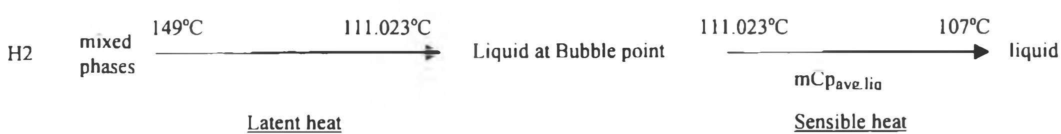
# CHAPTER IV
# RESULTS AND DISCUSSION

## 4.1 Design Case

### 4.1.1 The Collected Data and Heat Exchanger and Stream Data Modeling

After the heat exchangers and streams were simulated to check the phase change temperature (dew point and bubble point) and the enthalpy change from sensible heat and latent heat. The result from the simulation of ProII and the calculation of latent heat are shown in Table 4.1. In this study, 29 hot and 21 cold streams were selected. The location and information of each stream are described in Appendix A-1.

The example of calculation of latent heat for stream H2 is shown below: (note that the phase changes occur in stream from mixed phases to liquid at the bubble point temperature).




Latent heat = total heat – sensible heat (assume that there is no heat loss)

= overall duty of heat exchanger 100-E1 and 100-EA2

$-mCp_{avg,liq}(T_{bubble} - T_{out})$

$= 8.95 \times 10^3 - (132.558\ MW/^{o}C) \times (111.023-107)^{o}C$

= 23.227 MW

The heat exchanger network design or modification is usually done on grid diagram because of its simplicity. For the design case of existing plant, the grid diagram can be constructed by using the above data as shown in Figure 4.1.

