Techno-Economical Study on the Back Pressure Turbine Installation in the Water, Electricity and Steam Units of the Tehran Oil Refinery

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Abstract
The importance of energy crisis forced all industries to minimize energy consumption of the plants. The waste of energy in PRV (Pressure Reduction Valve) on the line of working fluid with high pressure and temperature in Tehran oil refinery is significant. This refinery uses PRV for reducing pressure of steam flow with 600 psi and 300 psi for some of their drivers such as medium and low pressure pumps and turbo compressors. Because of high amount of energy waste of high pressure working fluid on PRV, this study aimed to use this energy for turning a turbine to make work and making needed low pressure stream for drivers. After simulating the lines with turbines, some lines have output stream with lower temperature of targeted output stream temperature. To solve these problems, two extra simulations were performed: One with placing preheater on input steam stream to turbine and other with reducing input stream to turbine and mixing it with high pressure and temperature on outlet stream to increasing the temperature and pressure of steam to the targeted output conditions. Also, Economic calculations were done to choose optimal alternatives. The results of simulation and economical calculations showed that, the values of SPP for all simulated lines were less than one year and the IRR for all of them are significant. So investment on all lines for turbo expander installation is recommended. For second line of North Water, Electricity and Steam unit, investment on addition of turbo expander and preheater and for second line of Isomerization unit, investment on addition of turbo expander and mixer splitter are the optimal alternatives.

Keywords: Back Pressure Turbine; Pressure Reduction Valve; Thermoflex, Steam.

1. Introduction
Recent energy crisis and high costs of energy products encourage every plants and refineries to optimize and reduce energy consumptions of their products and utility lines.

Tehran oil refinery was established in 1974 by an American company (FLUOR) that involves two similar plants, Northern and Southern refineries. The steam networks in the two oil refineries are similar. A 16 inch 650 psig steam line and a 8 inch 60 Psig steam line interconnects the north and south refinery steam systems to provide operational flexibility and assist in the startup of refineries [1]. Figure 1 shows the complex steam network system [11].

Three units (North Water, Electricity and Steam unit, South Water, Electricity and Steam unit and Isomerization unit [2] use PRVs for converting High Pressure (HP) stream to Medium pressure (MP) or Low Pressure (LP) stream to utilize them for their drivers in utility units such as Heating Systems, Steam Strippers, Reboilers, Heating Coil Tanks, Utility stations, Distillation Ejectors and Mechanical Turbo Pumps. By Replacing Turbines with these PRVs, we can reduce the line steam stream pressure while produce work with the turbine.

1.1. Current schematic of the lines
The current schematic for every line is shown in Figure 2.
The purpose of the steam source in figure 2 is HP, MP and LP lines mentioned in figure 1 and the purpose of the steam sink is Drivers in utility units of the mentioned earlier lines such as Heating Systems, Steam Strippers, Reboilers, Heating Coil Tanks, Utility stations, Distillation Ejectors and Mechanical Turbo Pumps.

[Image: Figure1. Schematic of steam network]

[Image: Figure2. Current schematic for reducing pressure of steam stream for every line]

**1.2. Thermodynamic properties and Irreversibility Intensity of Current Conditions**

The thermodynamic properties of inlet and outlet stream of PRV of every line are presented in table 1. Using Equation 1 \[^3\] and assuming \((T_0 = 298.15K)\) the irreversibility intensity were calculated for the current operating condition of PRVs for every line and were presented in Table 1.

\[
i = \dot{m}_{\text{gen}}T_0\psi = \dot{m}(\psi_i - \psi_e) = W_{\text{rev}} - W = \dot{m}[(h_i - h_e) - T_0(s_i - s_e)]
\]

\[(1)\]
2. Review of previous studies

For many years, Turbo expanders have been used in cryogenic processing plants to provide low-temperature refrigeration. Current commercial models of Turbo expanders exist in the power range of 75 KW to +25 MW, so many applications are possible. Many Turbo expanders are designed to operate in the pressure within 130-200 bars. According to some publications [4] and the marketing web sites [5], the Turbo expanders are now available from 75 KW up to 130 MW. Natural gas expansion through Turbo expanders generates electric power with far greater efficiency than the conventional thermal power utilities burning gas as fuel. In addition, the Turbo expanders do not create greenhouse gases or significant environmental pollutions [6].

