A cost - benefit analysis for large scale implementation of MAST gas turbine technologies

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Mixed Air Steam Turbines Fired by Liquid Fuels

(MAST-B-LIQUID)

Contract No: ENK5-CT2002-00668

MAST-B-LIQUID Project

Partners

- Imperial College of Science, Technology and Medicine, UK (Coordinator)
- National University of Ireland, Ireland
- Halle University, Germany
- Institute of Chemical Engineering and High Temperature Chemical Processes, Greece
- Universitat Twente, Netherlands
- SIEMENS, Sweden
- Electricity Authority of Cyprus, Cyprus

MAST-B-LIQUID Project

Objectives

1. **Design guidelines for combustion chambers of mixed air-steam turbine (MAST) technologies -** **steam mass flow rate, intercooling, recuperation and mixture inhomogeneity**

2. **Technical, economic and environmental prospects of MAST technologies -** **capital outlay, water economy, base or peak load operation**

MAST technologies

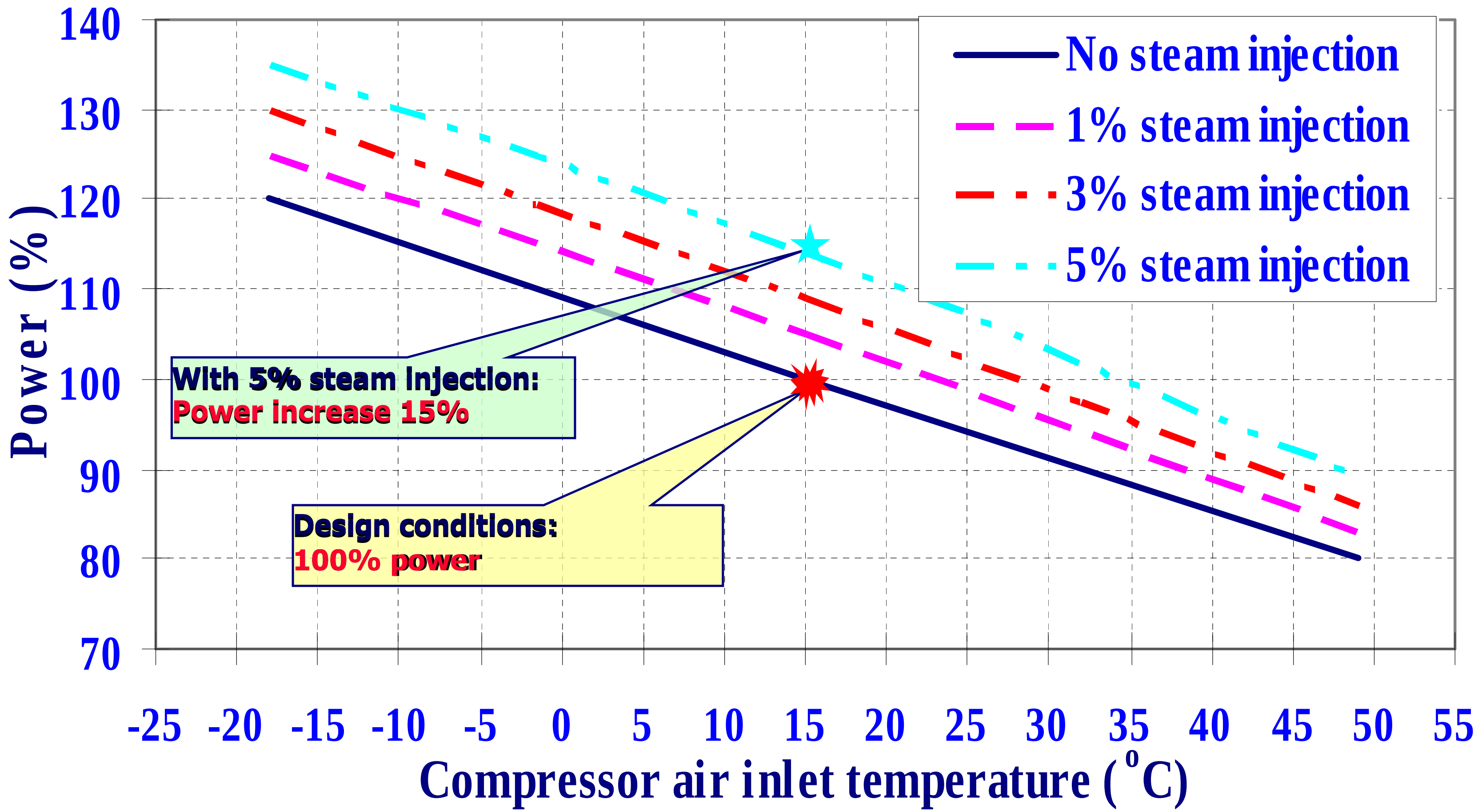
Mixed Air Steam Turbine (MAST) technologies*

