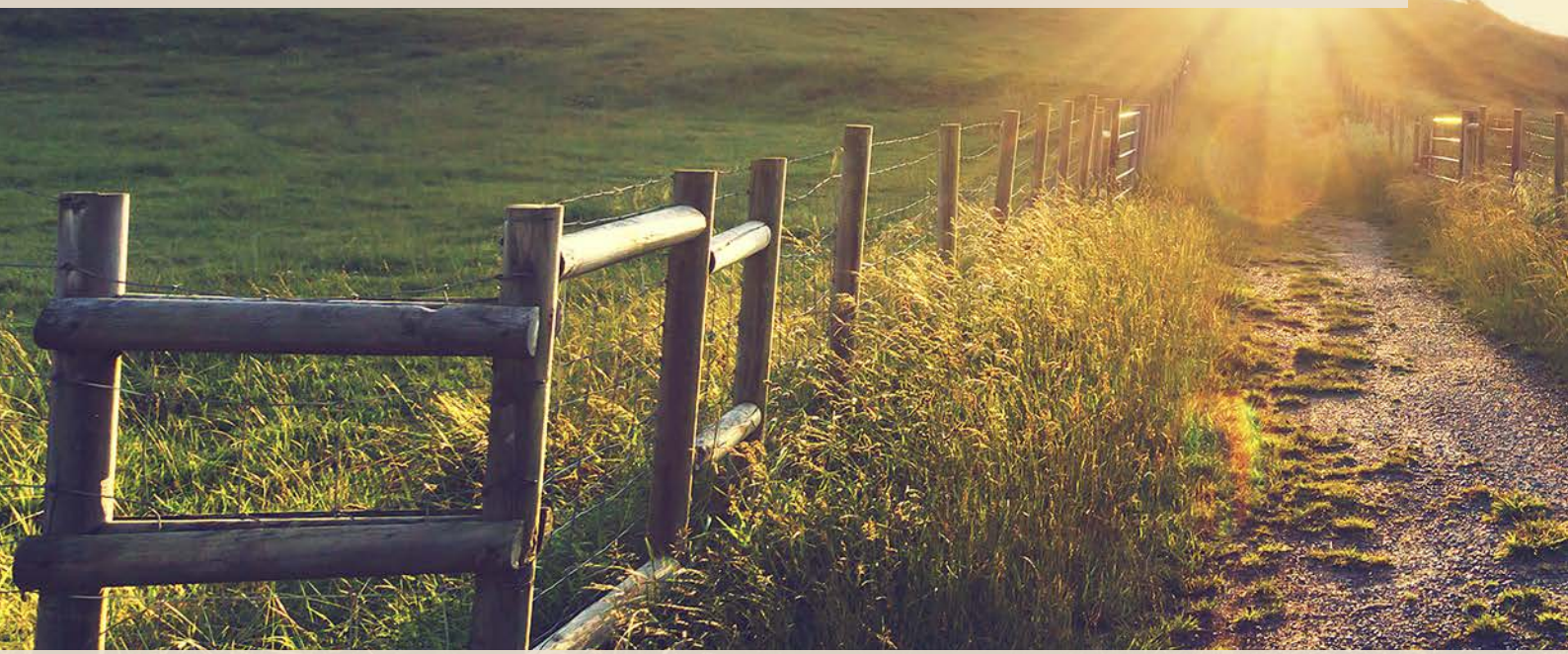
OPENING PATHWAYS TO DECARBONISATION



Heat generation makes up approximately two-thirds of industrial energy consumption and is a major contributor to direct CO_2 emissions from process industry.[1] Today, most of the heat produced in process facilities occurs through the combustion of fossil fuels (i.e. in gas or oil-fired boilers). Often, this heat is then converted into low, medium or high-pressure steam.

Decarbonising industrial heat and steam production will play a key role in achieving established climate targets and driving a successful energy transition. Significant opportunities exist to reduce industry reliance on fossil-fuel-based heat through waste heat recovery. By some estimates, as much as 50% of the energy consumed in industrial processes ends up as waste heat.[2]

High-temperature heat pumps (HTHPs), in combination with steam compression and mechanical vapour recompression (MVR) cycles, both represent sustainable methods of generating useable steam from waste heat. This is because they solely require electricity for input energy. These technologies can achieve the steam temperatures and pressures required by many processes across the downstream oil and gas, chemicals, and pulp and paper industries, opening new pathways for decarbonisation.

Combining HTHPs with steam compression

Heat pumps are a highly efficient technology for recovering waste heat and have been in use since the mid-19th century. They have gained significant traction in recent years as pressure to reduce emissions has increased.

