as bottomer on NG CS facilities to analyze:

- different organic fluids analyzed: **Cyclopentane, Cyclohexane**, refrigerant fluid **R1233zd(E)** etc.
- different condensation conditions analyzed: low, medium, high saturation temperature
- Influence of superheting degree values, according to fluids thermal stability limits, to identify max. ORC performance

Organic fluid property	Cyclopentane	R1233zd(E)
Molar weight [kg/kmol]	70.13	130.50
Critical Pressure [bar]	**45.1**	**37.7**
Critical Temperature [°C]	**238.6**	**165.6**
Normal Boiling point [°C]	49.3	18.3
Thermal stability limit [°C]	**300**	**250**
Flamability risk	**Flammable**	**None**
GWP [-]	0	1
ODP [-]	0	0.0003



GTs-ORC DESIGN ANALYSIS: preliminary investigations for optimum



Discussion:

- positive effect on P_{ORC} of low condensation temperature (max. values in LST case);
- depending on organic fluid, max. performance recorded for different SH degree values;
- Refrigerant shows a monotonic increase of power output values with SH degree while cyclopentane max. performance achieved for values close to 50 °C, considerably lower than thermal stability limit

GTs-ORC DESIGN ASSUMPTIONS

GTs-ORC DESIGN SPECIFICATIONS:
based on literature survey and Turboden experience on 10 MW ORC size

GT load [% of nameplate capacity]	80
Inlet/outlet duct pressure losses [mbar]	10
Minimum GT stack temperature [°C]	150
ORC working fluid	Cyclopentane
IHTF assumed	Therminol 66
ORC expander isentropic efficiency [%]	0.85
ORC evaporative pressure-critical pressure ratio [-]	0.76
ORC max. superheating degree [°C]	96.5
Boiler pressure drop, organic fluid/ IHTF/gas side [bar]	2/1/0.015
IHTF maximum temperature [°C]	315
IHTF loop max. pressure [bar]	15
pressure drop in IHTF loop [bar]	2

HE pressure drop, IHTF/ gas side [bar]	1.5/0.015
REG effectiveness [%]	85
REG pressure drop ORC liquid/vapour side [bar]	1/0.55
Subcooling ORC outlet condenser [°C]	5
Condensation temperature [°C]	35
Condenser pressure drop, organic fluid side [bar]	0.1
Air draft losses [mbar]	2
Heat exchangers thermal loss [%]	1
Electro/mechanical efficiency [%]	97
Pumps mechanical efficiency [%]	80
Pumps/Fun nominal isentropic efficiency [%]	60
Miscellaneous GT aux. load [% of GTs power]	0.7

- ✓ ORC bottomer cycle design with **GTs @ 80% of nameplate capacity**
- ✓ **Cyclopentane** and **Therminol 66** assumed as organic and intermediate fluids
- ✓ **Subcritical ORC** cycle condition with **superheating**
- ✓ **Air cooled condenser** assumed
- ✓ **Pressure and heat losses** accounted

