Saving Energy in Multilevel Steam Systems

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Avoid some common pitfalls by taking this holistic approach when implementing projects to reduce the consumption of steam.

Steam is one of the most common and most important utilities used in the chemical process industries (CPI). It is used for a variety of tasks, the most significant of which is process heating. Because of its high heat-transfer coefficient, steam is often used instead of hot oil for process heating, allowing for the use of smaller heat-exchange equipment, among other advantages. Steam is also used for drying and concentrating chemicals, reforming and cracking petroleum, and driving equipment such as pumps and compressors using steam turbines.

Steam does have disadvantages, however, including high capital and operating costs. While the capital investment for boilers and high-pressure piping, as well as the required feedwater conditioning, demineralization, and deaerating systems, is relatively fixed, with few opportunities for cost reduction, operating costs can often be lowered through steam-saving projects. Such projects have become increasingly popular as energy costs continue to rise.

This article identifies some common pitfalls of steam-saving projects and discusses how to avoid them. It also describes the types of steam turbines commonly used in the CPI and offers guidance on selecting the appropriate turbine for a particular application.

Multilevel steam for various process requirements

Large chemical processing plants typically run a single (or several, for reasons discussed later) boiler(s) to produce steam at the highest pressure level required, which is then distributed at various pressures to different processes within the plant (Table 1). This approach requires a lower capital investment than several dedicated boilers, one for each pressure level.

Such multilevel steam systems are found in crude oil refineries, where three levels of steam pressure are common — high pressure (HP) at 40–42 barg, medium pressure (MP) at 9–10 barg, and low pressure (LP) at 3–4 barg — and in olefins plants, which use as many as six levels of steam pressure — super-high pressure (SHP) at 125 barg, HP at 42 barg, MP at 19 barg and at 13 barg, and LP at 4 barg and at 2 barg. Large chemical plants and refineries generally have more than one boiler, with one kept on standby in case another boiler is shut down because of a malfunction or for inspection or maintenance. Multiple boilers are also used to meet capacity requirements that exceed the maximum capacity of a single boiler.

The heart of a multilevel steam system is the boiler, where heat released during the combustion of

Table 1. Steam is typically produced at the highest pressure needed within a plant, and then its pressure is reduced as needed to satisfy the requirements of various process units.

	Pressure, barg	Process Temperature (for heating by steam)	Other Uses
Super-High Pressure (SHP)	120–130	280–320°C (536–608°F)	Large steam turbine drivers
High Pressure (HP)	40–42	210–240°C (410–464°F)	Small-to-medium steam turbine drivers
Medium Pressure (MP)	9–20	140–200°C (284–392°F)	Steam jet ejectors
Low Pressure (LP)	2–4	90–140°C (194–284°F)	Steam stripping Equipment purging

fuel is transferred to water to produce high-pressure steam. The steam then travels to a distribution system, where its pressure is reduced (let down) to meet the requirements of individual process units. Steam pressure can be reduced in two ways: efficiently through turbines, and inefficiently through pressure-reducing valves (often called letdown valves).

Before entering a turbine, the steam is typically superheated to a temperature slightly above the boiling point of the corresponding saturated water. Superheated steam is generally used to drive turbines because it is dryer than saturated steam and thus does not erode turbine blades, and it is more efficient for extracting work than saturated steam. Superheated steam also ensures that the steam remains a single-phase vapor (minimum condensation) during distribution and before entering the pressure-reducing valve, which prevents valve seat erosion and flow control problems related to mixed-phase flow. Steam gets drier (more superheated) when its pressure is reduced across the pressure-reducing valve despite a temperature drop.

Saturated steam is preferred for process heating because of its ability to quickly give up latent heat and its high condensing heat-transfer coefficient. Thus, it is common to install desuperheaters at the turbine exhaust or at the valve outlet to reduce the steam temperature to match that of the outlet steam pressure level. Desuperheaters inject a fine mist of water into the steam flow; the superheated vapor gives up heat to the water mist, which causes its temperature to drop.

Common pitfalls in steam-saving projects

Many steam-saving projects focus on improving the efficiency of individual equipment or components in a steam system, without consideration of the multilevel steam system as a whole — *i.e.*, the plant's fuel and steam balances. Disregarding plantwide steam and fuel balances is one of the most common mistakes engineers make when evaluating energy-saving projects for multilevel steam systems.