**Table 4.1** The result from design case simulation of Pro II and calculation of latent heat (hot streams)

| stream | stream in | | stream out | | phase | $T_{dew}$ | $T_{bubble}$ | flowrate | Cp in | Cp out | Cp avg | mCp | Tin | Tout | Temp change for sensible heat | total duty | sensible heat | atent heat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | name | phase | name | phase | change | C | C | kg/hr | kWhr/kgC | kWhr/kgC | kWhr/kgC | kW/C | C | C | (C) | MW | MW | MW |
| H1 | 346 | liq | 351 | liq | ✗ | - | - | 71144 | 0.00086 | 0.00061 | 0.00074 | 52.44 | 239 | 49 | 239-49 | 8.95 | - | - |
| H2 | 306 | mixed | 310 | liq | ✓ | - | 111 | 220951 | 0.00057 | 0.00063 | 0.00060 | 132.56 | 149 | 107 | 111.022-107 | 23.76 | 0.533 | 23.227 |
| H3 | 540 | liq | 544 | liq | ✗ | - | - | 19333 | 0.00117 | 0.00073 | 0.00095 | 18.34 | 109.00 | 38.00 | 109-38 | 1.19 | - | - |
| H4 | 606 | vapor | 604 | mixed | ✓ | 60.89 | - | 3566 | 0.00069 | 0.00089 | 0.00079 | 2.81 | 64 | 40 | 64-60.887 | 0.23 | 0.009 | 0.221 |
| H5 | 605 | mixed | 525 | mixed | ✓ | - | - | 792 | 0.00067 | 0.00082 | 0.00075 | 0.59 | 38 | 23 | - | 0.04 | - | 0.040 |
| H6 | 511 | liq | 565 | liq | ✗ | - | - | 35173 | 0.00079 | 0.00063 | 0.00071 | 24.88 | 116 | 38 | 116-38 | 1.98 | - | - |
| H7 | 499 | vapor | 498 | mixed | ✓ | 53.93 | - | 45847 | 0.00056 | 0.00079 | 0.00068 | 31.06 | 56 | 47 | 56-53.925 | 4.31 | 0.064 | 4.246 |
| H8 | 006 | | 008 | | ✗ | - | - | 242137 | 0.00084 | 0.00061 | 0.00072 | 175.31 | 220 | 60 | 220-60 | 27.07 | - | - |
| H9 | 131 | vapor | 132 | mixed | ✓ | 276.7 | - | 148267 | 0.00081 | 0.00068 | 0.00074 | 110.31 | 343 | 131 | 343-276.642 | 32.22 | 7.317 | 24.903 |
| H10 | 136 | mixed | 137 | mixed | ✓ | - | - | 153252 | 0.00067 | 0.00059 | 0.00063 | 96.04 | 121 | 49 | - | 8.04 | - | 8.040 |
| H11 | 307 | vapor | 309 | mixed | ✓ | 51.45 | - | 21174 | 0.00093 | 0.00083 | 0.00088 | 18.67 | 162 | 50 | 162-51.449 | 3.21 | 2.064 | 1.146 |
| H12 | 341 | liq | 399 | liq | ✗ | - | - | 146465 | 0.00084 | 0.00064 | 0.00074 | 108.10 | 222 | 109 | 222-109 | 14.45 | - | - |
| H13 | 194 | vapor | 195 | vapor | ✗ | - | - | 208.9 | 0.00097 | 0.00072 | 0.00085 | 0.18 | 524 | 180 | 524-179.9 | 0.06 | - | - |
| H14 | 167 | mixed | 181 | mixed | ✓ | - | - | 176380 | 0.00069 | 0.00090 | 0.00080 | 140.33 | 103.2 | 48.5 | - | 15.07 | - | 15.070 |
| H15 | 1204 | vapor | 1212 | mixed | ✓ | 61.71 | - | 22648 | 0.00134 | 0.00128 | 0.00131 | 29.71 | 132.9 | 55 | 132.9-61.71 | 2.32 | 2.115 | 0.205 |
| H16 | 1122 | vapor | 1123 | mixed | ✓ | 63.57 | - | 4080 | 0.00105 | 0.00128 | 0.00116 | 4.75 | 111.8 | 8 | 111.8-63.567 | 0.60 | 0.229 | 0.371 |
| H17 | 1164 | mixed | 1165 | mixed | ✓ | - | - | 153530 | 0.00095 | 0.00098 | 0.00096 | 147.52 | 46.86 | 37.9 | - | 1.09 | - | 1.087 |
| H18 | 1214 | mixed | 1215 | mixed | ✓ | - | - | 137680 | 0.00118 | 0.00126 | 0.00122 | 168.15 | 56.19 | 37.8 | - | 1.87 | - | 1.873 |
| H19 | 1254 | vapor | 1265 | mixed | ✓ | 44.58 | - | 2519 | 0.00168 | 0.00167 | 0.00168 | 4.22 | 59.54 | 37.8 | 59.54-44.584 | 0.09 | 0.063 | 0.029 |
| H20 | 1474 | liq | 1469 | liq | ✗ | - | - | 126970 | 0.00075 | 0.00059 | 0.00067 | 85.09 | 211.7 | 103 | 211.7-103.4 | 9.77 | - | - |
| H21 | 1406 | vapor | 1409 | mixed | ✓ | 65.2 | - | 27055 | 0.00058 | 0.00075 | 0.00067 | 18.02 | 66.75 | 38.3 | 66.75-65.202 | 2.67 | 0.028 | 2.642 |
| H22 | 1411 | vapor | - | mixed | ✓ | 37.32 | - | 985.8 | 0.00056 | 0.00065 | 0.00061 | 0.60 | 37.78 | 8 | 37.78-37.323 | 0.08 | 0.000 | 0.080 |
| H23 | - | - | - | - | ✗ | - | - | 60062 | 0.00127 | 0.00126 | 0.00127 | 76.00 | 40 | 38 | 40-38 | 0.15 | - | - |
| H24 | - | - | - | - | ✗ | - | - | 2750.4 | 0.00119 | 0.00111 | 0.00115 | 3.16 | 135 | 55 | 135-55 | 0.25 | - | - |
| H25 | - | - | - | - | ✗ | - | - | 525.6 | 0.00125 | 0.00103 | 0.00114 | 0.60 | 295 | 66 | 295-66 | 0.14 | - | - |
| H26 | - | - | - | - | ✗ | - | - | 309.6 | 0.00152 | 0.00124 | 0.00138 | 0.43 | 477 | 66 | 477-66 | 0.18 | - | - |
| H27 | - | vapor | - | vapor | ✗ | - | - | 34157 | 0.00032 | 0.00032 | 0.00032 | 10.94 | 517 | 482 | 517-482 | 0.38 | - | - |
| H28 | 1154 | vapor | 1162 | mixed | ✓ | 69.39 | - | 29600 | 0.00012 | 0.00111 | 0.00061 | 18.20 | 131 | 56.1 | 131-69.391 | 2.65 | 1.121 | 1.529 |
| H29 | 170 | vapor | 173 | liq | ✓ | 94.27 | 68.66 | 113987 | 0.00058 | 0.00070 | 0.00064 | 72.70 | 97 | 52 | 97-94.268<br>69.391-52 | 13.11 | 1.463 | 11.647 |