ORC DESIGN RESULTS

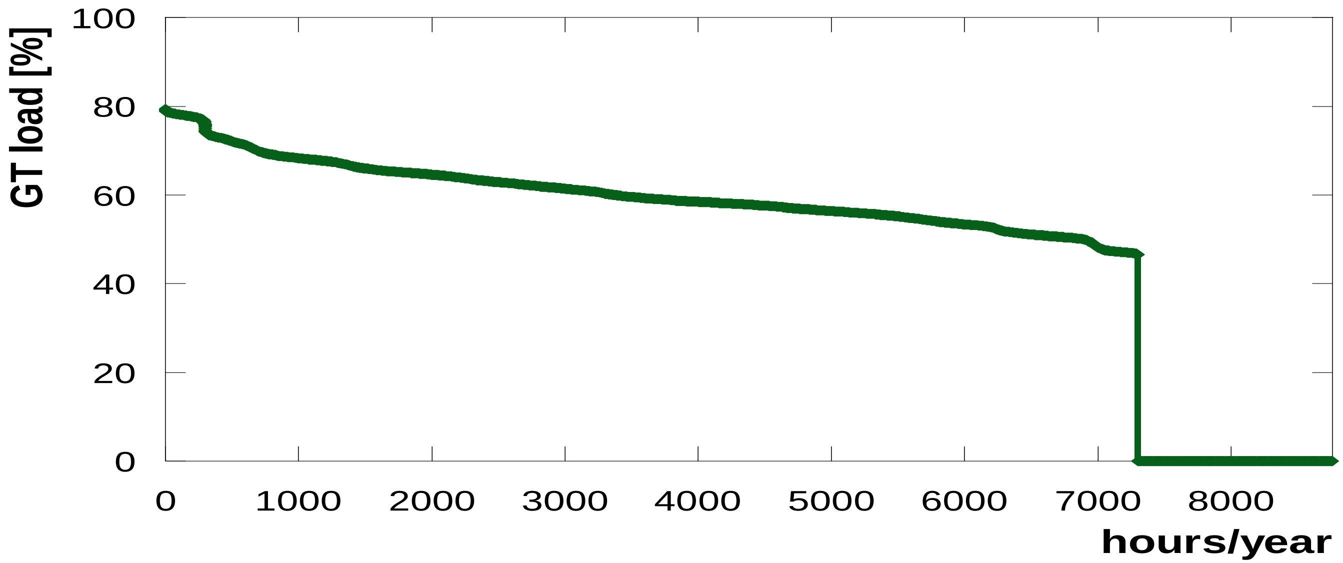
ORC Performance results @ design conditions	DHE CASE	IHTF CASE
Bottomer cycle thermal power input [kW]	**46856**	**47294**
ORC turbine inlet pressure [bar]	**34**	**34**
ORC turbine inlet temperature [°C]	**280**	**250**
Condenser pressure [bar]	**0.61**	**0.61**
ORC fluid mass flow rate [kg/s]	**80**	**84**
IHTF inlet/outlet temperatures [°C]	-	130/315
IHTF fluid mass flow rate [kg/s]	-	112
ORC gross electric power [kW]	**12039**	**11433**
ORC Specific power [kJ/kg]	**155**	**140**
Thermal power to condenser [kW]	34593	35436
Turbine expansion pressure ratio [-]	56	56
Turbine expansion volume ratio [-]	35	38
Organic fluid/IHTF pumps consumptions [kW]	728/-	739/185
Air cooled condenser fun consumptions [kW]	953	977
Net ORC electric power output [kW]	**11311**	**10509**
Net ORC electric efficiency [-]	**0.241**	**0.222**

GTs OPERATION IN A NG CS

To predict bottomer yearly performance operation

⇩

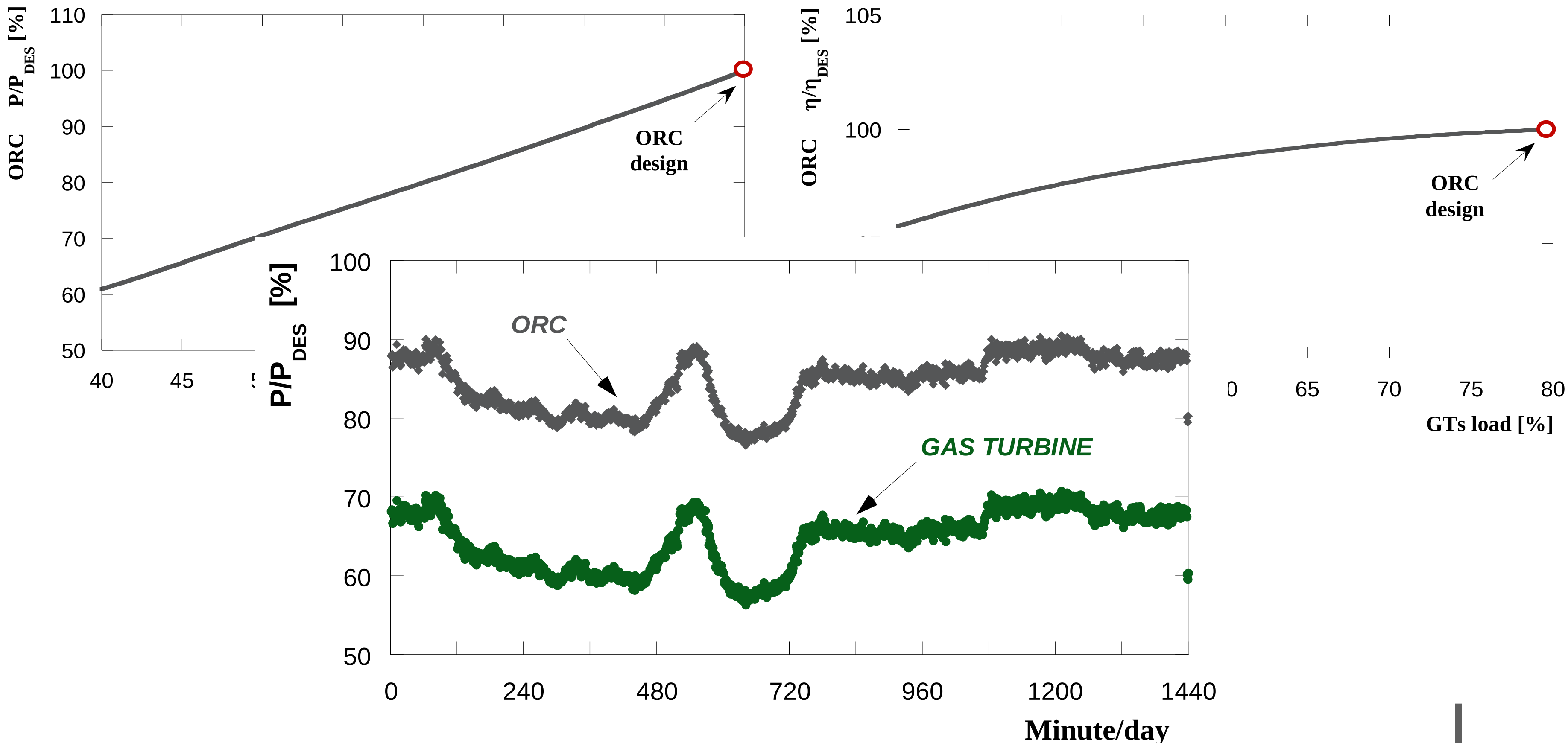
Real 1 min. data of GT working as mechanical driver in a NG CS