For more reliability and safety of operation, the existing conventional pressure reduction valves are held, and the expansion turbines are installed in parallel with them. In this condition, the redundant standby regulator valve ensures continued safe operation in the event of Turbo expander failure [7]. Most gases cool during the expansion (Joule-Thompson effect) [8]. Nevertheless, a temperature drop of the gas is high in the case of employing the Turbo expanders so; preheating of the gas is required to avoid gas freezing at the outlet [9].

In some gas compositions, water or liquid hydrocarbons are produced at low temperatures which yield to hydrates, blockage of the pipeline, corrosion of the blades of the turbine and failure of the equipment. Therefore, it is essential to keep the outlet temperature above the hydrate formation range [10].

Khodaei et al. [1] simulated Steam Network with STAR used for determining optimized conditions and with this method energy saving potential and total operational cost in two states (fixed fuel proportion and variable fuel proportion) were calculated. Khodaei et al. selected the Tehran refinery steam network as a case study and after steam network simulation and optimization, best scenario with lowest total cost and minimum reduction of \( \text{CO}_2 \) gas were determined. Neelis et al. [11] used backpressure turbines for reducing produced steam pressure in process that extra produced energy recovery in this turbines is possible and this turbines are the best alternative stead of PRVs (that waste working fluid energy). US Department of energy [12] emphasized on using ultra-high-pressure boilers and mentioned to increase operational power of steam boilers because of reduction outlet steam temperature when substituting PRVs with Backpressure turbines that it’s like as preheating inlet stream of backpressure turbines. They also reminded modern steam boilers have efficiency about 80%. Another study [6] used backpressure turbines for energy recovery of gas pressure reduction stations stead of PRVs. They used Dresser Flo System reference to show the amount of power.
generation. Howard [7] studied the performance of a hybrid Turbo expander and fuel cell (HTEFC) system for power recovery at natural gas pressure reduction stations. He preheated inlet stream to Turbo expander in order to compensate temperature reduction of outlet stream of Turbo expander. Andrei et al. [13] investigated the recovery of wasted mechanical energy from the reduction of natural gas pressure.

3. Energy recovery, power production, validation and economic evaluation method

3.1. Using Turbo expander for reducing pressure of steam stream for all lines in order to energy recovery during pressure reduction

In order to recover the lost energy during steam stream pressure reduction in three mentioned earlier units, the schematic shown in Figure 3 is used.

![Figure 3. Alternative schematic for reducing pressure of steam stream for every line](image)

For this schematic, the amount of produced work with Turbo expander is calculated using Equation 2, and the amount of irreversibility intensity is calculated by Equation 1.

\[ \dot{m}_h = \dot{m}_h + \dot{w} \]  

(2)

The efficiency of Turbo expander is calculated by:

\[ \eta = \frac{\dot{w}_a}{\dot{w}_s} = \frac{h_{iU} - h_{eU}}{h_{iU} - h_{eU}} \]  

(3)

The simulated Turbo expander with Thermoflex Lite Version 13.0 (Thermoflow Inc, USA) has throttle inlet pressure control, and it is a single shaft with 3600 rpm shaft speed. After simulation with thermoflex, we realized that by Turbo expander with outlet pressure of 74.69 psi abs, the outlet stream temperature will be lower than the desired temperature, and therefore we need to preheat inlet stream in order to achieve desired outlet stream temperature. Two scenarios are offered: First, by preheating inlet stream with gas fired preheater that is illustrated in Figure 4 and second, with reducing inlet stream to Turbo expander and mixing its outlet stream with inlet remain stream didn’t pass of Turbo expander in order to achieve desired outlet condition as illustrated in Figure 5.

![Figure 4. First Alternative schematic for lines with outlet pressure 74.69 psi abs](image)

![Figure 5. Second Alternative schematic for lines with outlet pressure 74.69 psi abs](image)
The amount of produced work for a unit with Turbo expander and preheater is calculated using Equation 4 and the amount of irreversibility intensity is calculated with Equation 5. The calculations were done with first low efficiency equal to 80% for gas fired preheater [3].

\[
\dot{m}h_i + \dot{Q} = \dot{m}h_e + \dot{w}
\]

\[
\dot{i} = T_0S_{gen} = \sum(1 - \frac{T}{T_0}) \dot{Q}_{cv} + \dot{m}[(h_i - h_e) - T_0(s_i - s_e)] - \dot{W}
\]

The value of irreversibility is depended to the hot reservoir temperature [14]. So for making results of produce work for a unit with Turbo expander and preheater more comparable with the results of the unit with Turbo expander and splitter-mixer, we did all calculations at the same temperature for inlet stream and temperature of gas fired preheater.