**Table 4.1** (Continued) The result from design case simulation of Pro II and calculation of latent heat (cold streams)

| stream | stream in | | stream out | | phase change | $T_{dew}$ C | $T_{bubble}$ C | flowrate kg/hr | Cp in kWhr/kgC | Cp out kWhr/kgC | Cp avg kWhr/kgC | mCp kW/C | Tin C | Tout C | Temp change for sensible heat (C) | total duty MW | sensible heat MW | latent heat MW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | name | phase | name | phase | | | | | | | | | | | | | | |
| C1 | 131 | liq | 138 | mixed | ✓ | - | 192.3 | 160237 | 0.00077 | 0.00074 | 0.00076 | 121.11 | 188 | 201 | 188-192.322 | 16.40 | 0.523 | 15.877 |
| C2 | 103 | liq | 110 | liq | ✗ | - | - | 265176 | 0.00057 | 0.00072 | 0.00065 | 172.10 | 38 | 143 | 38-143 | 18.18 | - | - |
| C3 | 517 | liq | 513 | liq | ✗ | - | - | 19690 | 0.00074 | 0.00086 | 0.00080 | 15.80 | 43 | 78 | 43-78 | 0.54 | - | - |
| C4 | 525 | vapor | 527 | vapor | ✗ | - | - | 357 | 0.00066 | 0.00052 | 0.00059 | 0.21 | 24 | 42 | 24-42 | 0.00 | | - |
| C5 | 302 | liq | 305 | liq | ✗ | - | - | 49679 | 0.00070 | 0.00075 | 0.00073 | 36.02 | 52 | 76 | 52-76 | 0.86 | - | - |
| C6 | 507 | liq | 508 | mixed | ✓ | - | 116 | 207949 | 0.00079 | 0.00074 | 0.00076 | 158.75 | 116 | 118 | 116-116.008 | 5.49 | 0.001 | 5.489 |
| C7 | - | - | - | - | ✗ | - | - | 242137 | 0.00076 | 0.00084 | 0.00080 | 193.95 | 184.5 | 220 | 184.5-220 | 8.24 | - | - |
| C9 | - | - | 002 | - | ✗ | - | - | 241836 | 0.00055 | 0.00076 | 0.00066 | 158.84 | 36.8 | 189 | 36.8-188.7 | 24.17 | - | - |
| C10 | 112 | liq | 115 | vapor | ✓ | 289 | 263.5 | 148267 | 0.00058 | 0.00082 | 0.00070 | 103.80 | 63 | 339 | 63-263.482<br>288.984-339 | 38.73 | 20.80978<br>5.191599 | 12.729 |
| C11 | 151 | mixed | 306 | mixed | ✓ | - | - | 146965 | 0.00057 | 0.00072 | 0.00064 | 94.38 | 49 | 157 | - | 10.30 | - | 10.300 |
| C12 | 334 | liq | 338 | mixed | ✓ | - | 222 | 261020 | 0.00084 | 0.00073 | 0.00078 | 204.64 | 222 | 230 | - | 6.60 | - | 6.600 |
| C13 | 190 | vapor | 193 | vapor | ✗ | - | - | 263.6 | 0.00105 | 0.00123 | 0.00114 | 0.30 | 111.8 | 316 | 111.8-315.6 | 0.06 | - | - |
| C14 | 1720 | liq | 1405-<br>1420 | liq | ✗ | - | - | 23928 | 0.00067 | 0.00080 | 0.00073 | 17.57 | 86 | 162 | 86-162 | 1.33 | - | - |
| C15 | 1438 | liq | 1420 | liq | ✗ | - | - | 131800 | 0.00050 | 0.00065 | 0.00058 | 76.02 | 37 | 154 | 37-154.1 | 9.77 | - | - |
| C16 | 1449 | liq | 1451 | mixed | ✓ | - | 213.7 | 144620 | 0.00075 | 0.00066 | 0.00070 | 101.70 | 211.7 | 228 | 211.7-213.715 | 7.37 | 0.205 | 7.165 |
| C17 | - | - | - | - | ✗ | - | - | n/a | n/a | n/a | n/a | n/a | 38 | 149 | 38-149 | 9.78 | - | - |
| C18 | - | - | - | - | ✗ | - | - | n/a | n/a | n/a | n/a | n/a | 38 | 149 | 38-149 | 0.08 | - | - |
| C19 | - | vapor | - | vapor | ✗ | - | - | 679.68 | 0.00030 | 0.00031 | 0.00031 | 0.21 | 420 | 539 | 420-539 | 0.03 | - | - |
| C20 | - | vapor | - | vapor | ✗ | - | - | 34155 | 0.00032 | 0.00032 | 0.00032 | 10.86 | 452 | 482 | 452-482 | 0.32 | - | - |
| C21 | - | vapor | - | vapor | ✗ | - | - | 1336.7 | 0.00028 | 0.00031 | 0.00029 | 0.39 | 38 | 577 | 38-577 | 0.21 | - | - |
| C22 | - | - | - | - | ✗ | - | - | 244.8 | n/a | n/a | n/a | 0.40 | 38 | 570 | 38-570 | 0.21 | - | - |