The primary advantage of heat pumps is that the only required energy input is electricity, meaning that heat generation can be emissions-free if the power comes from a green source. Whilst electric boilers and heaters offer this same advantage, heat pumps can be up to 5 times more efficient because most of their energy requirement is provided by the waste heat.

Heat pumps are typically classified as either low-temperature or high-temperature. Most of the installed base of heat pumps today are the former, and are designed for

Lukas Biyikli, Siemens Energy, Germany, considers how it is possible to decarbonise industrial process heat through steam compression.



temperatures up to 100°C. They are commonly found in district heating applications. On the other hand, HTHPs are becoming more prevalent for steam generation in industrial facilities.

Depending on the refrigerant used, simple HTHP cycles, without steam compression, are usually limited to ~150°C in their maximum outlet temperature, and therefore a maximum steam pressure of 5 bara. The higher the temperature that the refrigerant reaches, the more the width of the two-phase region is reduced. This is due to the temperature approaching the critical point. As a result, there is less latent heat recoverable and useable in the condenser, reducing the coefficient of performance (COP) and benefit of the heat pump system. This is why the system should be designed with sufficient distance to the critical temperature of the refrigerant.

Furthermore, synthetic refrigerants lose stability when operated continuously at temperatures between 150 - 200°C. As requirements for process steam often lie above 150°C and 5 bara, in many cases a steam compressor will be required downstream of the heat pump system.

Steam compression technology

In the past, steam compression applications required relatively small pressure ratios, which could be handled by single-stage compressors/blowers. However, many of today's industrial heat applications require multi-stage compression.

The technology that Siemens Energy applies for steam compression is integrally geared compressors (IGCs) (Figure 1). Although some operators view IGCs as a novel technology, these machines have accumulated millions of hours of uninterrupted service in a broad range of industrial applications. Siemens Energy developed the first IGC in 1948 (formally named the VK).

IGCs are centrifugal compressors with a bull gear that can drive as many as four pinion shafts (with one or two impellers each). This allows each impeller to turn with its optimal velocity and frequency for maximum efficiency. Furthermore, each impeller sits in its own volute casing, which allows the process gas to exit the machine between the compression stages. Doing so enables intercooling after each stage, which is important for

minimising power consumption. It is also critical for preventing temperatures from exceeding the maximum allowable limits of the compressor, which may necessitate the use of more expensive materials.

Siemens Energy manufactures IGCs that can handle up to 1.2 million m^3/h in one compression stage, with impeller diameters up to 2 m. Flow rates as high as 2.4 million m^3/h are achievable in a double-floating design, where the volume flow at the inlet of the compressor is distributed to two parallel stages/impellers.

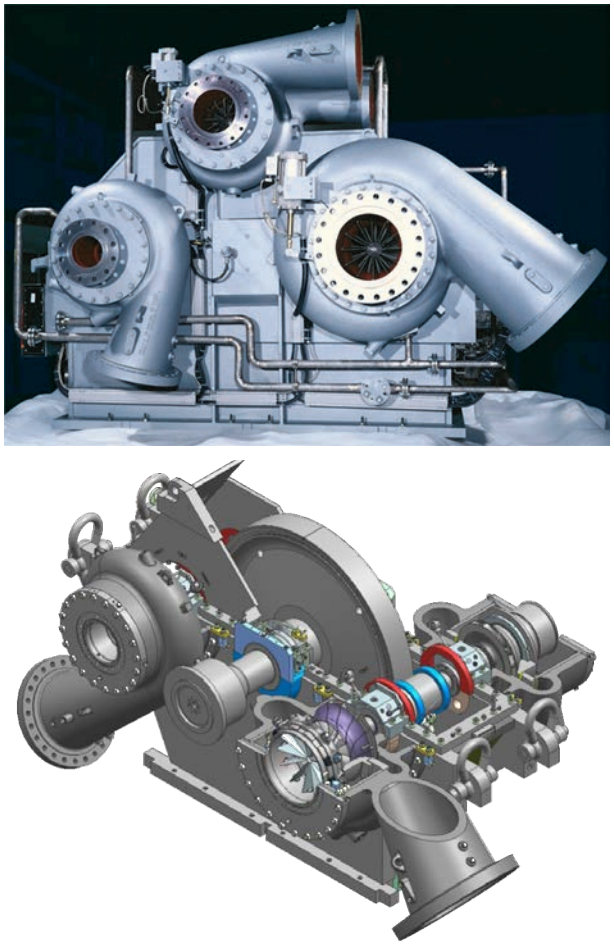


Figure 1. An integrally geared compressor (IGC) with independent volute casings.

