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FREE ELECTRICITY FROM 'HEAT-FIRST' CHP

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'If you want to reduce your costs, start by reducing your waste.' Sean Casten points the way to 'free' electricity from CHP by capitalizing on available steam pressure to generate extra power.

In every industry other than the electrical power industry, it is axiomatic that efforts to drive up processing efficiency have zero marginal operating cost. Whether a lumber mill is able to increase its board-feet per log by installing thinner saw blades, or a integrated chip manufacturer is able to increase its chip RAM per pound of silicon, all such investments are correctly assumed to 'make do with less'. In all cases, the facility is able to simultaneously increase its production of finished material and reduce its scrap rate without increasing raw material purchase.

Exactly the same logic can be applied to electricity. However, when such claims are made, they are all too frequently met with incredulous sneers from well-trained - but narrowly focused - thermodynamicists, who cry foul at an apparent violation of inviolable laws. This article will make the case that such free electricity is not only possible, but is also completely consistent with thermodynamic models - and is most cost-effectively targeted via combined heat and power (CHP). While the thermodynamic concepts here are not new, the impacts are staggering: electricity from low-cost conventional technology with no marginal costs and no marginal emissions.


150 kW back-pressure turbine generator installed at the district heating plant of the Franciscan Sisters of Perpetual Adoration in LaCrosse, Wisconsin, USA.

'HEAT-FIRST CHP' - A NEW WAY WITH OLD TECHNOLOGY

To understand how this is possible, it is worth first considering the marginal emissions associated with heat recovery in a conventional CHP plant. In these plants, a prime mover (gas turbine, engine, etc.) is used to generate electricity, and the waste heat thus produced is recovered and used for local thermal processes. In such instances, it is commonly understood that any heat thus recovered is 'free'. There is no marginal fuel purchase or combustion associated with the production and recovery of this heat, and it is treated as such. This obviously does not apply directly to gas turbines in which 'supplementary firing' is done to increase the quality of the exhaust heat. However, even in these circumstances - and as the language itself suggests - the marginal combustion is only assumed to be that associated with the supplemental fuel used, and not with the base heat provided by the turbine exhaust.

In fact, this heat is often considered to be better than free, since its recovery and utilization usually displaces a boiler or heater elsewhere, thus leading to a net reduction in emissions and heat-related expenses.

It is critical to recognize the guiding principle of this system design however: while the heat is recovered to improve overall economics, the primary objective of the CHP plant is obviously to produce electrical power. Once this power is generated, any heat that can be opportunistically recovered is free - but such a plant would never be built solely to produce heat. Since power is central to this architecture, it appropriate to label it as 'power-first CHP'. First make power, then recover the heat that is available.

However, the term 'combined heat and power' necessarily implies two forms of energy, without any implied preference for either. While power-first designs are quite common, there is also a host of installations that can be considered as an inversion of this logic, or 'heat-first CHP'. In these installations, the primary product is heat, and power is recovered from this heat stream only when it can be opportunistically extracted.

The most common type of heat-first CHP is in the form of back-pressure turbine generators, in which a turbine generator is placed in a steam distribution pipeline to take the place of a pressure reduction valve. High-pressure distribution steam is directed through a series of turbine blades before going on to serve low-pressure steam loads - and in the course of this pressure reduction, the turbine extracts high-value electricity from low-value steam. Other types of heat-first CHP include Stirling engines and condensing steam-turbines operating on process waste heat. In all cases, these heat-first architectures invert the logic and impact of their power-first cousins:

- the primary purpose of the design is to produce useful heat - using such systems solely to generate electricity makes no more economic sense than using a gas turbine and heat recovery steam generator (HRSG) solely to generate hot gas
- the net impact of the power recovery process is to reduce the cost of heat, by an amount that is directly dependent on the value of the displaced electricity
- the electricity recovered is - in most cases - free, with no marginal emissions impact or economic cost.

This latter point - while directly analogous to the cost of heat in power-first designs - is also the most contentious, and deserves a somewhat more thorough explanation.

FREE ELECTRICITY FROM BACK-PRESSURE STEAM TURBINE GENERATORS

In the case of Stirling engines or Rankine cycles operating on waste heat, it is fairly obvious that there is no marginal fuel combustion - after all, these units are simply using heat that would otherwise be rejected to the atmosphere. However, the argument is a bit subtler for back-pressure turbine generators.

In the conventional assessment of back-pressure turbine generators, they are compared to a pressure-reducing valve which would otherwise serve the same pressure reduction function. However, since the turbine generator is removing enthalpy from the steam (in the form of electricity), thermodynamics says that this enthalpy must no longer be present in the low-pressure steam. Most engineers stop their analysis at this point, concluding that since enthalpy has been removed, the turbine- generator must be charged an efficiency penalty in the process.

This analysis would lead one to the conclusion that the efficiency of back-pressure turbine generators is simply the cost of making up for this enthalpy reduction, or the efficiency of a steam boiler. While conservative, this still leads to a fuel-to-electrical efficiency of approximately 80%.

The primary product in these installations is heat. Power is recovered from this heat stream only when it can be opportunistically extracted.