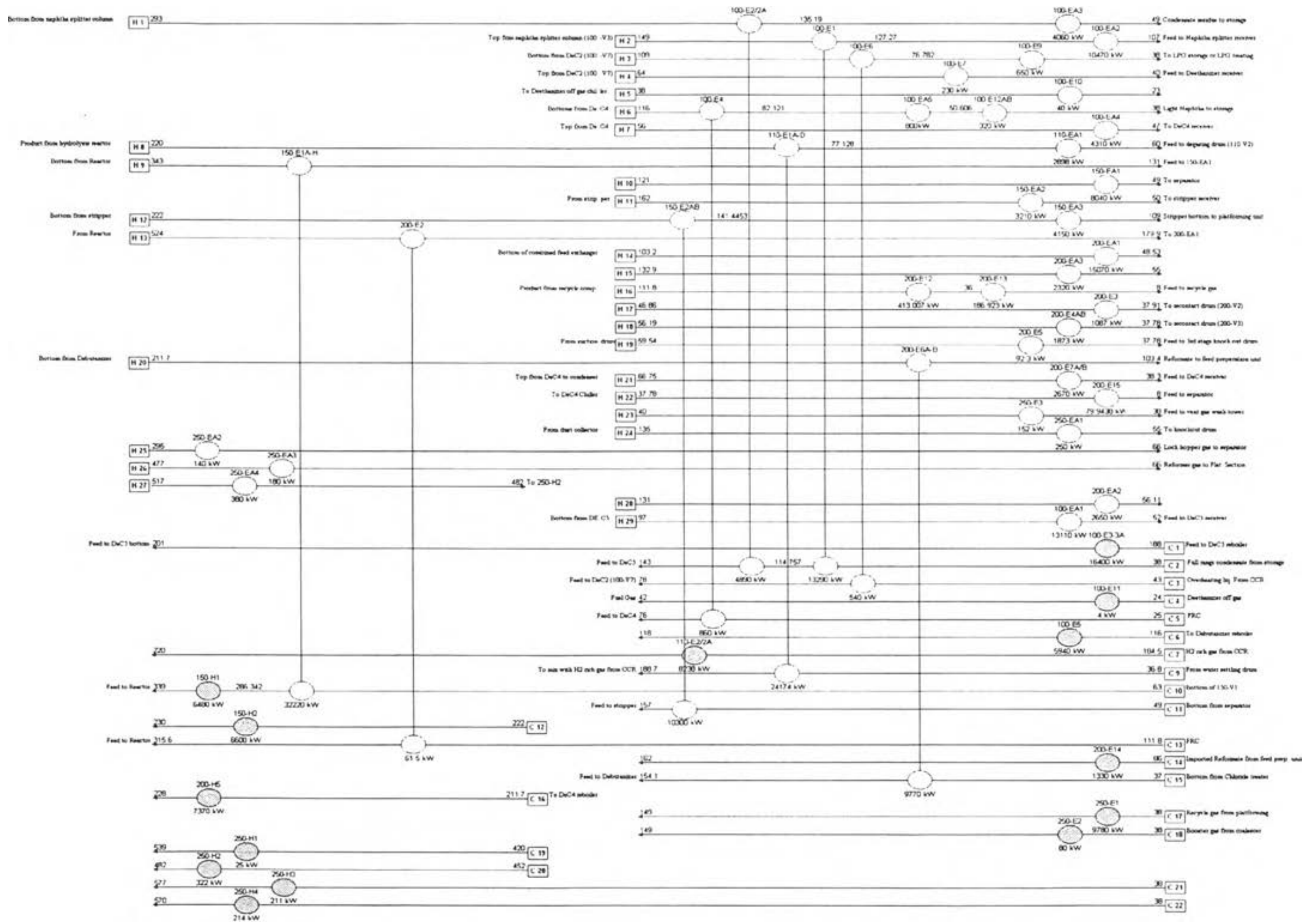


**Figure 4.1** Grid diagram for design case of existing plant.

### 4.1.2 Energy Target

The problem table analysis and grand composite curves at any minimum approach temperatures had been done as in the procedure in section 3.4. The data extracted from grand composite curve will give the minimum utility requirement which results in minimum total cost and minimum heat exchanger capital investment cost at any $\Delta T_{min}$. The Problem Table Algorithm for various $\Delta T_{min}$ is shown in Appendix B and the result of PTA is shown in Table 4.2.

**Table 4.2** Result of PTA at various $\Delta T_{min}$

| $\Delta T_{min}$ C | $Q_{Hmin}$ MW | $Q_{Cmin}$ MW | pinch C |
|---|---|---|---|
| 5 | 30.507 | 47.712 | 197.322 |
| 10 | 33.54 | 50.751 | 202.322 |
| 20 | 39.55 | 56.741 | 212.322 |
| 30 | 44.578 | 61.789 | 220.000 |
| 40 | 48.918 | 66.123 | 222.000 |
| 70 | 64.9376 | 82.243 | 149.000 |

The design case of existing plant uses 57.055 MW of hot utility and 74.36 MW of cold utility in the process. These values of both utilities tell that $\Delta T_{min}$ of the process is 58.91 °C. The $\Delta T_{min}$ of this process when comparing with the similar process in many literatures which is about 10-20 °C (Linnhoff, 1998) is very high. This can be conclude that the utility usage in the process is too high and can be reduced by recovering process to process energy.

### 4.1.3 Area Target

After the utility demand for global $\Delta T_{min}$ is carried out, the area requirement which is less than the existing one ($\Delta T_{min}$<$\Delta T_{min,existing}$) is required for doing retrofit. In retrofits, these plots only consider heat recovery area, i.e., process-to-process exchangers. The area of heat transfer with utilities is not considered.

The surface area of over all and each of existing heat exchanger is shown in Table 4.3. The hot and cold composite curves for calculating minimum area at various $\Delta T_{min}$ are shown in Figure 4.2. The procedure to construct the curves as in section 3.5 is shown in Appendix C-1.The result from this analysis is in Table 4.4.

**Table 4.3** Surface area of existing heat exchanger in the process

| HEX | Stream | surface area $m^2$ |
|---|---|---|
| 100-E1 | H2 | 661 |
| | C2 | |
| 100-E2/2A | H1 | 202.700 |
| | C2 | |
| 100-E4 | H6 | 76.700 |
| | C5 | |
| 100-E6 | H3 | 32.700 |
| | C3 | |
| 110-E1A-D | H8 | 2768.000 |
| | C9 | |
| 150-E1A-H | H9 | 1944.000 |
| | C10 | |
| 150-E2AB | H12 | 231.600 |
| | C11 | |
| 200-E2 | H13 | 6.977 |
| | C13 | |
| 200-E6A/B | H20 | 265.400 |
| | C15 | |
| | total area | 6189.077 $m^2$ |

**Table 4.4** Result from targeting area at various $\Delta T_{min}$

| $\Delta$Tmin C | $A_{ideal}$ $m^2$ |
|---|---|
| 5 | 11197.47 |
| 10 | 8711.433 |
| 20 | 6147.266 |
| 30 | 4891.984 |
| 40 | 4120.343 |
| 58.915 (existing case) | 2700.348 |

