Energy and exergy cost of thermal energy as a function of delivery temperature

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1. SYNOPSIS

Considering the value of thermal energy as a function of temperature is important in choices about operating temperature of heating systems, cogeneration and district heating.

2. SCOPE AND DEFINITIONS

Two bills passed by Italian Parliament in 1991 (laws 9 and 10) call, among other things, for increased activity in energy savings in the domestic and service sector and in cogeneration and district heating. In this context we can pose some questions:

- *might a tariff structure for thermal energy (T.E.) reflecting the energy quality associated with the* temperature level of delivered heat produce further energy savings beyond those already associated with cogeneration and heat pumps?

- do the usual figures of merit for cogeneration take into account the quality of energy?

We will say that a unit of T.E. has a "mechanical **cost** " of X Joules if to obtain 1 Joule of T.E. it is necessary to spend (or fail to deliver) X Joules of mechanical energy; similarly we define a thermal cost, a primary energy cost (PEC) and an exergy cost (ExC) . In contrast we will use the term "exergy **value** of T.E." to mean the maximum work transferable to a work reservoir when extracting a unit of thermal energy from a heat reservoir at temperature T in presence of an environment at temperature T_0.

The main goal of this paper is the evaluation of the "***exergy cost*** of delivered T.E.", defined as:
g(T) = (exergy spent or failed to deliver with best available technologies) / (T.E. delivered)
where T is the temperature at which energy is delivered.

Relying upon this function we define a new performance criteria for cogeneration systems:
WCU = $[W + g(T)*Q_u] / X_e$ (Weighted Coefficient of Utilization)

We propose a comparison with other indexes:

CU	= $(W+Q_u) / F_e$	Coefficient of Utilization of energy
II	= $[W + (1-T_0/T)*Q_u] / X_e$ = X_u / X_e	second law efficiency
CIP92	= $[W + 0,5667*Q_u] / F_e$	energy index in Italian legislation of June 1992

where:

W	=	mechanical work output (or electric output, depending on system boundaries)
Q_u	=	useful T.E. output
F_e	=	fuel energy expenditure.
X_e	=	exergy expenditure
X_u	=	useful exergy output

3. METHODOLOGY

We analyze different technologies:

(1) a standard module used by ENEL (National Electric Utility) in Italy: i.e. a 320 MW electric capacity Rankine cycle, with superheating and 7 regeneration stages; T.E. at useful temperature is obtained by deviating to a heat exchanger part of the steam from one of the 7 extraction points; this produces changes of flow in different parts of the plant and a loss of mechanical work which is evaluated and translated in primary and exergy costs;

(2) other Rankine cycles of lower size (4 to 130 MW) and complexity, directly designed for cogeneration;

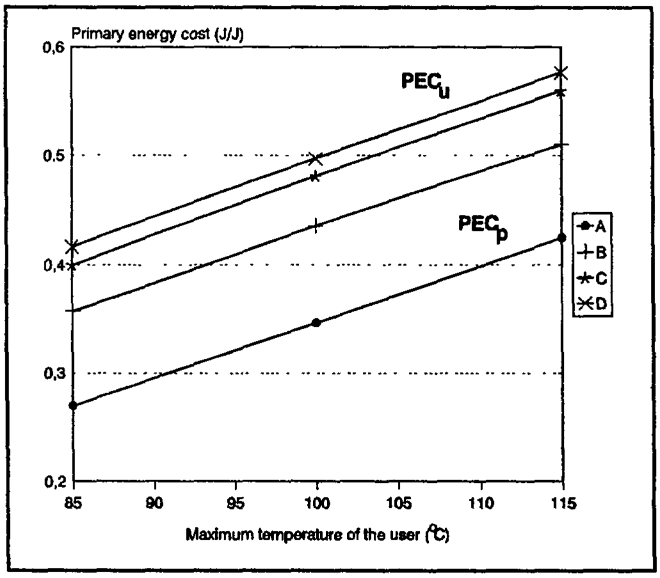

Figure 1. ***320 MWe Rankine cycle and feeder.***

(3) electric heat pumps delivering 1 to 8 MW of thermal power;

(4) "heat only" plants, where the mechanical or electric output of a cogeneration plant is used to operate a heat pump in order to increase the useful T.E. output.

Systems (2) (3) and (4) might be sited close to end users (i.e. a group of buildings, a district heating system or a factory), but generally the large Rankine cycle (1) will not. For this last system the Primary Energy Cost at the *u*ser level (PEC_u) will have to include a contribution due to the transmission of T.E from the plant to the user (accounting for thermal losses, pumping energy and energy requirement of materials).