Thus for working based on desired inlet and outlet thermodynamic properties, the stream splitting coefficient (x) in splitter is calculated by equations 3, 6 and 7 and real produced work of Turbo expander is calculated by equation 8 [3].

\[
x\dot{m}h_i = x\dot{m}h_{esTu} + \dot{w}_{stu}
\]

\[
x\dot{m}h_{esTu} + (1-x) \dot{m}h_i = \dot{m}h_e
\]

\[
\dot{w}_{acTu} = x\dot{m}(h_{stu} - h_{eTu})
\]

Also for all units, we assume the first low efficiency of the generator is equal to 75%.

### 3.2. Economic evaluation method

In order to economic evaluation, we used the initial cost data from Tehran oil refinery and HHV of methane gas [15] as presented in Table 2 and for the prices of turbo expander & preheater, we used equations 9 and 10 [16]. The coefficients to calculate the cost of preheater is shown on Table 3.

\[
C_{Tu} = 0.378(HP)^{0.81} K$, 20 < HP < 5000 (1HP = 0.7457KW)
\]

\[
C_{PreH} = 1.218 k (1+f_d+f_p)Q^{0.82} K$, 2 < Q < 30 M Btu/hr(1Btu = 1055.06J)
\]

**Table 2. Provided cost data from Tehran oil refinery**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total cost (IRR)</th>
<th>Total cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ton of HP Steam production</td>
<td>580 000</td>
<td>17.576</td>
</tr>
<tr>
<td>Cost of production 1KWh electricity</td>
<td>4 800</td>
<td>0.145</td>
</tr>
<tr>
<td>Cost of annual maintenance</td>
<td>16 500 000</td>
<td>500</td>
</tr>
<tr>
<td>Price per cubic meter of methane gas</td>
<td>3 000</td>
<td>0.091</td>
</tr>
</tbody>
</table>

**HHV per cubic meter of methane gas with p=0.8 kg/m³ ≈ 39 MJ ≈ 10.833 KWh [15]**

**Inflation Rate = 20%**

**Discount Rate = 22%**

1USD ≈ 33000 IRR

**Table 3. Coefficients of preheater capital cost equation**

<table>
<thead>
<tr>
<th>Tube Material</th>
<th>k</th>
<th>Design Type</th>
<th>f_d</th>
<th>Design Pressure (psi)</th>
<th>f_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>27.3</td>
<td>Cylindrical</td>
<td>0</td>
<td>Up to 500</td>
<td>0</td>
</tr>
<tr>
<td>Cr Mo steel</td>
<td>40.2</td>
<td>Dowtherm</td>
<td>0.33</td>
<td>1,000</td>
<td>0.15</td>
</tr>
<tr>
<td>Stainless</td>
<td>42.0</td>
<td></td>
<td></td>
<td>1,500</td>
<td>0.20</td>
</tr>
</tbody>
</table>

We selected stainless tube material and cylindrical type of preheater for our calculations, and so in equation 10 we will have k=42 and f_d= 0.

To estimate the cost of generator we used figure 6 [17], where in A is synchronous power generator in terms of KW and n is allowed generator speed and we assume it is 3600 rpm. In addition, we assume 1Euro ≈ 1.12946$.

We used equations 11-14 [18] to plot cash flow diagram and for calculating Simple Payback Period (SPP), Net Present Value (NPV) and Internal Rate of Return (IRR) for every line in a period of 15 years that is almost equal to the useful life of the equipment.

\[
DF = (1 + \frac{DR}{100})^{-n}
\]
\begin{equation}
IF = \left(1 + \frac{IR}{100}\right)^{-n}
\end{equation}

Real Interest Rate = Discount Rate - Inflation Rate \tag{13}

\text{Simple Payback Period} = \frac{\text{Capital Cost}}{\text{Annual Net Cost Saving}} \tag{14}

4. Results of technical simulation and economic evaluation

4.1. Results of Thermoflex software simulation

4.1.1. Results of the first line of North Water, Electricity and Steam unit with Turbo expander simulation

Having thermodynamic properties of inlet and outlet Stream of PRV of the first line of the north unit, simulation of the system was performed. The results are shown on Table 4 and Figure 7.