Neglecting the overall fuel balance. The real objective of a steam-saving project is not to reduce the consumption of steam itself, but instead to reduce the amount of fuel required to produce the steam. In many large process plants, fuel is produced internally. For example, in petroleum refineries, fuel oil is typically obtained from fluid catalytic cracking (FCC) unit bottoms, and fuel gas is obtained from the light ends overhead of an atmospheric distillation column. In olefins plants, fuel gas used in cracking furnaces and boilers comes from the ethylene production process, where it is a byproduct found in the demethanizer column overhead and the hydrogen pressure-swing adsorption off-gas.

A plant-wide fuel balance determines the amount of fuel produced and the amount of fuel required for each process unit. If the amount produced is less than the amount required, fuel must be purchased from outside of the plant. However, if fuel production exceeds fuel use, the surplus needs to be flared or, preferably, sold to another plant. If fuel gas is already being flared, a steam-saving project will result in more flaring of surplus fuel. In short, it would be meaningless to save steam if there is no good use for the excess fuel.

Common Sources of Excessive Steam Consumption

The consumption of steam (and the fuel used to produce it) in a poorly designed and inefficiently operated steam system can easily be double that of a well-designed and efficiently operated one. Several common reasons for this include:

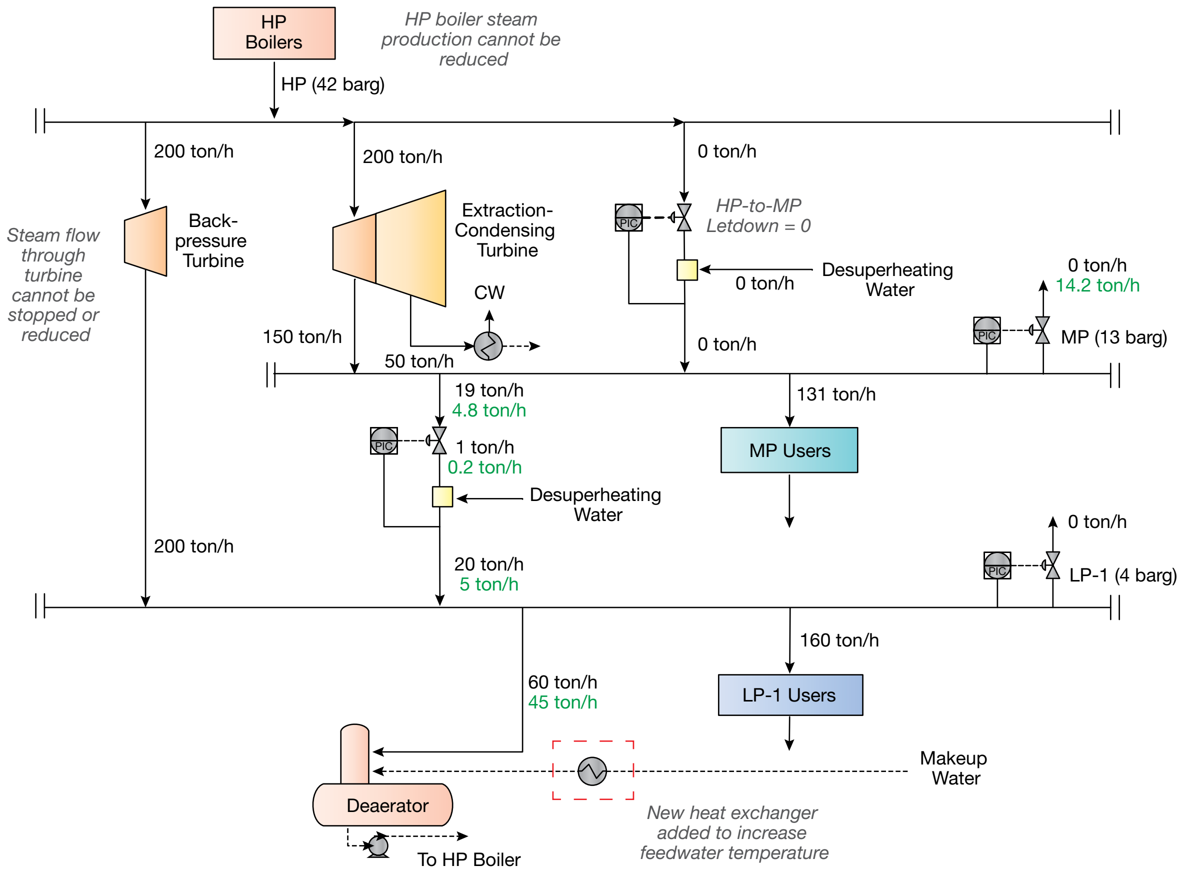
- inefficient boiler design and operation (*e.g.*, no economizer, excessive blowdown rate)
- steam and hot condensate losses due to poor operation and inadequate maintenance
- lack of hot condensate return recovery (which requires large volumes of ambient-temperature, demineralized make-up water, which in turn has additional treatment costs for demineralizing the water and energy costs for raising its temperature to the boiler feedwater temperature)
- lack of flash steam generation using high-pressure condensate
- malfunctioning or unsuitable steam traps
- poor or inadequate thermal insulation
- process-side heat exchanger fouling
- improperly designed or operated steam turbines.