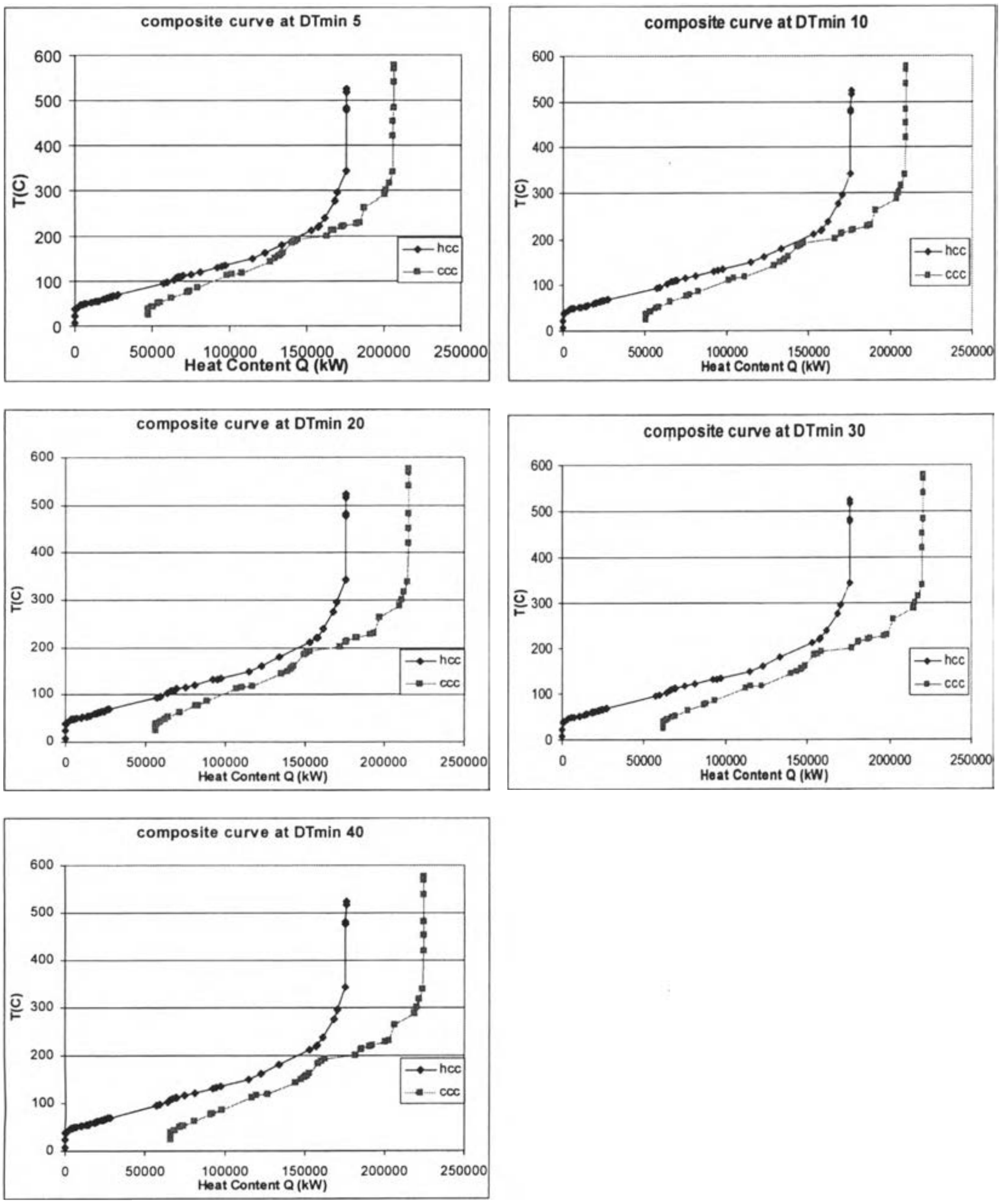



**Figure 4.2** Hot and cold composite curves at various $\Delta T_{min}$.

4.1.4 Setting Retrofit Targets

First, the area efficiency of the existing network is calculated and a path for retrofitting is established on an area-energy plot. Next, the area energy plot is converted to an investment-savings plot and the payback period line used to determine the target $\Delta T_{min}$.

Step1. Calculation of Area Targets for Various Energy Levels and Area Efficiency of Existing network

The existing HEN has an area efficiency of 0.436309, where the existing area ($A_{existing}$) and target area ($A_{ideal}$) for the existing energy recovery are 6187.01 and 2700.35 $m^2$ respectively.

Step 2. Calculation of the Retrofit Curve

The utility demands and area requirement for each global $\Delta T_{min}$ which were calculated in section 4.1.2 and 4.1.3 are concluded in Table 4.5 and the area-energy plot is shown in Figure 4.3.

