Optimising heat recovery with CPHEs

Compact plate heat exchangers are an efficient way to optimise heat recovery in refineries, especially when installation space or weight is crucial and exotic materials are needed to deal with corrosion issues

Eva Andersson  
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In today's refinery business, there is an increasing emphasis on expanding capacity while reducing energy consumption and maintaining a positive environmental profile. The inherent properties of compact plate heat exchangers (CPHEs) make them a more efficient and compact solution to traditional shell-and-tube heat exchangers (S&Ts). CPHEs make it possible to achieve increased capacity and to recover more heat using fewer heat exchangers, which are also much smaller and can easily be fitted within the footprint of existing installations. The greater energy recovery results in savings in fuel consumption as well as reductions in emissions, giving investment payback times that are typically very attractive.

Satisfied operators also confirm that the use of CPHEs provides faster response to changes in the process, such as at plant startup and shutdown, in addition to longer intervals in between services. When service is needed, unrestricted access to the heat-transfer surfaces means it is easier to restore full heat-transfer efficiency.

Heat-transfer efficiency
The main feature differentiating the CPHE from the traditional S&T is the use of corrugated plates to form the heat exchanger channels. When these plates are stacked, the many contact points force the fluid to spiral its way through the channels, thereby inducing high turbulence (Figure 1). This means that for the same flow velocity through the channels, a CPHE achieves greater turbulence than a S&T, thus giving rise to thermal efficiency that is three to five times higher.

This greater turbulence leads to a higher wall shear stress, permitting the CPHE to operate for longer intervals with no need for maintenance. This is because the wall shear stress has a cleaning effect that reduces any fouling inside the heat exchanger.

Heat-recovery possibilities
Another important feature of the CPHE is that it can operate with a counter-current flow (ie, the hot fluid enters the heat exchanger at the end where the cold fluid exits). This makes it possible to handle crossing-temperature programs (where the cold fluid is heated to a temperature that is higher than the outlet temperature of the hot fluid) in a single heat exchanger (Figure 2). This is especially important in heat recovery, where the cold fluid can be heated to temperatures very close to those of the hot fluid, hence recovering as much energy as possible.

The temperature difference between the hot and the cold fluids (mean temperature difference — MTD) acts as the driving force for heat transfer. The larger the MTD, the more the heat transfer, and vice versa. The effort needed to carry out a certain heat-transfer duty is often measured in terms of its NTU value (theta [θ] value or thermal length). For single phase service, this parameter is calculated as:

Equation 1:  \( NTU = \theta = \frac{T_1 - T_2}{MTD} \)
\( T_1 = \) inlet temperature
\( T_2 = \) outlet temperature

For heat-recovery duties, the temperature program (the difference between the inlet temperature and outlet temperature) is normally large and/or the temperature difference between the two fluids (MTD) is very small. Equation 1 shows that this results in a large NTU value. In reality, this means the driving force for the heat-recovery duty is low and the two fluids have to remain in contact for a long time for them to exchange heat.

In a S&T, this is tackled by making the tubes longer, arranging the tubes with many passes and/or connecting several tubes in series. This often results in hydraulic problems, because the channel velocity through the large units is reduced, thereby lowering the thermal efficiency of the heat exchanger even more (as well as increasing the fouling problems).

In contrast, the high thermal efficiency of the CPHE, combined with opportunities for operating with a counter-current flow, allows the CPHE to deal with long temperature programs with a small MTD. As a result, in many

Figure 1  Turbulent flow through heat exchanger channels, generated by corrugated plates

Figure 2  Crossing-temperature program
cases, only a single CPHE is needed to tackle the required heat-recovery duties, as shown in Table 1.

Installation concerns
As can be seen in Figure 3, the smaller heat-transfer area (HTA) is not the only source of savings. Since the CPHE features such a compact basic design, the HTA required for each specific duty can also be assembled in an effective way. This means a CPHE with around 320m² of HTA needs less than 1.5m² of floor space for the installation and around 10m² of total floor space, including the service area (with 1m added all around the equipment). A corresponding S&T heat exchanger with 6m-long tubes would need around 15m² of floor space for the installation and 60m² of floor space including the service area, because room for removing the tube bundle must be taken into consideration.