- ✓ PART LOAD OPERATION FOR 7300 h/y
- ✓ UNITS OPERATED BETWEEN 80 – 60 % OF NAMEPLATE CAPACITY FOR 4000 h/y

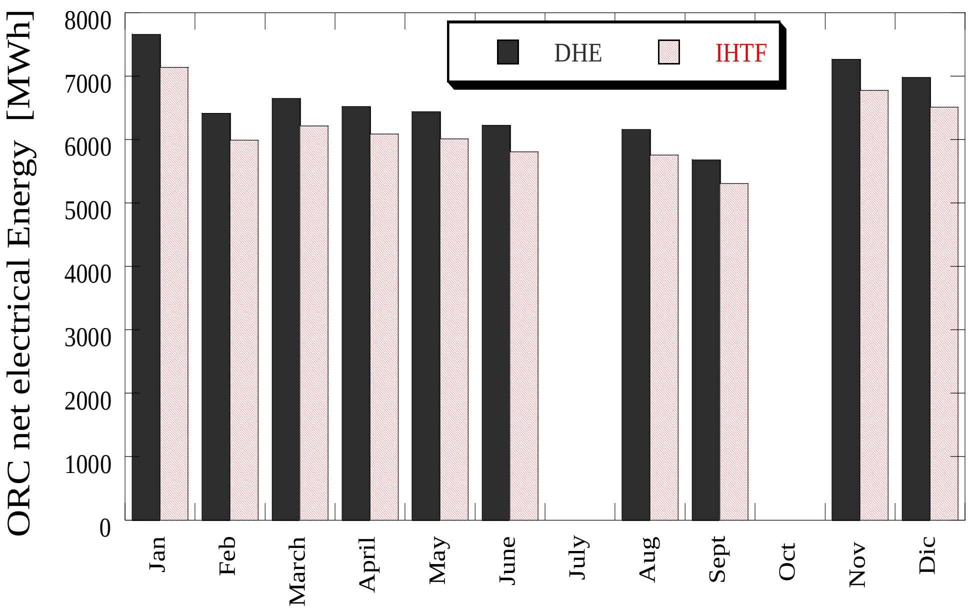
ORC OFF-DESIGN PERFORMANCE BEHAVIOUR

ORC off-design operation estimated through power output & efficiency curves as function of GT load (DHE layout)



GTs-ORC YEARLY PERFORMANCE RESULTS

Yearly results of ORC operation	DHE	IHTF
Average net Power output during operative hours [kW]	9084	8475
Average net electric efficiency during operative hours [-]	0.238	0.220
Generated net electrical energy [GWh/year]	66.03	61.60
Equivalent operating hours [h]	5838	5862
NG Primary energy saved [GWh/year]	182	170
CO_2 saved [tons/year]	36080	33661