Neglecting the overall steam balance. Just as neglecting the overall fuel balance can lead to problems, so can disregard for the overall steam balance. What seems to be an attractive energy-saving project may turn out to be much less attractive when the overall steam balance of the plant is considered.

Figure 1 is an example of a project that fails to save boiler fuel. In this example, an engineer determined that installing a heat exchanger to preheat demineralized water entering a deaerator by waste process heat would reduce the deaerator's low-pressure steam consumption by 15 ton/h (33,069 lb/h), which would reduce the consumption of fuel gas by 0.9 ton/h (1,993 lb/h). The total savings ($/h) is calculated as:

$$\text{Fuel Gas Savings} = \frac{(H_s - H_w) \times \Delta F_s}{E_b} \times \frac{1}{LHV} \times P \qquad (1)$$

where H_s = enthalpy of steam = 1,227 Btu/lb; H_w = enthalpy of water = 72 Btu/lb; ΔF_s = decrease in LP steam flow = 15 ton/h; E_b = boiler efficiency = 0.9; LHV = lower heating value of the fuel gas = 21,600 Btu/lb; and P = price of fuel gas. At a fuel gas price of $400/ton, the savings should be $3.1 million/yr.



▲ **Figure 1.** A steam-saving project was considered without taking into account the overall steam balance (black quantities). As a result, adding a heat exchanger to the feedwater by waste process heat before it enters the deaerator decreases LP-1 steam by 15 ton/h (green quantities). This does not reduce the overall HP steam needed to run the turbines, so MP steam must be exhausted.

Unfortunately, the project did not result in a fuel savings of $3.1 million/yr because the overall steam balance, in particular the steam required to run the turbines, was not considered. Steam turbines (not pressure-reducing valves) were used to let down HP steam — a backpressure turbine for low-pressure steam and an extraction-condensing turbine for medium-pressure steam. These turbines require the same amount of HP steam to operate, so the boiler must still generate the same amount of HP steam to run the turbine drivers, which (as explained later) cannot be shut down because of plant reliability concerns.

Overestimating steam consumption during plant design. When a new plant is being designed, the engineer responsible for the steam system needs to know the steam consumption rate and the pressure level at which the steam will be used in each process unit. He or she uses heat and material balances to calculate these values, and then adds appropriate safety margins.

According to the exergy concept in the second law of thermodynamics, a multilevel steam system should be designed to minimize steam letdown flowrates through pressure-reducing valves (preferably close to zero) and maximize steam letdown flowrates through turbines, as much as turbine output power requirements allow. In operation, however, a certain level of steam flow through pressure-reducing valves is inevitable, because actual steam consumption will deviate from the design steam balance.

A common mistake made by process engineers is inflating the steam consumption with excessive safety margins, assuming that the steam production of an oversized boiler can be reduced if the actual steam requirement turns out to be significantly lower than that of the design. The problem with this assumption is that a boiler's efficiency drops when it is operated at high turndown.

Overestimating steam consumption can also lead to inefficiencies. Consider a scenario where the amount of LP steam needed has been overestimated. When a large quantity of LP steam is required, backpressure turbines are commonly used to exhaust LP steam instead of using a pressure-reducing valve to let down MP steam. If the actual