The compactness of the CPHE design also accounts for a reduced weight, which cuts down on installed cost (investment plus installation), especially when construction and/or foundation work is needed. When estimating the installed cost, a factor of 3.0-3.5 times the initial investment cost is often used for S&Ts, while for CPHEs the corresponding factor is normally less than 2.0. In addition, the reduced hold-up volume means the CPHE responds much faster to any changes in the process operating parameters, such as at startup and shutdown. Table 2 summarises the benefits of CPHEs relative to S&Ts.

Service needs
As has already been pointed out, the greater turbulence and the elimination of hydraulic problems extend the operating intervals between services. Service work is also done more quickly when needed, which saves money on both maintenance costs and production downtime. With the better response to process changes, the plant can be shut down and restarted more quickly. If chemical cleaning is used, the lower hold-up volume makes this process faster, with fewer chemicals to dispose of once the cleaning is complete.

If mechanical cleaning is needed, simply unbolting the frame provides complete access to the heat-transfer surface for cleaning using a hydro jet of up to 500 bar, as shown in Figure 4.

Heat recovery in crude preheat trains
In a refinery, the one process that requires the largest amount of energy is the preheating of the crude oil. This is therefore where most of the gains from using CPHEs for heat recovery can be made. However, as will be discussed in further detail, CPHEs can also bring benefits to many other parts of the refinery where heat recovery is an issue. For the following discussion, the crude preheat train is used as an example, but similar calculations can be made for any heat-recovery duty where heater savings are achieved. For detailed calculations, please see Appendix A at the end of the article.

For a 100 000 bpd refinery, around 120 MW of energy input is needed to preheat the crude from 25–350°C. Most of this energy is recovered, either from the atmospheric residue or from other hot fractions in the refinery. The final part of the preheating is carried out in a fired heater.

It is obvious that the more energy that can be sourced via heat recovery and implemented prior to the heater, the greater the savings in heater size, and the greater the reductions in energy consumption and emissions from that heater. For 1.0 MW less energy input in the heater, around 1070 tons of fuel is saved. Using a fuel cost of $40/bbl (the

Table 1

<table>
<thead>
<tr>
<th></th>
<th>CPHE</th>
<th>S&amp;T</th>
<th>CPHE</th>
<th>S&amp;T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of heat</td>
<td>1</td>
<td>1</td>
<td>3 (parallel)</td>
<td>4 (series)</td>
</tr>
<tr>
<td>exchangers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of passes</td>
<td>11/4</td>
<td>4/1 (tube/shell)</td>
<td>16/16</td>
<td>4/1 (tube/shell)</td>
</tr>
<tr>
<td>Pressure drop, kPa</td>
<td>85/115</td>
<td>60/82</td>
<td>90/120</td>
<td>90/115</td>
</tr>
<tr>
<td>Shear, Pa</td>
<td>31/112</td>
<td>4 (tube)</td>
<td>16/21</td>
<td>3.2 (tube)</td>
</tr>
<tr>
<td>Total HTA, m²</td>
<td>70</td>
<td>400</td>
<td>770</td>
<td>3344</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th></th>
<th>CPHE</th>
<th>S&amp;T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall shear stress</td>
<td>5–8</td>
<td>1</td>
</tr>
<tr>
<td>Heat transfer efficiency</td>
<td>3–5</td>
<td>1</td>
</tr>
<tr>
<td>Heat transfer area</td>
<td>1</td>
<td>3–5</td>
</tr>
<tr>
<td>Pressure drop</td>
<td>1.2–1.5</td>
<td>1</td>
</tr>
<tr>
<td>Temperature pinch</td>
<td>3–5°C</td>
<td>N/A</td>
</tr>
<tr>
<td>Footprint</td>
<td>1</td>
<td>5–10</td>
</tr>
<tr>
<td>Service area</td>
<td>1</td>
<td>4–10</td>
</tr>
<tr>
<td>Weight empty</td>
<td>1</td>
<td>1.5–4</td>
</tr>
<tr>
<td>Weight full</td>
<td>1</td>
<td>2–5</td>
</tr>
<tr>
<td>Installation cost</td>
<td>1</td>
<td>1.5–2</td>
</tr>
<tr>
<td>Hold-up volume</td>
<td>1</td>
<td>30–40</td>
</tr>
</tbody>
</table>

Figure 3 Difference in heat-transfer area and ground space for a S&T compared with a CPHE installation in a heat-recovery installation (atmospheric residue: 288 → 162°C; crude: 107 → 201°C; heat load: 7MW). S&T total heat transfer area is more than 1000 m² and CPHE heat transfer area is only 170 m²
normal level for internal energy charges), a substantial amount of money, amounting to as much as $300,000, can be saved for every year of operation.