- Water or steam injection
- Before or in the combustion chamber
- Increase in mass flow, thus, power
- NO_X reduction
- Water consumption

* Also, referred as mixed gas turbine or as wet gas turbine technologies

MAST technologies

Effect of steam injection



With 5% steam injection:
Power increase 15%

Design conditions:
100% power

MAST technologies

Commercially available MAST gas turbines +

Turbine	Manufacturer	Power (MWe)		Efficiency (%)	
		without steam injection	with steam injection	without steam injection	with steam injection
M1A-13CC	KAWASAKI Heavy Industries	1,3	2,4	22,3	33,7
501-KH	Allison Engine Company	4,9	6,8	31,5	39,9
LM1600 STIG*	General Electric	13,0	17,0	35,5	39,5
LM2500 STIG*	General Electric	22,8	28,1	36,8	41,0
LM5000 STIG*	General Electric	34,5	51,6	37,2	43,8

* STIG^{TM} = STeam Injected Gas turbine

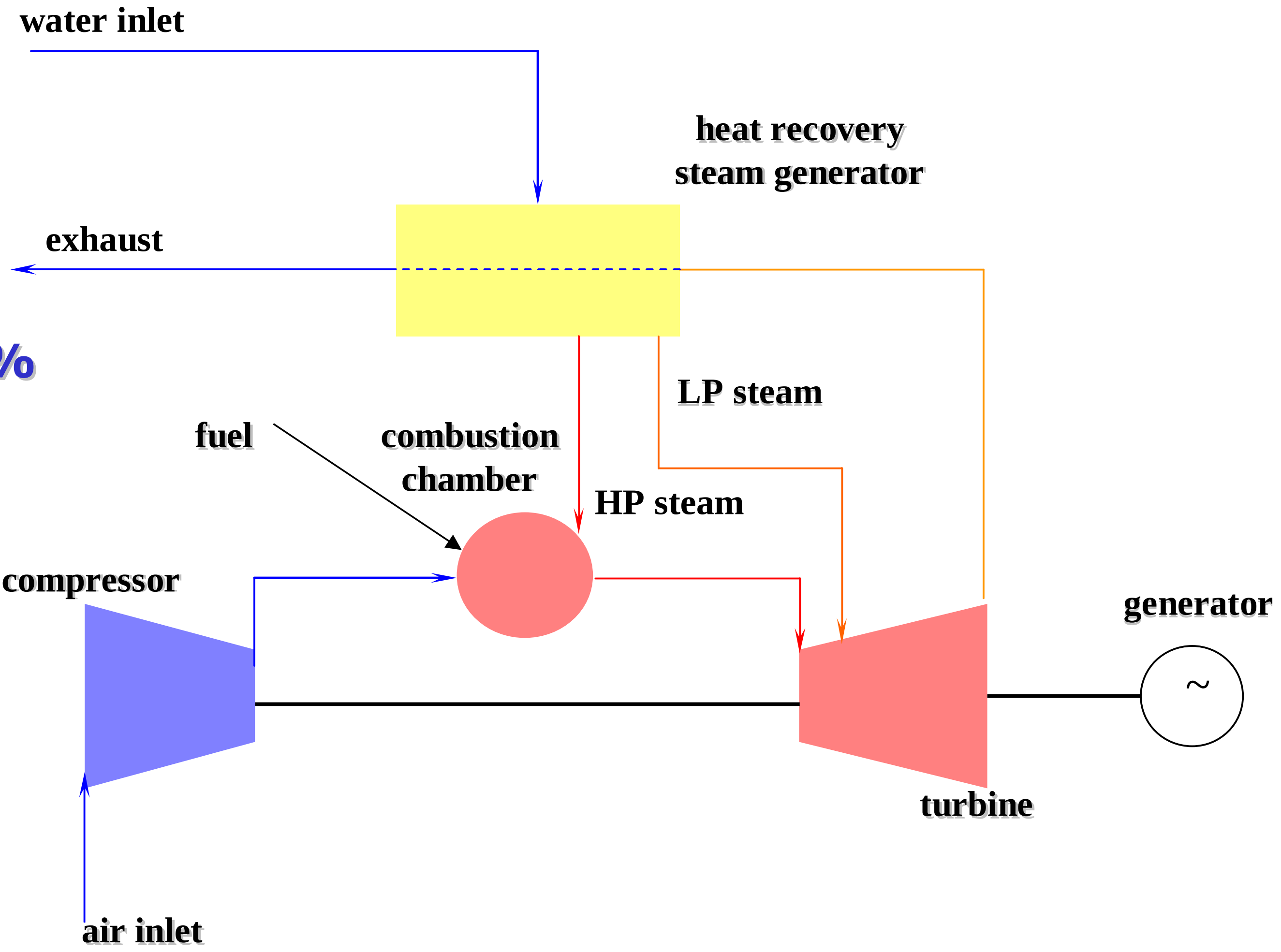
\+ Poullikkas A., "An overview of current and future sustainable gas turbine technologies", *Renewable and Sustainable Energy Reviews*, 2005.