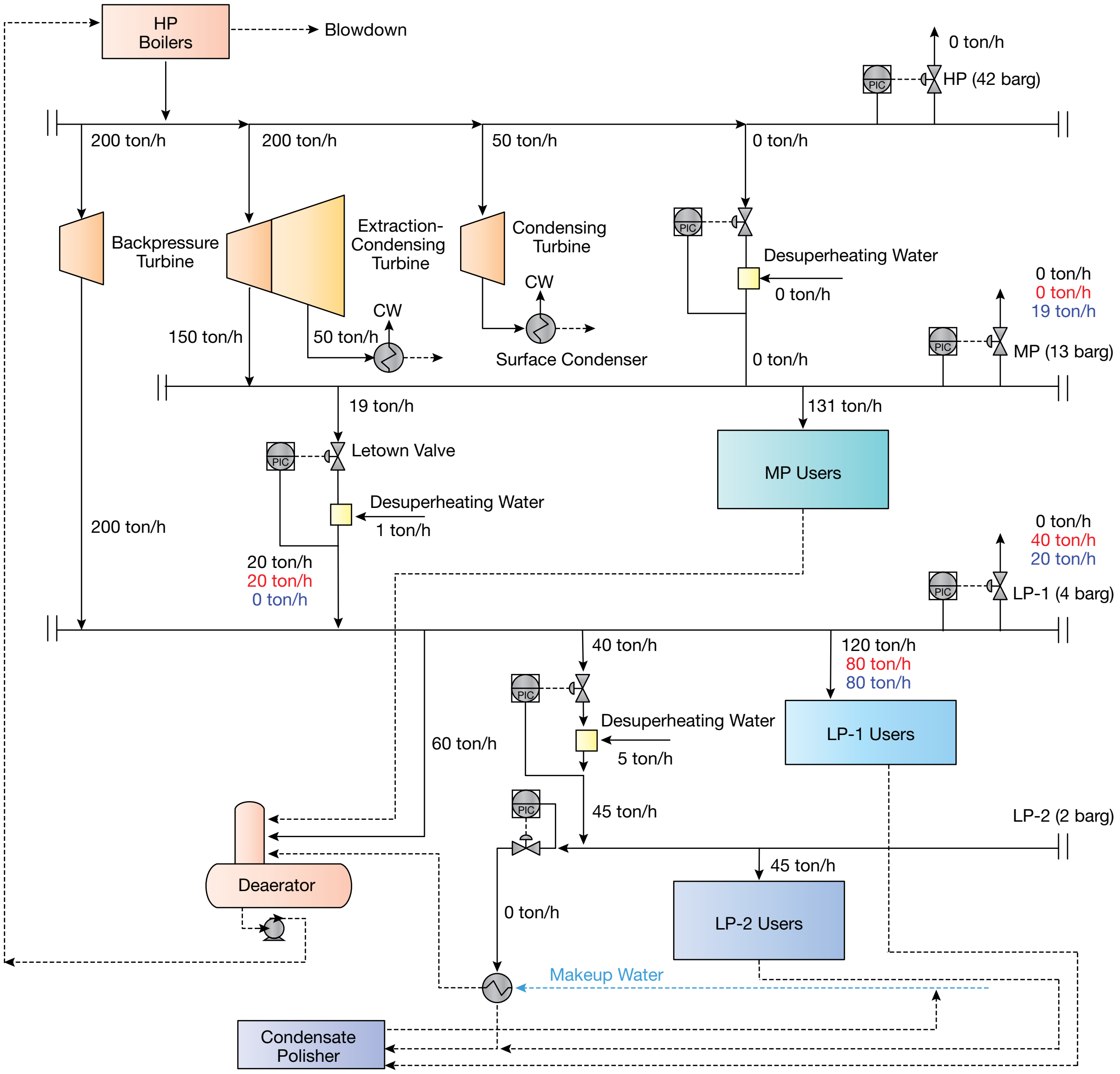
LP steam requirement is lower than the quantity exhausted from the backpressure turbine, the surplus LP steam will need to be either wastefully vented or condensed and recycled to produce more steam.

Figure 2 illustrates how excessively overestimating steam consumption can result in a steam imbalance. The design engineer grossly overestimated LP-1 steam consumption to be 120 ton/h, which is 50% more than the actual consumption of 80 ton/h. The steam system was thus designed (Figure 2, black quantities) with a backpressure turbine to generate 120 ton/h of LP-1 steam. Consequently, in operation (Figure 2, red quantities), 40 ton/h of excess LP-1 steam needed to be vented. If the 20-ton/h flow through the valve that reduces the pressure of MP steam is stopped, the amount of excess LP-1 steam needing to be vented drops from 40 ton/h to 20 ton/h at the expense of additional MP venting of 19 ton/h (Figure 2, blue quantities).

Steam turbine selection

Three types of steam turbines are widely used in the chemical process industries:

- backpressure turbines
- extraction-condensing turbines
- condensing turbines.



▲ **Figure 2.** The required amount of LP-1 steam in this design has been severely overestimated, which resulted in the use of a larger-than-needed backpressure turbine. To make up for the imbalance, 40 ton/h of excess LP-1 steam could be vented (red quantities), or the flow of MP steam through the pressure-reducing valve upstream of LP-1 could be stopped (blue quantities).

Table 2. The total useful energy of each turbine is the sum of its mechanical work and thermal heating duty.