Substantial savings can also be made on emissions. For each ton of natural gas burned, approximately 2.6 tons of CO₂ are released. According to the terms of the Kyoto Protocol, one CO₂ emission allowance (also called a permit or credit) gives the right to emit one metric ton of CO₂ (or CO₂ equivalent). Companies can buy and sell CO₂ credits, and market forces will then set the price of the traded credits. Some US emission traders have forecast market prices of around $20 per credit before 2008 (the first commitment year of the Kyoto Protocol). This is approximately half of the shortfall fines (€40 per credit) proposed in Europe.¹ Using $20 per credit, an additional $50,000 can be saved on reduced CO₂ emissions for each 1.0 MW of energy reduction in the heater on an annual basis.

Other emissions that can be traded are SOₓ and NOₓ permits. Refiners with emissions below the permitted cap values can sell their surplus permits, and vice versa. The normal trading price for SO₂ and NOₓ is in the region of $1000 per ton, and for each ton of fuel burned about 15kg of SO₂ (assuming 0.6% S in the fuel) and 12kg of NOₓ (including both thermal and fuel NOₓ and assuming 0.25% N in the fuel) are released. This means that an additional $30,000 can be saved on reduced SO₂ and NOₓ emissions for each 1.0 MW of energy reduction in the heater on an annual basis (Table 3).

### CPHE heat-recovery cases

#### Crude preheating

A refinery in the US wanted to increase the preheating of its crude. Thermal and hydraulic constraints in the S&Ts had previously limited the preheating to 239°C prior to the heater. It proved possible to achieve additional preheating by installing a CPHE, operating as:

<table>
<thead>
<tr>
<th>Process</th>
<th>Temperature</th>
<th>Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVGO</td>
<td>298 → 271°C</td>
<td>7.0 MW</td>
</tr>
<tr>
<td>Crude</td>
<td>263 &lt; - 239°C</td>
<td></td>
</tr>
</tbody>
</table>

Note that all the payback calculations listed in this discussion are based on current market prices and monetary values. Savings are calculated as laid out in Appendix A.

The installed cost (investment plus installation) of two CPHEs (one on standby) was around $1.1 million (Figure 5), but the annual savings in fuel costs and emission reductions amounted to more than $2.7 million ($2.2 million in fuel savings and $500,000 in emission reductions). This energy-saving project thus resulted in a payback time of less than five months. The CPHEs have been in operation since 2004.²

#### BFW preheating

A refinery in Switzerland (Figure 6) wanted to use its virgin naphtha overhead vapour from the atmospheric distillation tower to preheat both crude and boiler feed water (BFW). Important criteria when selecting the correct equipment were compactness (as the installation was high above the ground) and corrosion resistance (as the virgin naphtha contained a high level of chlorides). The refinery therefore chose to go for four CPHEs made of titanium (two in parallel and two in series), operating as follows:

<table>
<thead>
<tr>
<th>Step 1 - BFW preheating:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha</td>
</tr>
<tr>
<td>BFW</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>124 → 101°C</td>
</tr>
<tr>
<td>95°C &lt; -</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2 - Crude preheating:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphtha</td>
</tr>
<tr>
<td>Crude</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>101 → 77°C</td>
</tr>
<tr>
<td>71 &lt; - 25°C</td>
</tr>
</tbody>
</table>

Q = 16.5 MW.

Each CPHE pair requires an installation space of about 15m² (including the service area) and weighs around 25 tons.

The energy recovered corresponds to annual fuel and emission savings of $5 million and $1.3 million respectively. With an installed cost of $2.2 million, the payback time was little more than four months. The two CPHE pairs have been in successful operation since 1997.