MAST technologies

Cheng cycle*

Power increase ~ 60%

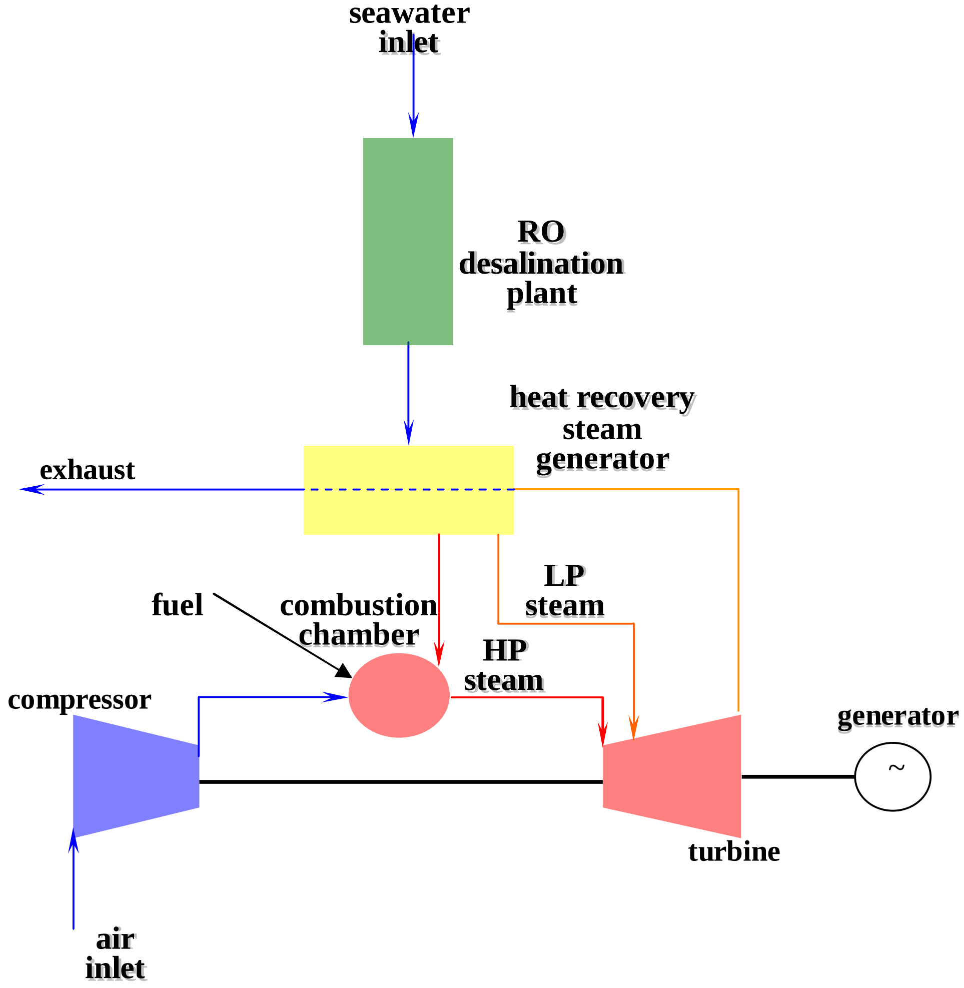
Gain in efficiency ~ 10%



* Poullikkas A., "An overview of current and future sustainable gas turbine technologies", *Renewable and Sustainable Energy Reviews*, 2005.

