How sustainable is cogeneration? A long-term, real-life evaluation

Giuseppe Dell'Olio, GSE, Italy

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All assessments are based solely on the author's personal opinions

Which technology is best suited to be employed in cogeneration?

- More than six hundred generating units were analysed:
  - *Gas turbines*
  - *Internal combustion engines*
  - *Steam turbines*

- "Real life" operation data were collected for years 2011 to 2019 (more than 12.000.000 equivalent operating hours).

Which technology is best suited to be employed in cogeneration?

- Efficiency indicators were calculated as weighted averages. Statistical correlation among indicators was investigated, i.a.

  - *Electric efficiency;*
  - *thermal efficiency;*
  - *overall efficiency;*
  - *Power to Heat Ratio (PTOH);*
  - *Equivalent Operation Hours (Heq);*
  - *Load Factor.*

Statistical correlation among indicators was investigated, i.a.

- *Correlation between equivalent operating hours and electric efficiency;*
- *Correlation between equivalent operating hours (Heq) and load factor (Fc);*
- *Correlation between electric efficiency and thermal efficiency.*
- *Correlation between electric efficiency and commissioning year*

Efficiency indicators (weighted averages)

- Electric efficiency: ratio of electricity produced by the CHP unit in a given year to energy (fuel) consumed to do so.

- Thermal efficiency: ratio of heat produced by the CHP unit in a given year to energy (fuel) consumed to do so.

- Overall efficiency: sum of the above efficiencies

Efficiency indicators (weighted averages)

- Power to Heat Ratio (PTOH): ratio of electricity to useful heat, produced by a CHP unit in a given year.
  - *A CHP unit with a high PTOH produces a larger amount of "valuable" energy (electricity) than a unit with a lower PTOH.*
  - *A high PTOH indicates that the heat carrier (e.g., steam) was exploited efficiently, as it produced a significant amount of electricity before being further used for thermal purposes.*

Efficiency indicators (weighted averages)

- **Equivalent operating hours (Heq): number of hours during which the generating unit would have been in operation, if it had constantly been kept at maximum load.**

- *Heq: when close to one, it suggests that the generating was operated with few starts and stops.*
- *In such a favourable operating mode, close to design conditions, the performance of the unit (the efficiency, in particular) is expected to be high.*

- *Conversely, a low Heq indicates that starts and stops have been numerous.*
  - *It is unlikely for a generating unit to be kept in constant operation during few months of the year, and to be constantly shut down during the remaining ones.*
  - *Frequent starts and stops are a more realistic scenario.*

Efficiency indicators (weighted averages)

- When Heq is low, no indications as to the duration of operating periods:

- the unit may have been operated:
  - few hours at full load, or
  - many hours at partial load (e.g., long starting time).

- Heq was divided by the actual yearly operating hours (Heff). This yielded the load factor (Fc), always less than one.

- *Load factor Fc : if close to one, the generating unit was kept close to full load.*
  - *Starts and stops took place rapidly:*
  - *heat dissipation was limited.*

Main results

(SMALLSCALE: 60 kW to 1 MW; MICRO: 5 kW to 45 kW)

Technology			Electric efficiency (p.u.)	Overall efficiency (p.u.)	Load factor (p.u.)	Equivalent hours (%)	PTOH
ORC			0,13	0,23	0,94	86,23	1,40
ORC	SMALLSCALE		0,17	0,71	0,73	58,53	0,30
Microturbine			0,30	0,82	0,45	34,19	0,59
Microturbine	SMALLSCALE		0,26	0,71	0,58	47,55	0,58
Microturbine	SMALLSCALE	MICRO	0,19	0,69	0,79	43,36	0,37
Internal Combustion Engine			0,41	0,70	0,89	66,59	1,40
Internal Combustion Engine	SMALLSCALE		0,36	0,72	0,86	63,82	1,00
Internal Combustion Engine	SMALLSCALE	MICRO	0,28	0,83	0,87	54,76	0,51
Gas turbine			0,32	0,82	0,84	71,27	0,64
Gas turbine	SMALLSCALE		0,29	0,73	0,74	62,47	0,67
Back-pressure steam turbine			0,17	0,89	0,83	76,75	0,23
Back-pressure steam turbine	SMALLSCALE		0,10	0,72	0,88	77,48	0,15

Green: excellent; yellow: average; red: poor

Statistical correlation among indicators was investigated, i.a.

Correlation:

If correlation=+1, direct proportionality

If correlation=-1, inverse proportionality

If correlation=0, no relation

Correlation can be anything between -1 and +1

Beta1:

Y=Beta0+XBeta1

Statistical correlation among indicators was investigated, i.a.

*Correlation between **electric efficiency** and **thermal efficiency***

Technology	Equivalent hours	Correlation	Beta1		
ORC	20.508,29	0,9464	16,4855	SMALLSCALE	
Back-pressure steam turbine	21.299,81	0,6396	2,6856		
ORC	22.664,59	0,2469	1,6724		
Gas turbine	33.203,15	0,6383	0,7043	SMALLSCALE	
Gas turbine	888.689,24	-0,2405	-0,9345		
Internal Combustion Engine	7.686.875,20	-0,3559	-1,0228		
Internal Combustion Engine	2.639.782,05	-0,4219	-1,1473	SMALLSCALE	
Back-pressure steam turbine	27.114,65	-0,5378	-1,2971	SMALLSCALE	
Internal Combustion Engine	504.311,93	-0,9398	-2,3422	SMALLSCALE	MICRO

Beta1 ↓

Micro ICEs: strong, inverse relationship;the amount of heat wasted is low (possibly influenced by method of assessment).