### Table 3

#### Annual savings for 1 MW of increased heat recovery, resulting in a 1 MW reduction in energy needs for heater

<table>
<thead>
<tr>
<th>Savings</th>
<th>Ton/year and MW</th>
<th>$/year and MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater fuel</td>
<td>1070</td>
<td>300 000</td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>2500</td>
<td>50 000</td>
</tr>
<tr>
<td>SO₂ and NOₓ emissions</td>
<td>30</td>
<td>30 000</td>
</tr>
</tbody>
</table>

Major assumptions: fuel cost $40/bbl, 65% heater efficiency, 0.6% S and 0.25% N in fuel, CO₂ credit $20/ton and SO₂ and NOₓ credits $1000/ton

#### Figure 5

Two CPHEs used for crude preheating by means of HVGO

#### Figure 4

CPHE provides unrestricted access to the heat-transfer surface for mechanical cleaning

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two S&Ts in series or one CPHE, while the solution with increased heat recovery required four S&Ts in series or two CPHEs in parallel, rendering the S&T solution not feasible. However, as the CPHE solution meant increased fuel and emission savings of $750 000/year and $200 000/year respectively, the refinery therefore selected eight CPHEs with Hastelloy plates (four in parallel and two in series), operating as follows:

- **Step 1 - BFW preheating:**
  - Overhead vapour: 141 -> 87°C
  - BFW: 128 <- 43°C
  - Q = 14 MW.

- **Step 2 - Cooling:**
  - Overhead vapour: 87 -> 29°C
  - Cooling water: 45 <- 24°C
  - Q = 9 MW.

The heat recovery of 14 MW means annual savings in fuel and emissions amounting to $4.3 million and $1.1 million respectively, and with the installed cost of around $7 million the installation was paid back in 15 months. The CPHEs have been in operation since 2002 (Figure 8).

Steam generation

A refinery in The Netherlands wanted to use mid pump-around (MPA) from the hydrocracker fractionator to generate steam. Due to the close temperature program, it would not have been feasible to do this using S&Ts. Instead, four CPHEs were used: one to preheat the BFW, two for the actual steam generation and one for superheating the steam, as follows:

- **Step 1 - BFW preheating:**
  - MPA: 186 -> 181°C
  - BFW: 179 <- 120°C

- **Step 2 - Steam generation:**
  - MPA: 220 -> 186°C
  - Water/steam: 180 <- 179°C

- **Step 3 - Steam superheating:**
  - MPA: 221 -> 220°C
  - Steam: 215 <- 180°C

Q = 8.4 MW.

With this arrangement, 8.4 MW of heat is recovered from the MPA and 15 tph of 9.0 barg superheated steam is generated. This means annual savings in fuel and emissions amounting to $2.5 million and $600 000 respectively. With an installed cost of approximately $800 000, the installation was paid back in around three months. Or, using a price of $10/ton of 9.0 barg steam, the value of the generated steam amounted to $1.2 million. When combined with the emission savings, this gives a project payback time of only five months. The CPHEs have been in service since autumn 2002.

**Heat recovery in desalting units**

<table>
<thead>
<tr>
<th>Traditional case</th>
<th>Increased heat recovery</th>
<th>Q = 12 MW</th>
<th>Q = 14.5 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm res</td>
<td>165 -&gt; 103°C ; NTU = 1.7</td>
<td>165 -&gt; 90°C ; NTU = 3.4</td>
<td></td>
</tr>
<tr>
<td>BFW</td>
<td>132 &lt; 60°C ; NTU = 2.0</td>
<td>148 &lt; 60°C ; NTU = 4.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4

*Figure 6 One of the two CPHE pairs mounted on top of each other for preheating BFW and crude by means of naphtha toppings*

*Figure 7 Heat-recovery installation in UK, preheating BFW by means of atmospheric residue*
In the desalting process, the desalter water from the crude oil desalter is normally used to preheat the fresh feed water going to the desalter. As much heat recovery as possible is required, but the desalter water contains substantial quantities of chloride. This means carbon steel is often not sufficiently corrosion resistant. A solution involving large S&Ts made of stainless steel or another high-performance alloy material would be extremely expensive.

Due to corrosion problems, a refinery in Germany needed to replace its six carbon-steel S&Ts used for heat recovery in the desalting process. Due to the need for corrosion-resistant material, the refinery decided on three CPHEs featuring Hastelloy plates, installed in series and operating as follows:

- **Step 1 - Heat recovery:**
  - Desalted water: 130 → 50°C
  - Fresh water: 120 → 40°C

- **Step 2 - Cooling:**
  - Desalted water: 50 → 30°C
  - Cooling water: 40 → 25°C

Q = 3.7 MW.