MAST technologies

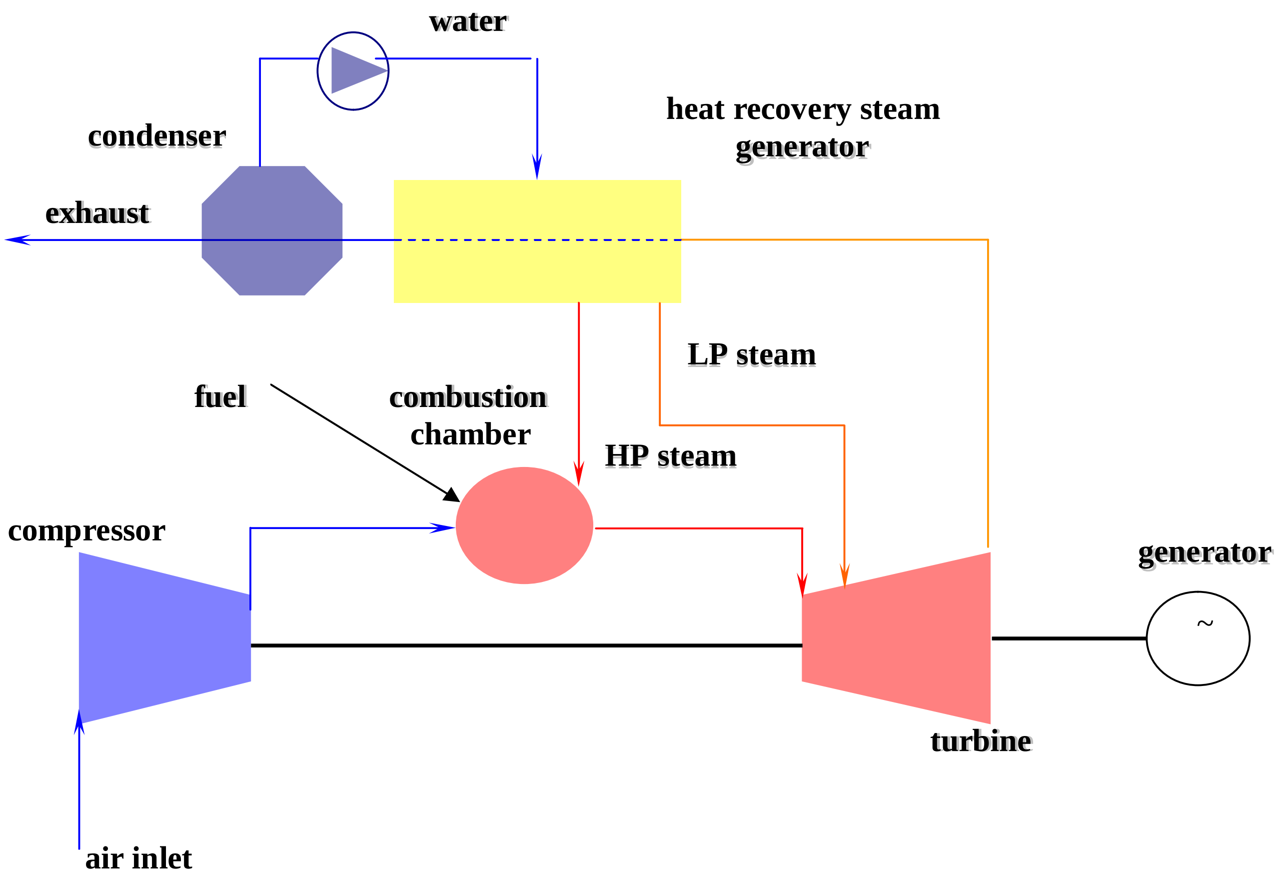
Cheng cycle with desalination*



* Poullikkas A., “Technical and economic analysis for the integration of small reverse osmosis desalination plants into MAST gas turbine cycles for power generation”, *Desalination*, 2005.

MAST technologies

Cheng cycle with water recovery condenser



* Poullikkas A., "Operating cost and water economy of mixed air steam turbines", *Applied Thermal Engineering*, 2005.

Simulation tools

Simulation tools

I.P.P. ALGORITHM

Software for power technology selection in competitive electricity markets*

C.A.R.O.C.

Computer aided reverse osmosis calculations**

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* Poullikkas A., “A technology selection algorithm for independent power producers”, *The Electricity Journal*, 2001.