Table 4. Results of first North Water, Electricity and Steam unit simulation with Turbo expander

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2O$ in</td>
<td>253.9</td>
<td>42.38</td>
<td>371.10</td>
<td>15</td>
<td>3141.82</td>
<td>6.631</td>
</tr>
<tr>
<td>$H_2O$ out</td>
<td>216.6</td>
<td>21.70</td>
<td>296.64</td>
<td>15</td>
<td>3011.50</td>
<td>6.708</td>
</tr>
<tr>
<td><strong>Shaft Power = 434.4 KW</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall apparent isentropic efficiency = 76.07%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Generator = 324.7 KW

Steam Superheat = 80.10 °C

Figure 7. Process plot of enthalpy in terms of entropy of first line of north unit with Turbo expander
4.1.2. Results of second North Water, Electricity, and Steam unit simulation

4.1.2.1. Results of the second line of North Water, Electricity and Steam unit with Turbo expander and gas fired preheater simulation

By simulation line in accordance with Figure 4 and based on Considering the thermodynamic properties of inlet and outlet stream of PRV of the second line of the north unit (Table 1) and the data on Figure 4, the line is simulated, and the results are shown in Table 5 and Figure 8.

Table 5. Output results of second North Water, Electricity and Steam unit with Turbo expander and gas fired preheater simulation

<table>
<thead>
<tr>
<th>Component</th>
<th>T [℃] Sat</th>
<th>P [bar]</th>
<th>T [℃]</th>
<th>M [ton/h]</th>
<th>h [KJ/Kg]</th>
<th>s [KJ/Kg K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Input to Heat Adder</td>
<td>216.51</td>
<td>21.688</td>
<td>279.4</td>
<td>18</td>
<td>2969.67</td>
<td>6.635</td>
</tr>
<tr>
<td>2. Output of Heat Adder</td>
<td>215.5</td>
<td>21.263</td>
<td>341.7</td>
<td>18</td>
<td>3118.01</td>
<td>6.895</td>
</tr>
<tr>
<td>3. Output of Steam Turbine</td>
<td>152.96</td>
<td>5.150</td>
<td>225.6</td>
<td>18</td>
<td>2909.23</td>
<td>7.157</td>
</tr>
</tbody>
</table>

Heat input to Heat Adder = 741.7 kW  Heat transferred from external source

Shaft Power = 835.2 kW  Total Generator = 624.2 KW
Overall apparent isentropic efficiency = 63.39%
Steam Superheat = 72.68 ℃

4.1.2.2. Results of second North Water, Electricity, and Steam unit with Turbo expander and mixer-splitter simulation

Having thermodynamic properties of inlet and outlet Stream of PRV of the second line of the north unit, simulation of the system was performed. The results are shown on table 6 and figure 9.

Table 6. Output results of second North Water, Electricity and Steam unit with turboexpander and mixer-splitter simulation

<table>
<thead>
<tr>
<th>Component</th>
<th>T [℃] Sat</th>
<th>P [bar]</th>
<th>T [℃]</th>
<th>M [ton/h]</th>
<th>h [KJ/Kg]</th>
<th>s [KJ/Kg K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Input of Source</td>
<td>216.6</td>
<td>21.698</td>
<td>279.4</td>
<td>18</td>
<td>2969.67</td>
<td>6.635</td>
</tr>
<tr>
<td>2. Input to Turbine</td>
<td>216.6</td>
<td>21.698</td>
<td>279.4</td>
<td>12.5856</td>
<td>2969.67</td>
<td>6.635</td>
</tr>
<tr>
<td>4. Output of Splitter to Mixer</td>
<td>216.6</td>
<td>21.698</td>
<td>279.4</td>
<td>5.4144</td>
<td>2969.67</td>
<td>6.635</td>
</tr>
<tr>
<td>5. Output to Sink</td>
<td>152.96</td>
<td>5.150</td>
<td>212.8</td>
<td>18</td>
<td>2882</td>
<td>7.101</td>
</tr>
</tbody>
</table>