Turbine Type	Inlet Steam	Exhaust Steam	Energy Use Breakdown: Useful Mechanical Work	Energy Use Breakdown: Useful Heating by Latent Heat	Energy Use Breakdown: Wasted Heat Lost to Cooling Water	Energy Use Breakdown: Unutilized Energy Gap	Total Useful Energy
Backpressure	HP	LP	10%	70%	0%	20%	80%
Extraction-Condensing							
Extraction Section	HP	MP	5%	69%	0%	26%	74%
Condensing Section	MP	Vacuum Mixed-Phase	22%	0%	72%	6%	22%
Condensing	HP	Vacuum Mixed-Phase	26%	0%	68%	6%	26%

Table 3. These conditions were used to calculate the efficiency of the turbines described in Table 2.

Type of Steam	Temperature	Pressure, barg	Steam Enthalpy, Btu/lb
HP Steam	720°F	42	1,362
MP Steam	540°F	13	1,290
LP Steam	390°F	4	1,227
Vacuum Surface Condenser (mixed-phase, 10% liquid)	115°F	–0.9	1,009
MP Condensate	380°F	13	354
LP Condensate	305°F	4	275
Vacuum Surface Condenser (water)	115°F	–0.9	82
Standard Condition Water	32°F	0	0

Table 2 gives an example of turbine inlet (HP steam) and outlet (MP and LP steam, and vacuum mixed-phase) conditions. The larger the difference between turbine inlet and outlet enthalpies, the more mechanical work extracted from a turbine.

Backpressure turbines exhaust LP steam. Thus, they are advantageous when the LP steam requirement is large enough to match the turbine output power specification. Backpressure turbines are the most energy efficient turbines because their exhaust can be directly utilized in the process, whereas exhaust from extraction-condensing and condensing turbines is wasted as heat to the cooling water (CW) system through surface condensers. This wasted heat is a major cause of the lower energy-utilization efficiency (lower total useful energy) of extraction-condensing and condensing turbines.

For processes with a large MP steam requirement that matches the turbine output power specification, an extraction-condensing turbine is a good choice. Part of the inlet HP steam can be extracted as MP steam (in the extraction section) for process use while the remaining HP steam is expanded into a vacuum surface condenser (condensing section) to meet the turbine output power specification. Extraction-condensing turbines are more energy efficient than condensing turbines because the extracted MP steam can be utilized in the process. In contrast, the inlet HP steam to a condensing turbine is expanded directly into a vacuum surface condenser, thereby wasting a large part (65–70%) of its thermal energy through the surface condenser without providing any useful heating.

Table 2 provides a breakdown of the total useful energy — mechanical work and thermal heating duty — for each type of steam turbine. As noted earlier, the backpressure turbine is the most energy efficient (80% in this case, based on the data in Table 3), followed by the extraction-condensing turbine (22–74%, depending on the required amount of MP steam), and then the condensing turbine (26%). For extraction-condensing turbines, the more MP steam sent to the condensing section, the more mechanical work extracted from the turbine (due to the exhaust's vacuum condition) but the lower the total useful energy because more heat is wasted to cooling water.

Steam turbine and electric motor drivers

Many process engineers do not realize that, because of soaring crude oil prices and increasing fuel-gas prices, the cost of steam is rising faster than the cost of electricity. Today, the operating cost of an electric motor driver can be 30–40% less than that of its steam counterpart.

One might therefore conclude that maximizing the number of electric motor drivers will minimize costs. While logical from a cost perspective, increasing the number of electric motors also compromises reliability. One way to compensate for the reduced reliability is to have a backup, such as a diesel generator for an auto-start pump driver or hot steam for steam turbines.

Even with high steam costs, some plants will continue to use steam-turbine drivers because of their superior reliability in the event of a power failure. A large plant will generally operate critical-service pumps, such as plant air compressors, with both electric-motor and steam-turbine drivers. Some air compressors, for instance, must be driven by steam turbines to ensure that instruments receive a certain level of air and that control-valve actuators will still operate during a power failure. Olefins plants often combine steam and electric drivers to operate the pumps that circulate cooling water from cooling tower basins. This system requires a certain number of pumps to be steam-driven, the minimum number of which is determined by the minimum cooling water flowrate required to protect major equipment and maintain sufficient heat removal from equipment such as distillation tower condensers.

Steam saving in a nutshell

The secret to saving steam in a multilevel steam system is to focus on reducing the boiler load, rather than reducing steam consumption by any individual process or piece of equipment. The real benefit of reducing steam use by one process will always trace back to the impact of the reduction on the boiler.

Thus, a first priority should be reducing steam consumption at the highest pressure level, which is typically at the boiler. When considering reductions in MP and LP steam, it is necessary to analyze the actual steam balance and the actual status of steam letdown from turbines and pressure-reducing valves to avoid wasteful steam venting at an intermediate pressure level when MP or LP steam is saved. **CEP**

FURTHER READING

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