As can be seen in Figure 9, the refinery not only upgraded its heat exchangers to a corrosion-resistant material, it also substantially reduced the size of the installation (the three CPHEs marked with a circle replaced the six S&Ts to the left, as shown in Figure 9). The heat recovery achieved corresponds to energy and emission savings of around $1.1 million and $300 000 respectively. With an installed cost of approximately $600 000, this meant the installation was paid back in around five months. The CPHEs have been in operation since 1997.

**Conclusion**

It is a well-known fact that compact CPHEs, with their improved turbulence and counter-current flow, can achieve much higher heat-transfer efficiencies than traditional S&Ts, thereby reducing the heat-transfer area needed.

This is especially important in heat recovery, where the use of CPHEs makes it possible to carry out demanding energy-recovery duties that in some cases would not even be feasible using S&Ts, or would require many large S&Ts connected in series and thus suffer from hydraulic constraints and fouling problems.

The increased heat recovery means substantial savings, both in terms of fuel savings and savings on emissions from heaters and boilers. With today’s rocketing energy prices, the Kyoto Protocol and acid rain, these are facts that become ever more important when calculating the payback for a project.

Since CPHEs provide compact, low-weight solutions with minimal installation footprint and service ground space needs, the installation cost is normally 33–75% lower than for bulky S&Ts. Payback times of less than six months, including installation cost, are often feasible when considering heat-recovery projects that feature CPHEs.

Other advantages with using CPHEs include the reduced heat-transfer area, which makes it possible to utilise materials that are highly corrosion-resistant, and the low hold-up volume, which enables the unit to respond more quickly to any changes in the process operating parameters, making it easier to start up and shut down the process.

From a service point of view, the highly turbulent flow through the heat exchanger channels, measured as wall shear stress, ensures the heat exchanger is kept clean, resulting in longer service intervals. When cleaning is needed, the unrestricted access to the heat-transfer surface reduces the downtime and maintenance efforts to a minimum. If chemical cleaning can be carried out, chemical consumption and disposal costs are reduced on account of the much lower hold-up volume.

Many refineries have started to see the huge benefits of using CPHEs in their processes. Most of the installations are for heat-recovery applications (crude preheating, feed/effluent heat recovery and BFW preheating) when installation space or weight is crucial (overhead condensers) and exotic materials are needed to deal with corrosion issues (desalter water, naphtha toppings and alkylation mix). There is no lack of testimonials from operators who are convinced of the benefits.

**References**

1 Barnes P, Bussonnet P X, Reverdy F, Saving fuel costs with WPHEs, 2005.
3 Takacs T J, Juedes D L, Crane I D, Method estimates NOx from combustion equipment, Oil & Gas Journal, 21 June 2004.

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Detailed energy and emission savings calculations

Crude preheating

\[ Q = \text{flow rate of crude in kg/s} \times \text{Crude preheating} = 2.3 \times (350 - 25) = 120 \text{ 161 kW} = 120 \text{ MW} \]

\[ Q = \text{Heat load in kW} \]
\[ m = \text{specific volume for crude} = 7.2 \text{ bbl/ton} \]
\[ C_p = \text{Specific heat for crude} = 2.3 \text{ kJ/kg} \text{°C} \]
\[ T_1 = \text{Crude start temperature} = 25°C \]
\[ T_2 = \text{Crude final temperature} = 350°C \]
\[ M_wC = \text{Molecular weight of C} = 12 \text{ g/mole} \]
\[ M_wS = \text{Molecular weight of S} = 32 \text{ g/mole} \]
\[ M_wNOx = \text{Molecular weight of NO2} = 46 \text{ g/mole} \]
\[ M_wSOx = \text{Molecular weight of SO3} = 80 \text{ g/mole} \]
\[ M_wCO2 = \text{Molecular weight of CO2} = 44 \text{ g/mole} \]

\[ \text{savings} = \text{NG savings in heater in ton/year and MW} \]
\[ \text{priceNG} = \text{estimated CO2 credit price} = \frac{\text{PriceNG}}{\text{MW}} = \frac{\text{Price for NG}}{\text{MW}} \]

\[ m_{CO2} = \left( \frac{m_{NG} \times \text{wt%C}}{M_wC} \right) \times \text{MwCO2} = \frac{966 \times 0.71 \times 44}{12} = 2514 \text{ ton/year and MW} \]