Shaft Power = 434.9905 Kw  Total Generator = 326.2 Kw
Overall apparent isentropic efficiency = 63.16%
Steam Superheat = 59.22℃

Figure 8. Process plot of enthalpy in terms of entropy of second line of north unit with turboexpander and gas fired preheater

Figure 9. Process plot of enthalpy in terms of entropy of second line of north unit with turboexpander and mixer-splitter
### 4.1.3. Results of South Water, Electricity and Steam unit with turboexpander simulation

Having thermodynamic properties of inlet and outlet Stream of PRV of the first line of the north unit on table 1, simulation of the system was performed. The results are shown on table 7 and figure 10.

Table 7. Output results of South Water, Electricity and Steam unit simulation with Turbo expander

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O in</td>
<td>253.9</td>
<td>42.38</td>
<td>371.10</td>
<td>10</td>
<td>3141.82</td>
<td>6.631</td>
</tr>
<tr>
<td>H₂O out</td>
<td>216.6</td>
<td>21.70</td>
<td>296.63</td>
<td>10</td>
<td>3011.50</td>
<td>6.708</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaift Power</td>
<td>= 289.6 KWₑ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall apparent isentropic efficiency</td>
<td>= 76.06%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Generator</td>
<td>= 216.5 KW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Superheat</td>
<td>= 80.9°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.1.4. Results of Isomerization unit simulation

#### 4.1.4.1. Results of the first line of Isomerization unit simulation with Turbo expander

Having thermodynamic data, simulation of first line of isomerization unit was performed. The results are shown on table 8 and figure 11.

Table 8. Output results of first line of Isomerization unit simulation with turboexpander

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O in</td>
<td>253.9</td>
<td>42.38</td>
<td>371.10</td>
<td>30</td>
<td>3141.82</td>
<td>6.631</td>
</tr>
<tr>
<td>H₂O out</td>
<td>216.6</td>
<td>21.70</td>
<td>296.64</td>
<td>30</td>
<td>3011.50</td>
<td>6.708</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaift Power</td>
<td>= 868.8 KWₑ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall apparent isentropic efficiency</td>
<td>= 76.07%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Generator</td>
<td>= 649.3 KW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Superheat</td>
<td>= 80.10°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Figure 10. Process plot of enthalpy in terms of entropy of South Water, Electricity and Steam unit simulation with turboexpander

#### Figure 11. Process plot of enthalpy in terms of entropy of first line of Isomerization unit simulation with turboexpander

#### 4.1.4.2. Results of the second line of isomerization unit simulation with Turbo expander and gas fired preheater

Having thermodynamic data, simulation of the second line of isomerization unit with Turbo expander and gas fired preheater was performed. The results are shown in table 9 and figure 12.

Table 9. Output results of second line of Isomerization unit simulation with turboexpander and gas fired preheater

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Input to Heat Adder</td>
<td>253.76</td>
<td>42.38</td>
<td>371.11</td>
<td>45</td>
<td>3141.82</td>
<td>6.631</td>
</tr>
<tr>
<td>2. Output of Heat Adder</td>
<td>252.57</td>
<td>41.532</td>
<td>458.94</td>
<td>45</td>
<td>3349.39</td>
<td>6.945</td>
</tr>
<tr>
<td>3. Output of Steam Turbine</td>
<td>152.96</td>
<td>5.150</td>
<td>232.07</td>
<td>45</td>
<td>2922.89</td>
<td>7.183</td>
</tr>
<tr>
<td>Total generator</td>
<td>= 3187.6 KW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Superheat</td>
<td>= 79.11°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall apparent isentropic efficiency</td>
<td>= 79.2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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4.1.4.3. Results of the second line of Isomerization unit simulation with turboexpander and mixer-splitter

Having thermodynamic data, simulation second line of isomerization unit with Turbo expander and mixer-splitter was performed. The results are shown on table 10 and figure 13 (x= 0.8948).