** Poullikkas A., “Optimisation algorithm for reverse osmosis desalination economics”, *Desalination*, 2001.

Simulation tools

I.P.P. ALGORITHM V2.1*

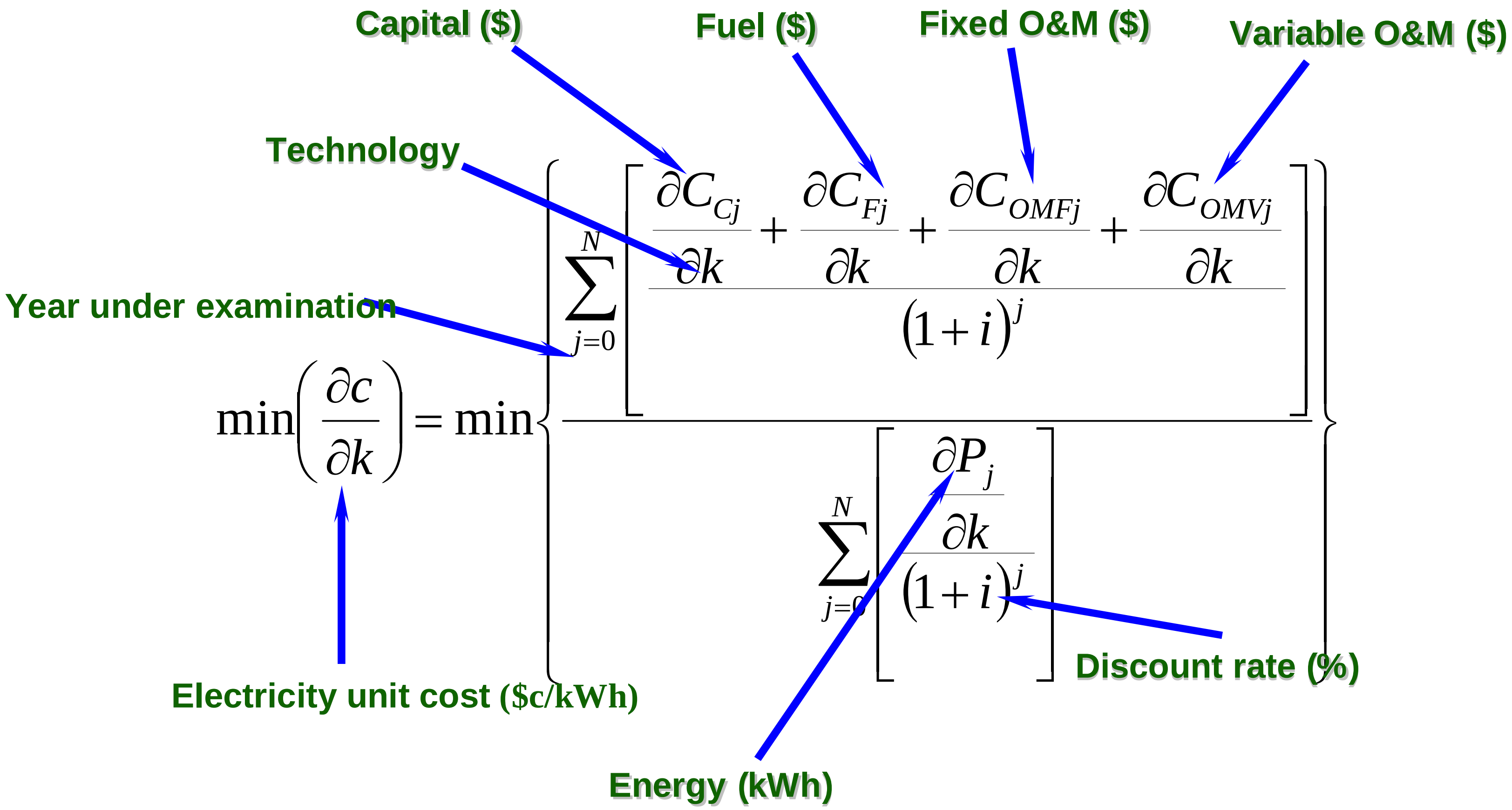
(Software for power technology selection in competitive electricity markets)

1. Technical, economic and environmental analysis
2. Evaluation of candidate power technologies:
   - Capital cost
   - Fuel consumption and cost
   - Operation and maintenance cost
   - Plant load factor
   - Life expectancy etc.
3. Least cost power generation configuration

*Poullikkas A., *IPP algorithm version 2.1*, User manual, © 2000-2006.

Simulation tools

Final cost function*



Capital ($)

Fuel ($)

Fixed O&M ($)

Variable O&M ($)

Technology

Year under examination

$$\min\left(\frac{\partial c}{\partial k}\right) = \min\left\{ \frac{\sum_{j=0}^{N} \left[\frac{\frac{\partial C_{Cj}}{\partial k} + \frac{\partial C_{Fj}}{\partial k} + \frac{\partial C_{OMFj}}{\partial k} + \frac{\partial C_{OMVj}}{\partial k}}{(1+i)^{j}} \right]}{\sum_{j=0}^{N} \left[\frac{\frac{\partial P_{j}}{\partial k}}{(1+i)^{j}} \right]} \right\}$$

Electricity unit cost ($c/kWh)

Discount rate (%)

Energy (kWh)

*Poullikkas A., *IPP algorithm version 2.1*, User manual, © 2000-2006.