However, such analyses fail to recognize the system-level impacts that result from this reduction in enthalpy. In the jargon of thermodynamics, a typical industrial- or district-steam plant is an 'open' system. Energy - in the form of heat losses - is constantly escaping from the boundaries of these facilities, and this simplistic assessment based on the first law of thermodynamics is valid only if one can show conclusively that the modest reduction in steam enthalpy has no net impact on the amount of heat that is rejected to the external environment. In practice, this simplifying assumption is almost always false. Consider:

- When supplied with saturated steam, pressure-reduction valves release low-pressure, superheated steam. By contrast, turbine generators usually release saturated (or slightly moist) steam, since they are removing enthalpy as electricity. However, saturated steam is typically three to ten times more effective as a heat transfer medium than superheated steam. With all else equal, this implies that post-turbine generator installation, operators find that they now need less heat exchanger surface area - and/or less input fuel energy - to meet the same thermal loads.
- Even without these considerations of superheat versus saturated steam, good engineering practice is to oversize heat exchangers to provide a safety margin during their operation. As a result, modest reductions in steam enthalpy at the inlet to the heat exchanger often do not compromise the ability of the heat exchanger to satisfy local thermal requirements at a given mass flow of steam. They simply lead to lower condensate temperatures at the heat exchanger exit.
- It is exceptionally rare to find a steam system with perfect (100%) condensate recovery. In fact, in many district energy systems, common practice is to have zero condensate recovery, due to the high capital costs required to install return pipes. In such cases, the reduced condensate temperature from over-designed heat exchangers post-turbine generator installation leads simply to a reduction in the amount of heat that is thrown away.
- Even when condensate is recovered, condensate return pipes are often poorly insulated - if they are insulated at all. Since the radiative heat losses experienced in the condensate pipe is a function of the temperature difference between the pipe and the ambient air raised to the fourth power, modest reductions in condensate temperature at a heat exchanger rarely lead to reductions in condensate temperature at the boiler inlet (which is the only place where such reductions would ever be noticed, energetically).
- Finally, even if - after all of the above factors are taken into account - one still finds that a back-pressure turbine generator will lead to an increased boiler duty, one must take into account that the marginal efficiencies of steam boilers are much higher than the average efficiencies. This results from the fact that while it takes a large amount of energy to start a boiler (heating up steel walls, combustion air, etc.), it requires a much smaller amount of energy to slightly increase the duty on an already-operating boiler.

Once all of these factors are taken into account, it is commonly found that there is little or no marginal increase in fuel combustion after the installation of a back-pressure turbine generator.

IMPLICATIONS

The economic and environmental implications of this calculus are truly staggering. Opportunities abound for back-pressure turbine generators in virtually every steam network, from industrial facilities to hospitals to college campuses. Furthermore, the application of this technology has been well established for over 100 years - there is no technology development required to capitalize on these opportunities. (Indeed, it is not uncommon to find 40-50 year old back-pressure turbine generators still in operation in many industrial facilities.) The installation and operation of these systems will thus lead to emissions reductions and marginal fuel costs that are on a par with renewable electricity and capital costs that are on a par with - and often lower than - reciprocating engines. This unique combination of high efficiency and low capital cost is illustrated in Figure 1.

This system installed at a college in Maine takes 300 psig (21 bar) steam from the campus steam boiler and exhausts 40 psig (3 bar) steam for campus heating loads, extracting 600 kW of 'free' electricity along the way.

There is often little or no marginal increase in fuel combustion after the installation of a back-pressure turbine generator

In other words, the technology only proves what the manufacturing sector has known for years: if you want to reduce your costs, start by reducing your waste.

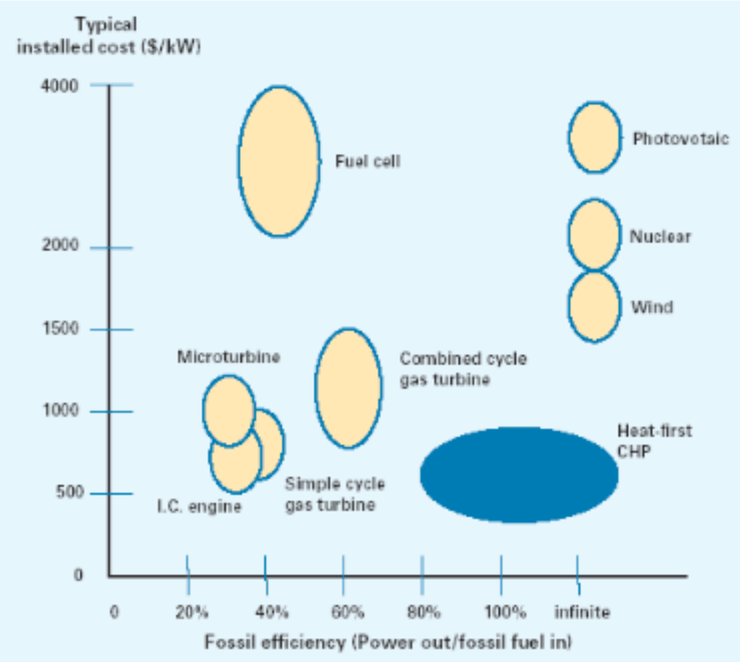

FIGURE 1. Fossil efficiency and capital cost for distributed generation (<5 MW) technologies

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