4. RESULTS

Figure 1 presents a decomposition of PEC_u in its different components. Line A represents the energy cost of T.E if we could withdraw it from the plant at the same temperature the user needs it. (The figure shows decomposition of primary energy cost at the user level (PECu) in its components, when thermal energy is transported from the plant to a user at 20 km distance with a 2000 h/y utilization factor, 60 °C maximum temperature difference in circulating water, 100 MWt thermal power delivered.) In reality, we must withdraw it at higher temperature because we want to operate in finite time with finite heat exchangers and there is a small temperature drop along the feeder (generally less than 1 °C every 20 km), so the Primary Energy Cost at the level of the plant (PEC_p) is actually represented by line B. Adding energy costs due to heat losses (accounting generally only for 0,5-3 % of total cost) and pumping we obtain line C and finally line D takes into account also the energy requirement of mater-

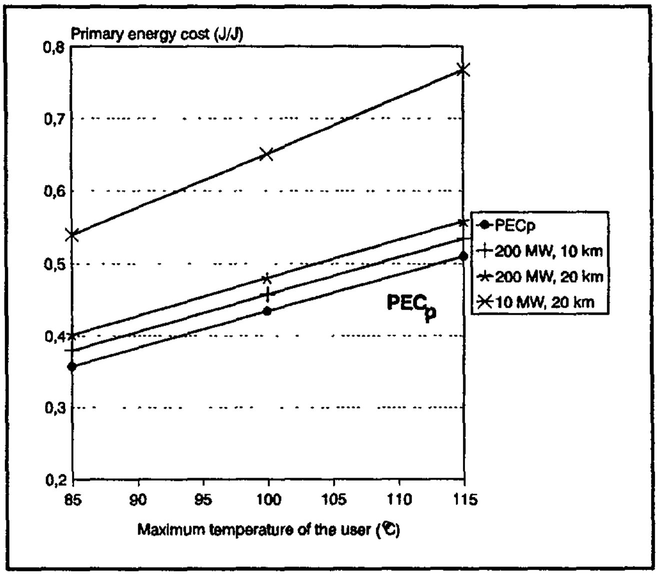

Figure 2. ***320 MWe Rankine cycle and feeder.***

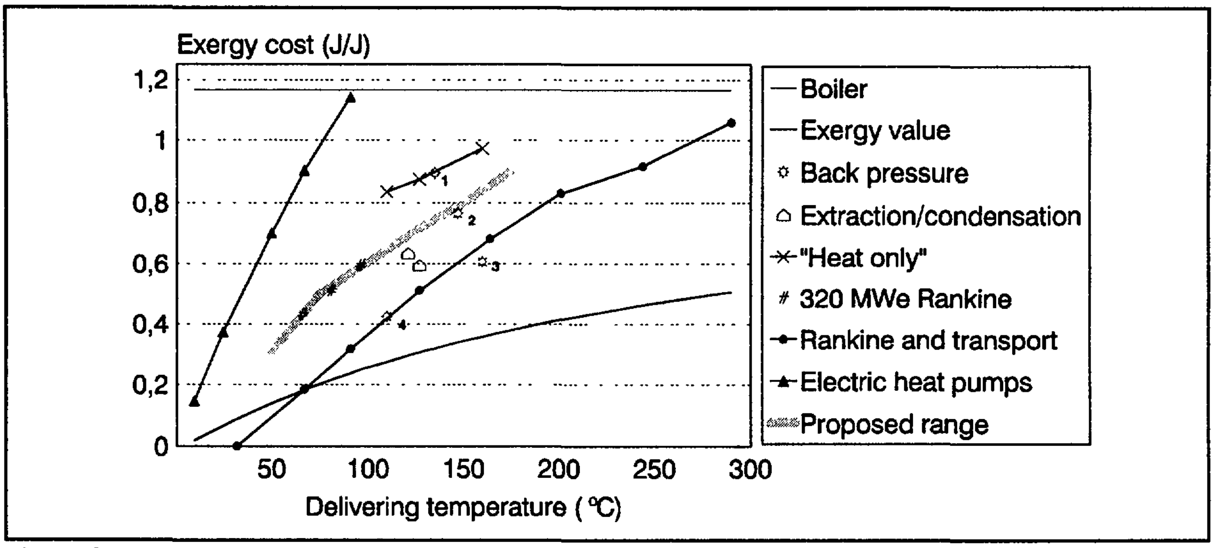

Figure 3. ***Exergy costs of delivered thermal energy for different technologies, compared with exergy value of thermal energy and proposed choice for the function*** $\gamma(T)$