**Table 4.5** Area-energy data for various $\Delta T_{min}$

| ΔTmin C | $Q_{cu,min}$ kW | $Q_{hu,min}$ kW | $A_{ideal}$ m2 | $A_{max,retr}$ $\Delta\alpha=1$ | $A_{max,retr}$ $\Delta\alpha=0.4365$ |
|---|---|---|---|---|---|
| 5 | 47712.2 | 30506.92 | 11197.47 | 14686.2 | 25664.102 |
| 10 | 50751.4 | 33539.8 | 8711.4331 | 12200.16 | 19966.216 |
| 20 | 56741.3 | 39549.44 | 6147.2659 | 9635.995 | 14089.259 |
| 30 | 61788.9 | 44577.71 | 4891.9839 | 8380.713 | 11212.209 |
| 40 | 66123.8 | 48666 | 4120.343 | 7609.072 | 9443.6421 |
| 58.915 | 78926.9 | 57055.27 | 2700.348 | 6189.077 | 6189.077 |

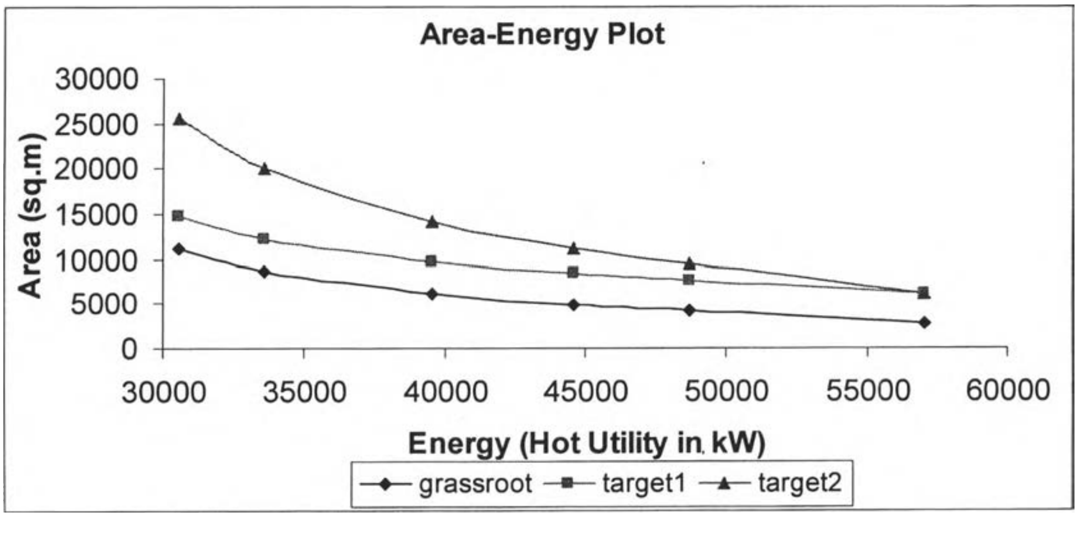



**Figure 4.3** Retrofit curve on area-energy plot.

Step3. Calculation of Energy Savings and Extra Area Required

Before calculating of the energy saving, the utility usage for multiple utility levels is required and Problem Table Analysis will be very useful in this step as shown in Appendix D-1. The data of target utility usage for various $\Delta T_{min}$ was concluded in the Table 4.6 where

| Annual utilities cost in $/(kWyr) for : | | |
|---|---|---|
| | Medium Pressure Steam | 207.62527 |
| | High Pressure Steam | 214.50967 |
| | Refrigerant | 0 |
| | Power | 415.278 |
| | Cooling Water | 21.04 |
| | Air | 0 |
| | Low Pressure Steam | 200 |

**Table 4.6** Data of target utility usage for multiple utilities

| utility i | Current uility usage | | Target utility required | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ΔTmin=5 | | ΔTmin=10 | | ΔTmin=20 | | ΔTmin=30 | | ΔTmin=40 | |
| | in kW | in $ | in kW | in $ | in kW | in $ | in kW | in $ | in kW | in $ | in kW | in $ |
| MP | 11190.0 | 2323326.8 | | | | | | | | | | |
| HP | 24638.0 | 5285089.2 | 30444.2 | 6530586 | 33474.0 | 7180506.1 | 39477.5 | 8468310.5 | 44499.6 | 9545598.4 | 48581.7 | 10421244.4 |
| RE | 306.9 | 0.0 | 308.0 | 0.0 | 1994.5 | 0.0 | 10877.0 | 0.0 | 20655.8 | 0.0 | 25510.6 | 0.0 |
| POWER | 21222.0 | 8813029.7 | 50.9 | 21138.3 | 54.9 | 22786.4 | 62.8 | 26082.6 | 70.7 | 29378.7 | 78.7 | 32672.1 |
| CW | 7487.4 | 157534.4 | 1300.5 | 27363.4 | 1539.4 | 32389.7 | 4434.9 | 93311.2 | 3895.9 | 81969.7 | 4701.2 | 98913.3 |
| AIR | 78638.0 | 0.0 | 46103.7 | 0.0 | 47217.4 | 0.0 | 41429.4 | 0.0 | 37237.2 | 0.0 | 35759.6 | 0.0 |
| LP | 5944.0 | 1188800.0 | | | | | | | | | | |
| total | | 17767780.1 | | 6579087 | | 7235682.2 | | 8587704.2 | | 9656946.8 | | 10552829.8 |

Step4. Economic Analysis of Investment vs. Savings

The calculated data for energy saving cost and investment cost is in Table 4.7. The investment-saving plot is in Figure 4.4.