Table 10. Output results of second line of Isomerization unit simulation with turboexpander and mixer-splitter

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Input of Source</td>
<td>253.9</td>
<td>42.38</td>
<td>371.11</td>
<td>45</td>
<td>3141.82</td>
<td>6.631</td>
</tr>
<tr>
<td>2. Input to Turbine</td>
<td>253.9</td>
<td>42.38</td>
<td>371.11</td>
<td>40.266</td>
<td>3141.82</td>
<td>6.631</td>
</tr>
<tr>
<td>3. Output of Turbine to Mixer</td>
<td>174.4</td>
<td>8.786</td>
<td>207.2</td>
<td>40.266</td>
<td>2844.574</td>
<td>6.8</td>
</tr>
<tr>
<td>4. Output of Splitter to Mixer</td>
<td>253.9</td>
<td>42.38</td>
<td>371.11</td>
<td>4.734</td>
<td>3141.82</td>
<td>6.631</td>
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<tr>
<td>5. Output to Sink</td>
<td>152.96</td>
<td>5.150</td>
<td>212.77</td>
<td>45</td>
<td>2882</td>
<td>7.101</td>
</tr>
</tbody>
</table>

Shaft Power = 3247.75KWₑ
Total Generator = 2435.8125 KW
Overall apparent isentropic efficiency = 78.73%
Steam Superheat = 59.818 °C

Figure 12. Process plot of enthalpy in terms of entropy of second line of Isomerization unit simulation with Turbo expander and gas fired preheater

Figure 13. Process plot of enthalpy in terms of entropy of second line of Isomerization unit simulation with Turbo expander and mixer-splitter

4.2. Final results of Thermoflex software simulation

Considering the thermodynamic data in table 1 and figure 3, 4 and 5, the system was simulated with Thermoflex. The results are presented on table 11.

Table 11. Results of turboexpander power generation and manual irreversibility intensity calculations

<table>
<thead>
<tr>
<th>Num</th>
<th>Unit</th>
<th>Pᵢ (psi)</th>
<th>Pₒ (psi)</th>
<th>m (ton/hr)</th>
<th>η₁lawTur (%)</th>
<th>Pₜur (KW)</th>
<th>I PRV line (KW)</th>
<th>η (KW)</th>
<th>P Gen with η=75% (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1N</td>
<td>614.69</td>
<td>314.69</td>
<td>15</td>
<td>76.07</td>
<td>434.4</td>
<td>745.68</td>
<td>204.31</td>
<td>324.7</td>
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<tr>
<td>2</td>
<td>2N with Preheater</td>
<td>314.69</td>
<td>74.69</td>
<td>18</td>
<td>63.39</td>
<td>835.2</td>
<td>1129.69</td>
<td>678.65</td>
<td>624.2</td>
</tr>
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<td>3</td>
<td>2N with Mixer Splitter</td>
<td>314.69</td>
<td>125.89</td>
<td>12.58</td>
<td>63.16</td>
<td>434.99</td>
<td>1129.69</td>
<td>694.69</td>
<td>326.2</td>
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<td>614.69</td>
<td>314.69</td>
<td>10</td>
<td>76.06</td>
<td>289.6</td>
<td>497.12</td>
<td>136.17</td>
<td>216.5</td>
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<td>314.69</td>
<td>30</td>
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<td>868.8</td>
<td>1491.19</td>
<td>408.51</td>
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<td>74.69</td>
<td>45</td>
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<td>4265</td>
<td>4964.13</td>
<td>2521.71</td>
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<td>127.43</td>
<td>40.27</td>
<td>78.73</td>
<td>3247.75</td>
<td>4964.13</td>
<td>1751.63</td>
<td>2435.81</td>
</tr>
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</table>

4.3. Results of economic evaluation

We calculated equipment capital cost with equations 9 and 10 and figure 6 and an annual investment of working fluid, annual net real energy product and annual net real saving of...
energy product. The results are presented in table 12. Cash flow diagrams are presented in figures 14 to 20 for lines and SPP, NPV and IRR presented in table 13.