Simulation tools

C.A.R.O.C. software*

1. Economic model

2. Evaluation of candidate RO technologies:

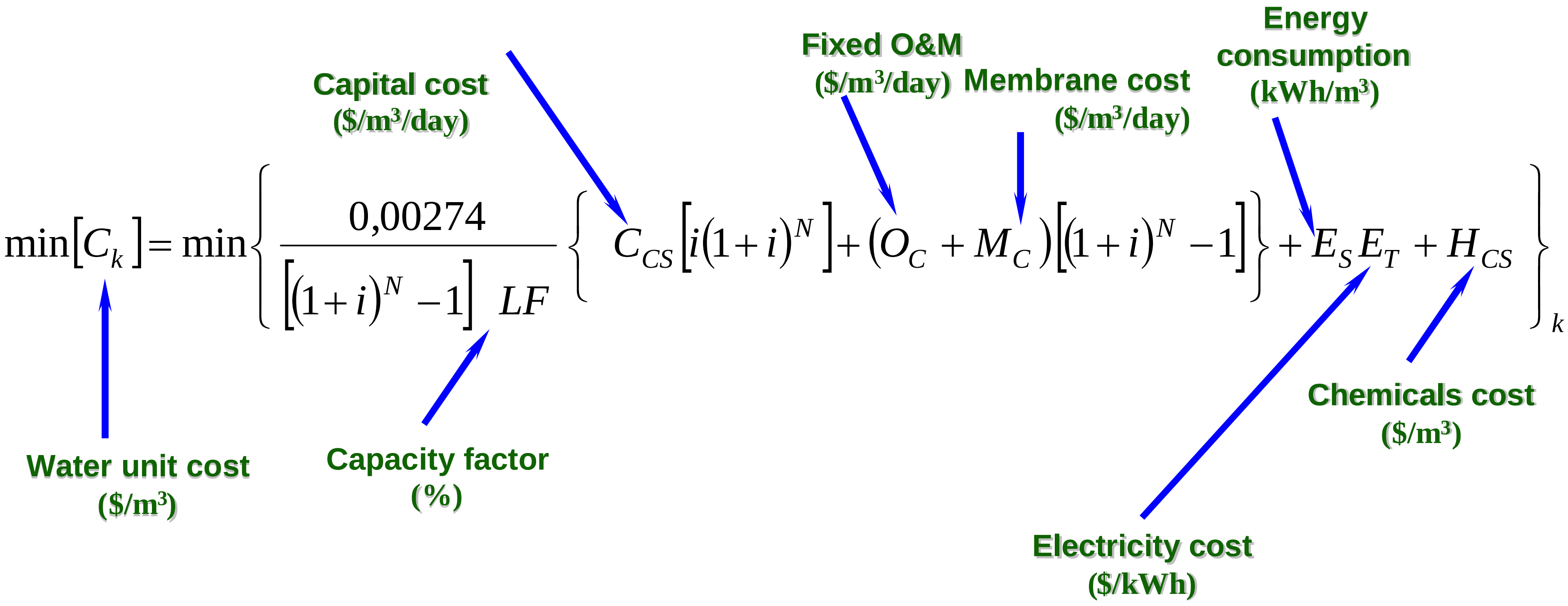
- Capital cost
- Energy consumption and cost
- Operation and maintenance cost
- Membrane replacement cost
- Chemicals cost
- Plant load factor
- Life expectancy etc.

3. Least cost RO desalination configuration

*Poullikkas A., "Optimisation algorithm for reverse osmosis desalination economics", *Desalination*, 2001.

Simulation tools

Cost function*



$$\min\left[C_k\right] = \min\left\{ \frac{0{,}00274}{\left[(1+i)^N - 1\right] \; LF} \left\{ C_{CS}\left[i(1+i)^N\right] + \left(O_C + M_C\right)\left[(1+i)^N - 1\right]\right\} + E_S E_T + H_{CS} \right\}_k$$

*Poullikkas A., "Optimisation algorithm for reverse osmosis desalination economics", *Desalination*, 2001.

Cost - benefit analysis

Eligible plants

1. **Rankine cycle (heavy fuel oil)**
2. **Open cycle gas turbine (gasoil)**
3. **Open cycle gas turbine (natural gas)**
4. **Combined cycle (gasoil)**
5. **Combined cycle (natural gas)**
6. **Cheng cycle with desalination (gasoil)**
7. **Cheng cycle with desalination (natural gas)**
8. **Cheng cycle with water recovery condenser (gasoil)**
9. **Cheng cycle with water recovery condenser (natural gas)**

Cost - benefit analysis

Technical and economic parameters of candidate technologies

Run No	Technology	Fuel type	Capacity	Capital Cost	Efficiency	Water recovery condenser	Water requirements	Fuel net calorific value	Fuel cost		Fixed O&M	Variable O&M
			MWe	€/kW	%		kg/s	GJ/t	€/t	€/GJ	€/kW-month	€/MWh
Non-MAST technologies												
1	Boiler/steam turbine	HFO	120,0	1258	37,3	-	-	41,3	167	4,04	1,40	1,50
2	Gas turbine	Gasoil	81,0	550	27,1	-	-	42,5	246	5,79	1,25	6,00
3	Gas turbine	Natural gas	81,0	532	28,4	-	-	45,0	141	3,13	0,83	4,00
4	Combined cycle	Gasoil	180,0	765	47,3	-	-	42,5	246	5,79	1,57	3,20
5	Combined cycle	Natural gas	180,0	700	50,0	-	-	45,0	141	3,13	1,25	2,50
MAST technologies												
6	LM2500 STIG	Gasoil	28,1	556	41,0	No	5,88	42,5	246	5,79	1,57	3,20
7	LM2500 STIG	Gasoil	28,1	598	41,0	Yes	-	42,5	246	5,79	1,68	3,42
8	LM2500 STIG	Natural gas	28,1	556	41,0	No	5,88	45,0	141	3,13	1,25	2,50
9	LM2500 STIG	Natural gas	28,1	598	41,0	Yes	-	45,0	141	3,13	1,34	2,68
10	LM5000 STIG	Gasoil	51,6	580	43,8	No	17,90	42,5	246	5,79	1,57	3,20
11	LM5000 STIG	Gasoil	51,6	620	43,8	Yes	-	42,5	246	5,79	1,66	3,39
12	LM5000 STIG	Natural gas	51,6	580	43,8	No	17,90	45,0	141	3,13	1,25	2,50