**Table 4.7** Calculated data for energy saving cost and investment cost

| ΔTmin | Energy Savings | Extra Area $\Delta\alpha=1$ | Extra Area $\Delta\alpha=0.4365$ | Savings | ΔN $\Delta\alpha=1$ | ΔN $\Delta\alpha=0.4365$ | Investment $\Delta\alpha=1$ | Investment $\Delta\alpha=0.4365$ | payback |
|---|---|---|---|---|---|---|---|---|---|
| C | kW | m2 | m2 | k$/yr | | | k$ | k$ | yr |
| 5 | 26548.4 | 8497.12 | 19475.03 | 11188.693 | 36 | 82 | 1203.752 | 2741.872 | 0.245 |
| 10 | 23515.5 | 6011.09 | 13777.14 | 10532.098 | 26 | 58 | 869.383 | 1939.373 | 0.184 |
| 20 | 17505.8 | 3446.92 | 7900.18 | 9180.076 | 15 | 33 | 501.568 | 1103.433 | 0.120 |
| 30 | 12477.6 | 2191.64 | 5023.13 | 8110.833 | 10 | 21 | 334.385 | 702.185 | 0.087 |
| 40 | 8389.3 | 1419.99 | 3254.57 | 7214.950 | 6 | 14 | 200.625 | 468.128 | 0.065 |

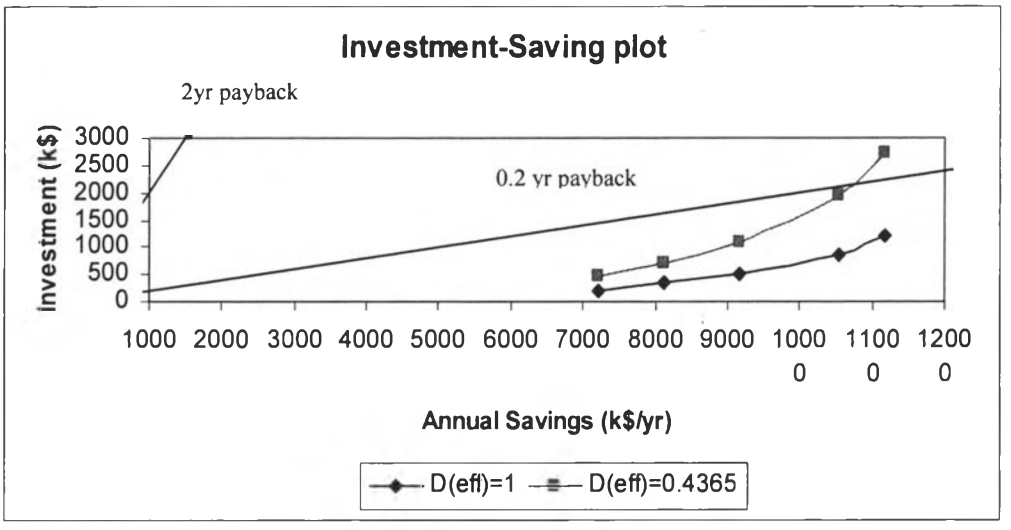



**Figure 4.4** Investment-saving plot.

Step5. Identification of Target $\Delta T_{min}$

Based on the specified payback period (2 years), the required target is the point where the investment is twice the savings. But from the table above at any $\Delta T_{min}$ , payback period is less than 2 years. Therefore, the payback period is now chosen to be 0.2 year which correspond to $\Delta T_{min}$ =10 °C.

### 4.1.5 Design Procedure

The potentials for energy savings in the retrofit project have been identified at the targeting stage. The design procedure will be as in section 3.6. The existing network is analysed where it violates the set targets, by determining the heat exchanger units transferring heat across pinch and having inappropriate utility placement. The grid for existing network (using $\Delta T_{min}$ identified in the targeting stage) was shown in the Figure 4.5 and the heat exchangers crossing the pinch are reported in Table 4.8.

**Table 4.8** Heat exchangers, heaters and coolers which transfer heat across the Pinch

| HEX | Hot stream | Cold stream | Heat load (kW) |
|---|---|---|---|
| 100-E2/2A | H1 | C2 | 4890 |
| 110-E1A-D | H8 | C9 | 24174 |
| 150-E1A-H | H9 | C10 | 32220 |
| 150-E2AB | H12 | C11 | 10300 |
| 200-E2 | H13 | C13 | 61.5 |
| 200-E6A-B | H20 | C15 | 9770 |
| 100-E3-3A | C1 | HP | 16400 |
| 100-E11 | C4 | LP | 4 |
| 100-E5 | C6 | LP | 5940 |
| 110-E2/2A | C7 | HP | 8238 |
| 200-E14 | C14 | MP | 1330 |
| 250-EA4 | H27 | AIR | 380 |
| 250-EA3 | H26 | AIR | 180 |
| 250-EA2 | H25 | AIR | 140 |
| 250-E1 | C17 | MP | 9780 |
| 250-H3 | C21 | POWER | 211 |
| 250-H4 | C22 | POWER | 214 |
| 250-E2 | C18 | MP | 80 |