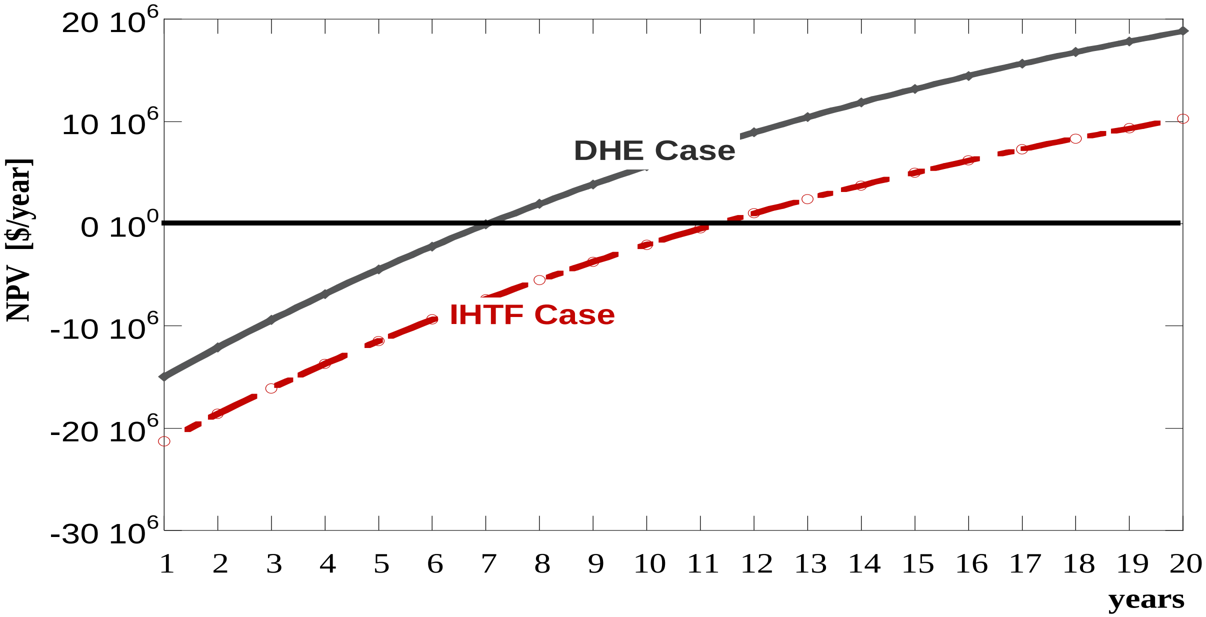


ECONOMIC RESULTS

$$NPV = \sum_{i=1}^{n} M_a \frac{R_i}{(1+q)^i} - I_{TOT}$$

Annual incomes represented by **fuel savings** (0,09 \$/Sm^3) and **avoided CO_2 taxes** (56 \$/t)

Total Investment costs depending on layouts **DHE 1500 \$/kW** and **IHTF 2000 \$/kW**



CONCLUSIONS

- a detailed techno-economic feasibility study of two different ORC configurations, as energy recovery technologies to be implemented in a 50 MW NG CS, has been performed.
- performance of the ORC cycle have been evaluated, based on the NG CS real demand data, taking into account the bottomer off-design operation.
- obtained results show that the direct heat exchange layout enables the saving of more than 182 GWh of fuel per year, generating up to 66 GWh/year of additional net electrical energy. The total amount of CO_2 saved is up to $36*10^3$ tons/year.
- performed economic analysis, based on the NPV method, shows that the ORC investment costs can be recovered within 7 years of CS operation in case of DHE. Pay-back time is increased up to 11 years in case of IHTF.
- performed investigation confirmed the ORC as a techno-economic profitable industrial technology, capable to recover significant amount of wasted heat in NG compression facilities.

IL PRESENTE MATERIALE È RISERVATO AL PERSONALE DELL'UNIVERSITÀ DI BOLOGNA E NON PUÒ ESSERE UTILIZZATO AI TERMINI DI LEGGE DA ALTRE PERSONE O PER FINI NON ISTITUZIONALI

4th International Seminar on ORC POWER SYSTEMS

clean energy ahead
TURBODEN
a group company of MITSUBISHI HEAVY INDUSTRIES, LTD.

V International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

TECHNO-ECONOMIC ANALYSIS OF ORC IN GAS COMPRESSION STATIONS TAKING INTO ACCOUNT ACTUAL OPERATING CONDITIONS

M. Bianchi, L. Branchini, A. De Pascale, F. Melino, V. Orlandini, A. Peretto
Università di Bologna – DIN, Bologna, ITALY

D. Archetti, F. Campana, T. Ferrari, N. Rossetti
Turboden S.p.A, Brescia, ITALY

IL PRESENTE MATERIALE È RISERVATO AL PERSONALE DELL'UNIVERSITÀ DI BOLOGNA E NON PUÒ ESSERE UTILIZZATO AI TERMINI DI LEGGE DA ALTRE PERSONE O PER FINI NON ISTITUZIONALI