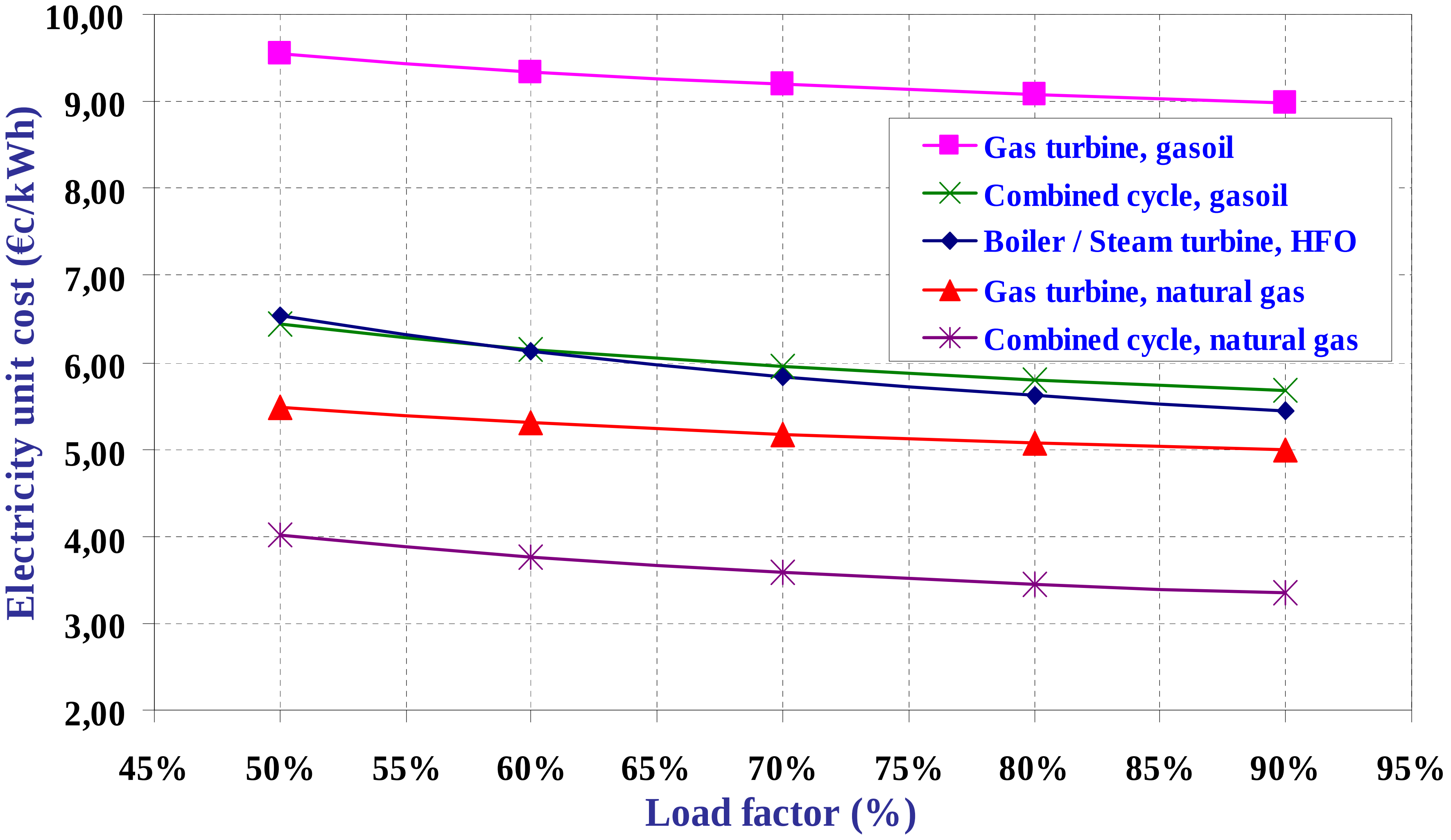
Cost - benefit analysis

RO desalination plants technical and economic parameters

Run No	MAST gas turbine	Capacity	Water recovery condenser	Water requirements at maximum capacity		RO plant capacity	Capital cost	Energy consumption	Fixed O&M		Variable O&M
									Labour, spare parts, overheads, etc.	Mebrane replacement cost	Chemicals cost
		MWe		kg/s	l/kWh	m^3/day	€/m^3/day	kWh/m^3	€/m^3/day	€/m^3/day	€/m^3
6	LM2500 STIG	28,1	No	5,88	0,75	508,0	669	3,77	26,79	16,30	0,05
7	LM2500 STIG	28,1	Yes	-	-	-	-	-	-	-	-
8	LM2500 STIG	28,1	No	5,88	0,75	508,0	669	3,77	26,79	16,30	0,05
9	LM2500 STIG	28,1	Yes	-	-	-	-	-	-	-	-
10	LM5000 STIG	51,6	No	17,90	1,25	1546,6	663	3,77	13,23	16,30	0,05
11	LM5000 STIG	51,6	Yes	-	-	-	-	-	-	-	-
12	LM5000 STIG	51,6	No	17,90	1,25	1546,6	663	3,77	13,23	16,30	0,05