Figure 14. Cash flow diagram of first line of north unit

Figure 15. Cash flow diagram of second line of north unit with preheater

Figure 16. Cash flow diagram of second line of north unit with mixer and splitter

Figure 17. Cash flow diagram of south unit line

Figure 18. Cash flow diagram of first line of Isomerization unit
Figure 19. Cash flow diagram of second line of Isomerization unit with preheater

Figure 20. Cash flow diagram of second line of Isomerization unit with mixer and splitter

Table 12. Annual investment of working fluid, annual net real saving of energy product and equipment capital cost of simulated lines

<table>
<thead>
<tr>
<th>Num</th>
<th>Unit</th>
<th>Annual maintenance capital cost ($)</th>
<th>Annual investment of working fluid ($)</th>
<th>Annual fuel cost of preheater ($)</th>
<th>Annual net real energy product (kWh)</th>
<th>Annual net real saving of energy product ($)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1N</td>
<td>500</td>
<td>2309486.4</td>
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<td>2844372</td>
<td>412433.94</td>
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<tr>
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<td>2771383.68</td>
<td>68223.66</td>
<td>5467992</td>
<td>792858.84</td>
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<td>-</td>
<td>2857512</td>
<td>414339.24</td>
</tr>
<tr>
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<td>South</td>
<td>500</td>
<td>1539657.6</td>
<td>-</td>
<td>1896540</td>
<td>274998.3</td>
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<tr>
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<td>500</td>
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<td>-</td>
<td>5687868</td>
<td>824740.86</td>
</tr>
<tr>
<td>6</td>
<td>2ISO with Preheater</td>
<td>500</td>
<td>692845.92</td>
<td>238655.4135</td>
<td>27923376</td>
<td>4048889.52</td>
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<tr>
<td>7</td>
<td>2ISO with Mixer Splitter</td>
<td>500</td>
<td>692845.92</td>
<td>-</td>
<td>213377.5</td>
<td>3093969.038</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Num</th>
<th>Unit</th>
<th>Annual net real saving ($)</th>
<th>Turboexpander capital cost ($)</th>
<th>Gas fired preheater capital cost ($)</th>
<th>Generator capital cost ($)</th>
<th>Capital cost of project ($)</th>
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<td>65675</td>
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<td>232080</td>
<td>297755</td>
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<td>724135.17</td>
<td>111523</td>
<td>109538</td>
<td>247167</td>
<td>468228</td>
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<td>65748</td>
<td>-</td>
<td>232104</td>
<td>297852</td>
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<td>29399</td>
<td>-</td>
<td>225794</td>
<td>255193</td>
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<td>824240.86</td>
<td>71580</td>
<td>-</td>
<td>248332</td>
<td>319912</td>
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<td>3809734.107</td>
<td>417781.6</td>
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<td>335040.1</td>
<td>21337717.5</td>
<td>315292.8</td>
<td>650333</td>
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5. Discussion

5.1. Turbo expanders power production validation

We compared our results of turbo expander power production with Figure 21 that shows power production potential at various levels of steam pressure reduction [12]. Figure 21 shows lines of constant power output (expressed in kW of electrical output per 1,000 pounds per hour of steam throughput) as a function of turbine inlet and exhaust pressures. We specified results pressure reduction points of 5 units of Tehran refinery that are simulated in this project on Figure 21 for comparison of our simulation results. The results are shown on tables 14 and 15.

Table 13. SPP, NPV and IRR of simulated lines

<table>
<thead>
<tr>
<th>Num</th>
<th>Line</th>
<th>Capital cost of project ($)</th>
<th>SPP (year)</th>
<th>NPV ($)</th>
<th>IRR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>297755</td>
<td>0.7228</td>
<td>1452549.145</td>
<td>98.62</td>
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<tr>
<td>2</td>
<td>2N with Preheater</td>
<td>468228</td>
<td>0.6466</td>
<td>2608616.793</td>
<td>112.211</td>
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<tr>
<td>3</td>
<td>2N with Mixer Splitter</td>
<td>297852</td>
<td>0.7197</td>
<td>1460547.75</td>
<td>99.1176</td>
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<tr>
<td>4</td>
<td>South</td>
<td>255193</td>
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<td>72.969</td>
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<td>0.388</td>
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<td>198.038</td>
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<td>1108811.1</td>
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<td>15078719.8</td>
<td>269.656</td>
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<tr>
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<td>2ISO with Mixer Splitter</td>
<td>650333</td>
<td>0.21023</td>
<td>12493793.2</td>
<td>379.729</td>
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Table 14. Approximate turbo expander power production potential prediction of US Dept. of Energy