Because each impeller sits in its own casing, each compression stage is independent, enabling the application of combined refrigerant/steam compressors (when the steam compressor is applied downstream of a heat pump).

In a combined configuration, two different process gases – in this case the refrigerant for the heat pump and the steam – are compressed within the same machine, as shown in Figure 2. Any number of refrigerant and steam stage counts are possible. For example, four stages/impellers can be used for the refrigerant and four stages for the steam, as long as a total of eight stages is not exceeded. This reduces the number of compressor trains required for such an application from two to one, which saves approximately 20 - 30% on CAPEX for the compression equipment.

The cooling in a steam compressor is not done by typical water or fin/fan coolers but instead by water injection into the process gas piping between the stages. The injected water is then evaporated by taking heat from the steam, as shown in Figure 3.

Due to the high latent heat requirement for water evaporation, the steam is cooled significantly and 100% of the compression heat, which is typically a byproduct, is utilised for additional steam production. The desired cooling temperature can be controlled by the amount of water injected (i.e. the more water that is injected, the more cooling is achieved).

By using HTHPs with subsequent steam compression, temperatures up to 300°C and pressures up to 60 bara are achievable. Even higher temperatures are possible through the installation of a small electric superheater downstream of the steam compressor. As previously stated, these levels are well within the range of what is required by many processes across the oil and gas, chemical, and pulp and paper industries, which have traditionally relied on fossil fuel burning for heat/steam production.

Mechanical vapour recompression (MVR) cycle

MVR cycles provide an alternative to classical heat pumps for recovering waste heat in order to produce low, medium or high-pressure steam.

With MVR cycles, thermal energy from a mid or low-temperature waste stream is used to directly evaporate feedwater. The steam is then compressed to the required temperature and pressure level of the process. The entire latent heat for evaporation is provided by the free-of-charge waste heat, and only the sensible heat, which is

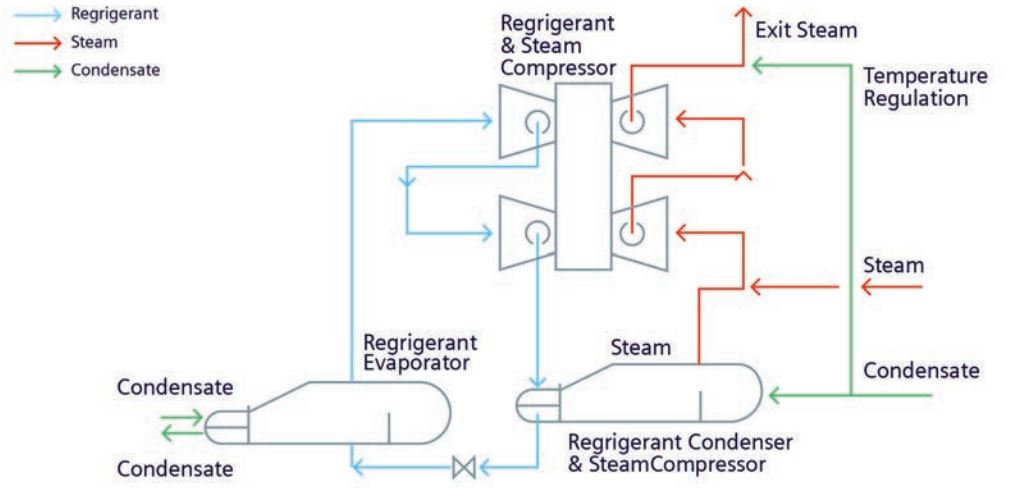


Figure 2. Combined refrigerant/steam compressor.

significantly lower than the latent/evaporation heat, is provided in the form of compression.

In nearly all cases, the waste heat source has a temperature below 100°C, which means that the water needs to be evaporated at sub-atmospheric pressure. While this requires additional considerations when it comes to equipment design (e.g. around the sealing system so that no ambient air is sucked in), these challenges can be solved with Siemens Energy's existing technology.

Compared to heat pumps, the MVR cycle does not require refrigerant. This is beneficial, as per- and polyfluoroalkyl substances (PFAS) restrictions are being considered in the EU for synthetic refrigerants. Natural refrigerants, on the other hand, are often toxic (e.g. NH_3) or hydrocarbons (e.g. pentane), which require additional considerations, including explosion protection. In many cases, CAPEX and footprint can also be reduced relative to heat pumps by eliminating the need for an expansion valve, the flash tank, the refrigerant condenser, and some ancillary piping.