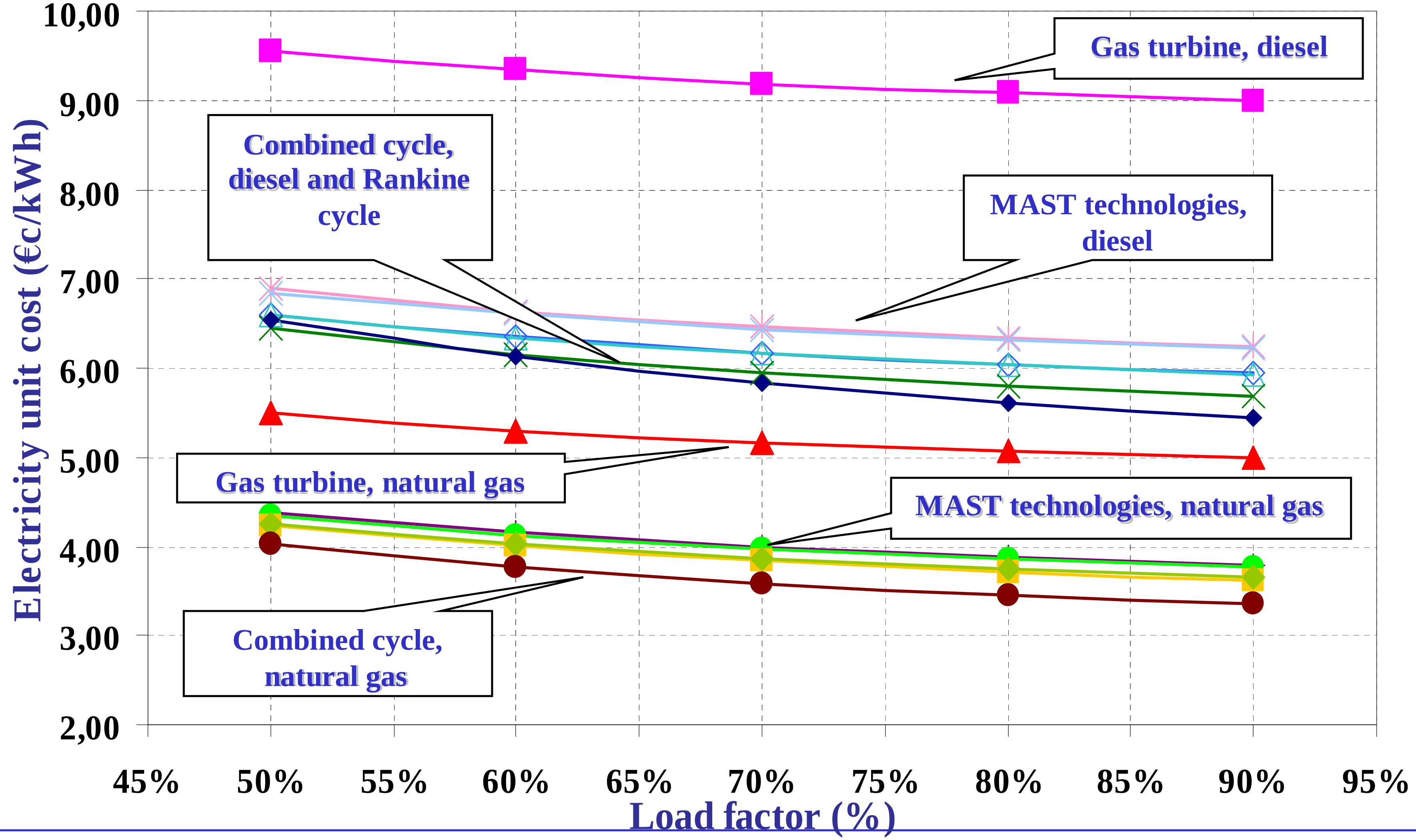
Cost - benefit analysis

Results for conventional technologies



Cost - benefit analysis

Comparisons: Conventional vs MAST



Conclusions

Integration of RO desalination plant or water recovery condenser into MAST technologies

Water recovery condenser slightly more cost effective than RO desalination plant

Least cost technology: Combined cycle technology with natural gas followed by the MAST technologies