<table>
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<tr>
<th>Num</th>
<th>Unit</th>
<th>$\eta_{\text{law, Tur}}$ (%)</th>
<th>$\eta_{\text{law, Gen}}$ (%)</th>
<th>$P_{\text{Tur}}$ (KW)</th>
<th>$\eta_{\text{law, line}}$ (%)</th>
<th>$\eta_{\text{law, Energy}}$ (KW)</th>
<th>$P_{\text{Gen with } \eta=75%}$ (KW)</th>
<th>$P_{\text{Turb}}$ (KW)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1N</td>
<td>76.07</td>
<td>75</td>
<td>434.4</td>
<td>57.05</td>
<td>48</td>
<td>324.7</td>
<td>231.483</td>
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<tr>
<td>2</td>
<td>2N with Preheater</td>
<td>63.39</td>
<td>75</td>
<td>835.2</td>
<td>47.54</td>
<td>48</td>
<td>624.2</td>
<td>595.242</td>
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<tr>
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<td>2N with Mixer Splitter</td>
<td>63.16</td>
<td>75</td>
<td>434.99</td>
<td>47.37</td>
<td>48</td>
<td>326.2</td>
<td>277.339</td>
</tr>
<tr>
<td>4</td>
<td>South</td>
<td>76.06</td>
<td>75</td>
<td>289.6</td>
<td>57.045</td>
<td>48</td>
<td>216.5</td>
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<td>75</td>
<td>868.8</td>
<td>57.05</td>
<td>48</td>
<td>649.3</td>
<td>462.966</td>
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<tr>
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<td>79.2</td>
<td>75</td>
<td>4265</td>
<td>59.4</td>
<td>48</td>
<td>3187.6</td>
<td>2083.347</td>
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<tr>
<td>7</td>
<td>2ISO with Mixer Splitter</td>
<td>78.73</td>
<td>75</td>
<td>3247.75</td>
<td>59.047</td>
<td>48</td>
<td>2435.81</td>
<td>1509.247</td>
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Table 15. Comparison results of Thermoflex turbo expander power production simulation with turbo expander power production prediction of US Dept. of Energy.

<table>
<thead>
<tr>
<th>$P_0/P_o$</th>
<th>Electrical Power Generation ($KW/\text{Mb} - \text{hr}$)</th>
<th>Electrical Power Generation ($KW/1\text{ton} / \text{hr}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>614.69/314.69</td>
<td>7</td>
<td>15.4322</td>
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<tr>
<td>614.69/127.43</td>
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<td>37.4782</td>
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<td>214.69/74.69</td>
<td>21</td>
<td>46.2966</td>
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<td>314.69/125.89</td>
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<td>22.046</td>
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<tr>
<td>314.69/74.69</td>
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<td>33.069</td>
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</table>

In order to better compare, we plotted our results of turbo expander power production of Thermoflex simulation and turbo expander power production prediction of US Dept. of Energy on Figure 22. As Figure 22 shows, the results are almost the same between points 1 to 5. For points 6 and 7 the results are rather different which is due to different turbo expander and generator first law efficiency and the mass flow rate of these two points.
6. Conclusion

The values of SPP for all simulated lines are less than one year, and the IRR for all of them are significant. So, investment on all lines for turbo expander installation is recommended. Also for lines with two options (second line of North Water, Electricity and Steam unit and second line of Isomerization unit), higher IRR has a more significant role on investment. For the second line of North Water, Electricity, and Steam unit, investment on the addition of turbo expander and preheater and for the second line of Isomerization unit, investment on the addition of turbo expander and mixer splitter is the optimal alternatives.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>PRV</td>
<td>Pressure Reduction Valve</td>
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<tr>
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<td>High Pressure</td>
</tr>
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</tr>
<tr>
<td>LP</td>
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</tr>
<tr>
<td>I</td>
<td>Rate of Irreversibility</td>
</tr>
<tr>
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<td>Mass Flow Rate</td>
</tr>
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<td>Outlet Stream Availability</td>
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<td>Multiplication η_1law_tur and η_1law_gen of US Dept. of Energy Power Prediction Plot</td>
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<td>Capital Cost of Gas Fired Preheater</td>
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<td>Second Line of Isomerization unit</td>
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References


To whom correspondence should be addressed: MSC Amir Ashoori Barmchi, Department of Energy Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran, a.ashoori@srbiau.ac.ir