Statistical correlation among indicators was investigated, i.a.

Correlation between ***electric efficiency*** *and* ***commissioning year***

Technology	Equivalent hours	Correlation	Beta1		
Back-pressure steam turbine	27.114,65	0,7859	0,0834	SMALLSCALE	
Back-pressure steam turbine	21.299,81	0,9677	0,0631		
ORC	20.508,29	0,9421	0,0186	SMALLSCALE	
ORC	22.664,59	0,4217	0,0183		
Gas turbine	33.203,15	0,4104	0,0070	SMALLSCALE	
Internal Combustion Engine	7.686.875,20	0,1537	0,0013		
Gas turbine	888.689,24	0,1587	0,0010		
Internal Combustion Engine	2.639.782,05	0,0146	0,0002	SMALLSCALE	
Internal Combustion Engine	504.311,93	-0,6294	-0,0232	SMALLSCALE	MICRO

Beta1

Internal combustion engines, gas turbines: electric efficiency is NOT significantly dependent on the year of commissioning; both technologies have reached maturity

Statistical correlation among indicators was investigated, i.a.

Correlation between ***equivalent operating hours (Heq)*** *and* ***electric efficiency***

Technology	Equivalent hours	Correlation	Beta1		
Internal Combustion Engine	504.311,93	0,7074	0,0049	SMALLSCALE	MICRO
Back-pressure steam turbine	27.114,65	0,7125	0,0035	SMALLSCALE	
Gas turbine	33.203,15	0,8599	0,0026	SMALLSCALE	
Internal Combustion Engine	2.639.782,05	0,3024	0,0008	SMALLSCALE	
Gas turbine	888.689,24	0,3351	0,0006		
Internal Combustion Engine	7.686.875,20	0,2587	0,0005		
ORC	22.664,59	-0,1586	-0,0004		
ORC	20.508,29	-0,6075	-0,0005	SMALLSCALE	
Back-pressure steam turbine	21.299,81	-0,3472	-0,0018		

Beta1

Small scale steam turbines; small scale gas turbines: best suited for continuous operation.

Statistical correlation among indicators was investigated, i.a.

Correlation between ***equivalent operating hours (Heq)*** *and* ***load factor (Fc)***

Technology	Equivalent hours	Correlation	Beta1		
ORC	20.508,29	0,8932	136,8084	SMALLSCALE	
ORC	22.664,59	0,8975	120,6174		
Back-pressure steam turbine	27.114,65	0,9237	112,8444	SMALLSCALE	
Back-pressure steam turbine	21.299,81	0,9223	107,0478		
Gas turbine	888.689,24	0,4801	80,0619		
Internal Combustion Engine	2.639.782,05	0,5536	78,2973	SMALLSCALE	
Internal Combustion Engine	7.686.875,20	0,4270	74,7235		
Gas turbine	33.203,15	0,4690	74,4799	SMALLSCALE	
Internal Combustion Engine	504.311,93	0,0054	0,9696	SMALLSCALE	MICRO

Beta1 ↓

Steam turbines: long starting times; not suited for intermittent operation.

Main conclusions

- **Internal Combustion Engines (ICE):**
  - *Above 1 MW, very high Power to Heat Ratio (PTOH) and electric efficiency. However, both decrease with engine power. Only overall efficiency increases as capacity decreases.*
  - *Irrespective of engine power, load factor Fc is high, even if Heq is low. ICEs can be started and stopped rapidly: partial load operation is short.*
  - *Internal Combustion Engines seem to have reached technological maturity: electric efficiency is virtually independent of commissioning year.*

Main conclusions

- **Gas turbines:**
  - *Good (below 1 MW) or excellent (above 1 MW) overall efficiency, but a rather low electric one.*
  - *Above 1 MW, electric efficiency does not depend significantly on the equivalent operating hours (Heq).*
  - *Below 1 MW , positive correlation between electric efficiency and equivalent operating hours (Heq). : these turbines are best suited for continuous operation.*
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  - *PTOH: generally lower for gas turbines than for IECs (exception: ICEs below 50 kW).*
  - *Gas turbines seem to have reached technological maturity: electric efficiency is virtually independent of commissioning year.*

Main conclusions

- **Steam turbines:**
  - *low electric efficiency, PTOH and load factor. Only overall efficiency is good.*
  - *Tendency to suffer from load variations (at least for the small-scale ones): strong direct correlation between equivalent operating hours (Heq) and electric efficiency.*
  - *Strong direct correlation (affecting all steam turbines, irrespective of power) between load factor (Fc) and equivalent operating hours (Heq).*
  - *Poor aptitude to variable load - long times to reach full load after start up: not suited to intermittent operation (operational drawback).*

Thank you for your attention

giuseppe.dellolio@gse.it

gidellolio@gmail.com