Figure 4 shows an MVR cycle example where 68 thermal megawatt (MWth) of waste heat at 75°C can be utilised to produce 100 MWth of steam at 6 bar and 180°C. The resulting system has a COP > 3.

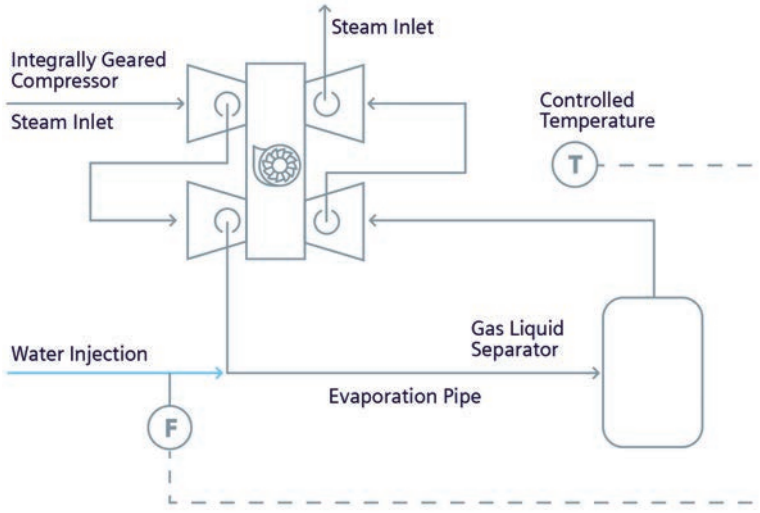


Figure 3. Steam cooling by water injection.

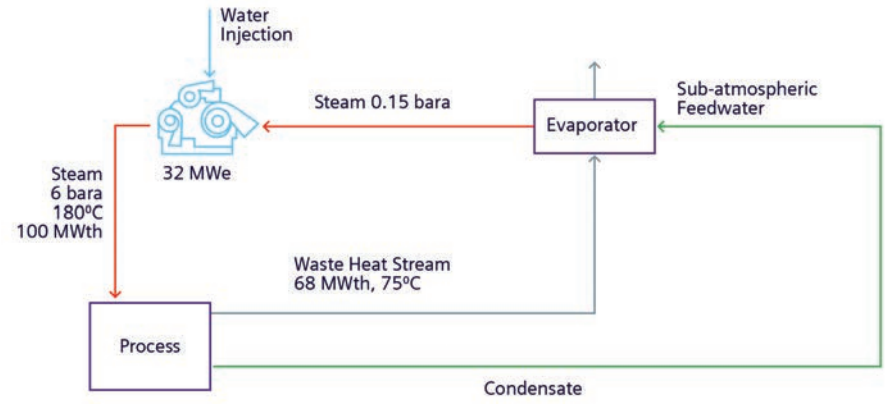


Figure 4. Mechanical vapour recompression (MVR) cycle.

In this application, the water is evaporated at 0.15 bara and then compressed in a steam compressor. Although the density of the sub-atmospheric steam is very low (at only 0.1 kg/m^3), the entire volumetric flow can still be handled within one Siemens Energy IGC machine. The COP of the system is similar to that of a comparable heat pump system, with the added benefit of reduced CAPEX due to the elimination of the aforementioned components.

COP can be increased and CAPEX lowered further if the heat source temperature is increased. In another example, where the waste heat source is ~105°C and the steam is required at 3 bara, a COP > 7 can be achieved. In this case, the steam for the MVR cycle was able to be produced at 0.65 bara, leading to a higher density and, therefore, a lower volumetric flow compared to the previous example with 0.15 bara.

Conclusion

Both heat pump and MVR cycles represent sustainable and efficient technologies for waste heat recovery. The choice of which to employ is largely dependent on the unique requirements of the process or facility.

The MVR cycle is typically more advantageous for heat sources with higher temperatures, as this results in an increase in steam evaporation temperature and pressure, which leads to a higher COP and a smaller system footprint through a reduction in volume flow. As the heat source temperature decreases, heat pumps become more economical due to a rising steam volumetric flow within a respective MVR cycle, which will increase the size and cost of the system. Furthermore, at a certain point, the steam pressure becomes excessively low, so that, for example, sealing can become too challenging, making the heat pump a better option.

Ultimately, there is no defined temperature threshold where one technology is always more advantageous than the other. Selection requires consideration of many different variables. Siemens Energy provides an in-depth evaluation of both options to determine the optimal cycle configuration, depending on the customer's requirements with respect to CAPEX, OPEX, footprint, lead time, complexity and environmental and safety aspects.

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