\[ m_{SOx} = \frac{\text{SOx emission reductions in heater}}{\text{in ton/year and MW}} \]
\[ \text{priceSOx} = \text{estimated SOx credit price} = \frac{\text{PriceSOx}}{\text{MW}} = \frac{\text{Price for SOx}}{M_wSOx} \]

\[ \text{savings} = \frac{\text{MW}_{\text{SOx}}}{\text{MW}_{\text{S}}} \times \frac{\text{PriceSOx}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wS} = 3 ± 1.3 \text{ ton/year and MW} \]

\[ m_{NOx} = \frac{\text{NOx emission reductions in heater}}{\text{in ton/year and MW}} \]
\[ \text{priceNOx} = \text{estimated NOx credit price} = \frac{\text{PriceNOx}}{\text{MW}} = \frac{\text{Price for NOx}}{M_wNOx} \]

\[ \text{savings} = \frac{\text{MW}_{\text{NOx}}}{\text{MW}_{\text{N}}} \times \frac{\text{PriceNOx}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wN} = 9.12 \times 1000 = \$16 655/\text{year and MW} \]

\[ m_{fuel} = \frac{\text{Fuel savings in heater in ton/year and MW}}{\text{pricefuel}} = \frac{\text{Fuel savings in heater in ton/year and MW}}{\text{MW}} \]

\[ \text{Pricefuel} = \text{Internal energy charges for fuel} = \frac{\text{Price for fuel}}{\text{MW}} \]
\[ H_v\text{Fuel} = \text{Average latent heat for fuel} = \frac{\text{HvFuel}}{\text{MW}} \]

\[ \text{savings} = \frac{\text{MW}_{\text{fuel}}}{\text{MW}_{\text{S}}} \times \frac{\text{Pricefuel}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wS} = 3 ± 1.3 \text{ ton/year and MW} \]

\[ m_{SOx} = \frac{\text{Fuel savings in heater in ton/year and MW}}{\text{MW}} \]
\[ \text{priceSOx} = \text{estimated SOx credit price} = \frac{\text{PriceSOx}}{\text{MW}} = \frac{\text{Price for SOx}}{M_wSOx} \]

\[ \text{savings} = \frac{\text{MW}_{\text{SOx}}}{\text{MW}_{\text{S}}} \times \frac{\text{PriceSOx}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wS} = 3 ± 1.3 \text{ ton/year and MW} \]

\[ m_{NOx} = \frac{\text{Fuel savings in heater in ton/year and MW}}{\text{MW}} \]
\[ \text{priceNOx} = \text{estimated NOx credit price} = \frac{\text{PriceNOx}}{\text{MW}} = \frac{\text{Price for NOx}}{M_wNOx} \]

\[ \text{savings} = \frac{\text{MW}_{\text{NOx}}}{\text{MW}_{\text{N}}} \times \frac{\text{PriceNOx}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wN} = 3 ± 1.3 \text{ ton/year and MW} \]

\[ \text{Pricefuel} = \text{Internal energy charges for fuel} = \frac{\text{Price for fuel}}{\text{MW}} \]
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\[ m_{SOx} = \frac{\text{Fuel savings in heater in ton/year and MW}}{\text{MW}} \]
\[ \text{priceSOx} = \text{estimated SOx credit price} = \frac{\text{PriceSOx}}{\text{MW}} = \frac{\text{Price for SOx}}{M_wSOx} \]

\[ \text{savings} = \frac{\text{MW}_{\text{SOx}}}{\text{MW}_{\text{S}}} \times \frac{\text{PriceSOx}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wS} = 3 ± 1.3 \text{ ton/year and MW} \]

\[ m_{NOx} = \frac{\text{Fuel savings in heater in ton/year and MW}}{\text{MW}} \]
\[ \text{priceNOx} = \text{estimated NOx credit price} = \frac{\text{PriceNOx}}{\text{MW}} = \frac{\text{Price for NOx}}{M_wNOx} \]

\[ \text{savings} = \frac{\text{MW}_{\text{NOx}}}{\text{MW}_{\text{N}}} \times \frac{\text{PriceNOx}}{10000} \times 4.19 \times \frac{3600 \times 24 \times 350}{10000 \times 4.19 \times 0.65} = 1110 \times \frac{1110}{M_wN} = 3 ± 1.3 \text{ ton/year and MW} \]