ials. This last component is small but not negligible, typically 2 to 4 % of PEC_u. Examples of values of PEC_u in different situations are presented in Figure 2. (The figure shows Primary Energy Cost at the plant (PECp) and user level (PECu), when thermal energy is transported from the plant to a user with a 2000 h/y utilization factor, 60 °C maximum temperature difference in circulating water and different values of distance and thermal power delivered.)

For subsequent calculations we choose to transport T.E. to the maximum distance at which this is economically competitive with the production of thermal energy close to the user with an industrial boiler.

In Figure 3 we can read the exergy cost of T.E. as a function of the temperature at which it is delivered at the border of the various supply systems studied.

The lowest curve represents the exergy value of T.E. (i.e. $1 - T_0/T$) and is zero at the ambient temperature. The exergy cost of "production" (ExC_p) at the level of the 320 MW Rankine ENEL cycle vanishes at around 30 °C, which is the temperature of the condenser, because the extraction of heat at this level of temperature is a necessity and not a cost for the cycle; then the exergy cost associated with this system increases rather steeply with temperature, with a change in slope between 200 and 250 °C due to energy saving in the reheater.

When we consider transport costs to the limiting economic distance we obtain a curve which is a parallel translation to the left of the previous curve and can be extended in the same way at higher temperatures, where transport costs will show essentially the same structure.

Backpressure plants (1,2,3 and 4) are numbered in order of growing capacity. Their closeness to the curve representing the ENEL plant is correlated to their degree of complexity and thermodynamic quality, roughly described by the vaporizing temperature in the boiler, respectively 241, 294, 336, and 304 °C. Moreover cycle 3, with the highest temperature, has also three regenerative stages, while cycle 4 has two, and cycles 1 and 2 have none. Electric heat pumps are interesting only at low temperatures.
Owing to the fact that cogeneration plants and heat-only systems are represented in a relatively narrow band of the diagram we might advance a first proposal for the range of values of the function g(T): a band centered around the exergy cost of T.E. delivered by the system "320 MW Rankine + feeder", as described in Figure 3.

We use the function g(T) in our definition of weighted coefficient of utilization for cogeneration systems and in Table 1 we compare the values assumed by different criteria of performance.

Table 1. Comparison of performance criteria for cogeneration. η_{II} and WCU are calculated for different values of the temperature of delivered heat

Plant type	Outputs		Performance criteria					
	W/F_e	Q_u/F_e	CU	*CIP92*	η_{II} (50 °C)	η_{II} (125 °C)	*WCU (50 °C)*	*WCU (125 °C)*
extraction-condensation	0,38	0,10	0,48	***0,44***	0,38	0,39	***0,39***	***0,43***
backpressure	0,25	0,60	0,85	***0,59***	0,32	0,41	***0,42***	***0,66***
gas turbine	0,30	0,55	0,85	***0,61***	0,36	0,44	***0,45***	***0,67***
combined cycle	0,40	0,42	0,82	***0,64***	0,44	0,50	***0,51***	***0,68***

5. CONCLUSIONS

All generation systems considered allow consistent savings that increase rapidly when lowering temperature. The exergy cost of thermal energy delivered at 60 °C can be as low as 0,4 even after transport from an electric power plant to a remote district heating system, as compared to a cost of 1,17 when produced on site with a high efficiency industrial boiler.

A widespread use of low temperature heating systems is the "conditio sine qua non" to capture these potential savings. Low temperature heating systems can also be more suitable to a switch to renewables (e.g. central solar heating plants with seasonal storage, which run efficiently at low temperatures). Ways to achieve this goal might be: making mandatory the use of low temperature heating systems, economic incentives, or pricing T.E. cogenerated and distributed via D.H. proportionally to its exergy cost g(T).

Our WCU gives a different ranking of plants, going beyond the poor information content provided by the usual Coefficient of Utilization and attributing more importance to useful heat than second law efficiency does; in this way we account for the fact that in the real world we need to operate in finite time and within technological constraints. This kind of approach has been taken in recent Italian legislation (CIP 6/92), where cogeneration is admitted to different levels of incentives according to the value of the index CIP92, but still the weight attributed to T.E. is independent of temperature.