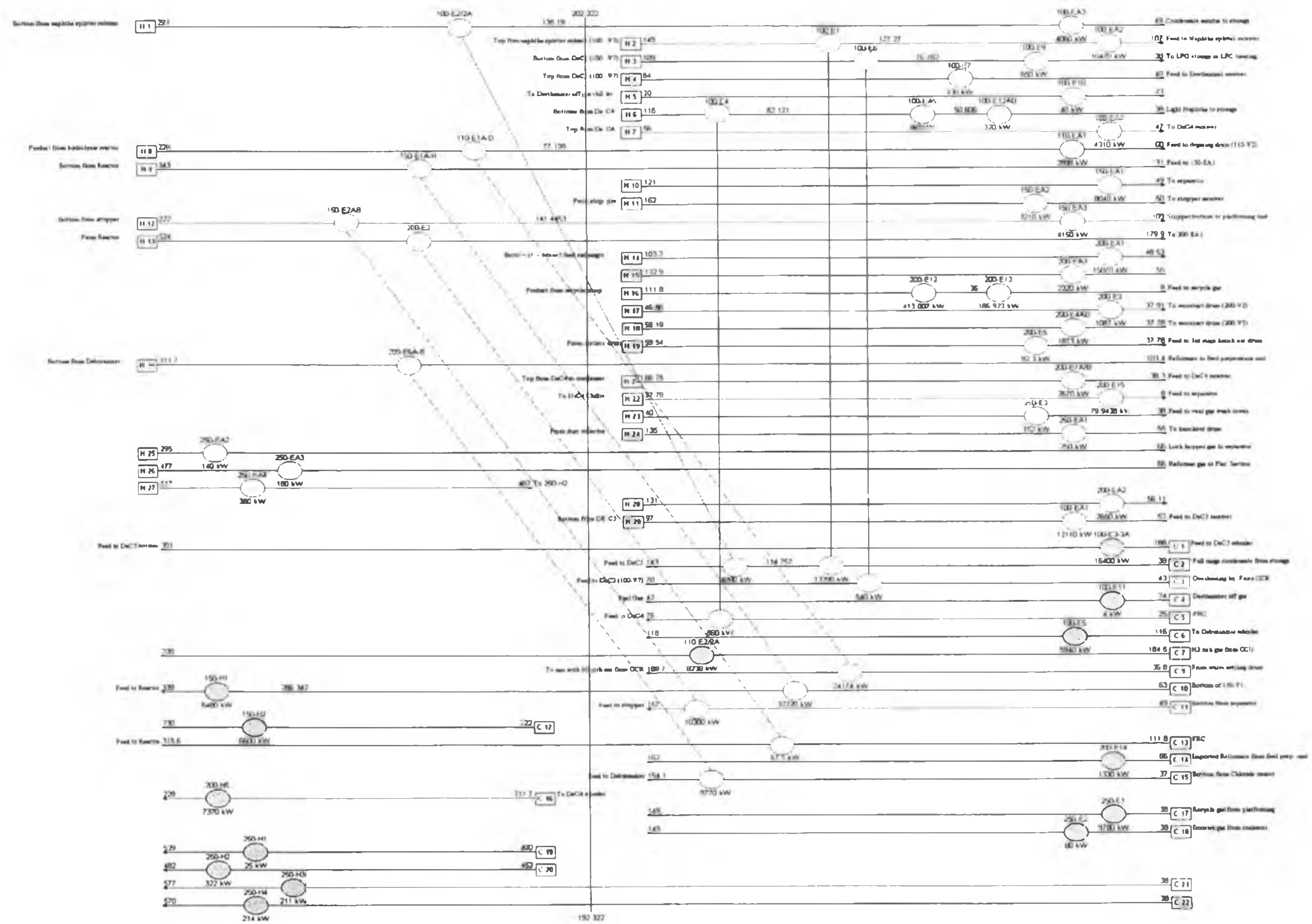


**Figure 4.5** Grid diagram of existing plant with pinch temperature.

Then the cross pinch exchangers were eliminated and the network was completed with the new and reused exchangers. However the network compatibility can be improved via heat-load loops and paths. After evolving this improvement to reuse area of existing exchangers as much as possible, the results are shown in Figures 4.6 and 4.7 as alternative design 1 and 2, respectively. The detailed costing for both alternatives is shown below

*4.1.5.1 Design Option A*

Tables 4.9 and 4.10 show the calculation of investment cost of existing exchangers with new area and new exchangers, respectively. The utility saving calculation is shown in Table 4.11.

**Table 4.9** Calculation of investment cost of existing exchangers with extra area for Design option A

| HEX | U<br>kW/m$^{2o}$C | Old Area<br>m$^2$ | New Area<br>m$^2$ | Extra Area<br>m$^2$ | Investment<br>$10^3$ \$ |
|---|---|---|---|---|---|
| 100-E2/2A | 0.516 | 194.11 | 194.22 | 0.00 | 0.000 |
| 100-E1 | 0.473 | 489.67 | 665.22 | 175.54 | 86.950 |
| 100-E6 | 0.565 | 29.55 | 29.55 | 0.00 | 0.000 |
| 100-E4 | 0.619 | 39.92 | 39.92 | 0.00 | 0.000 |
| 110-E1A-D | 0.303 | 2238.11 | 4476.97 | 2238.86 | 454.290 |
| 150-E1A-H | 0.412 | 1258.17 | 1853.55 | 595.38 | 348.905 |
| 150-E2AB | 0.607 | 217.69 | 217.69 | 0.00 | 0.000 |
| 200-E2 | 0.315 | 1.56 | 3.13 | 1.57 | 35.998 |
| 200-E6A-B | 0.613 | 257.50 | 257.50 | 0.00 | 0.000 |
| | | | | Total investment | 926.143 |

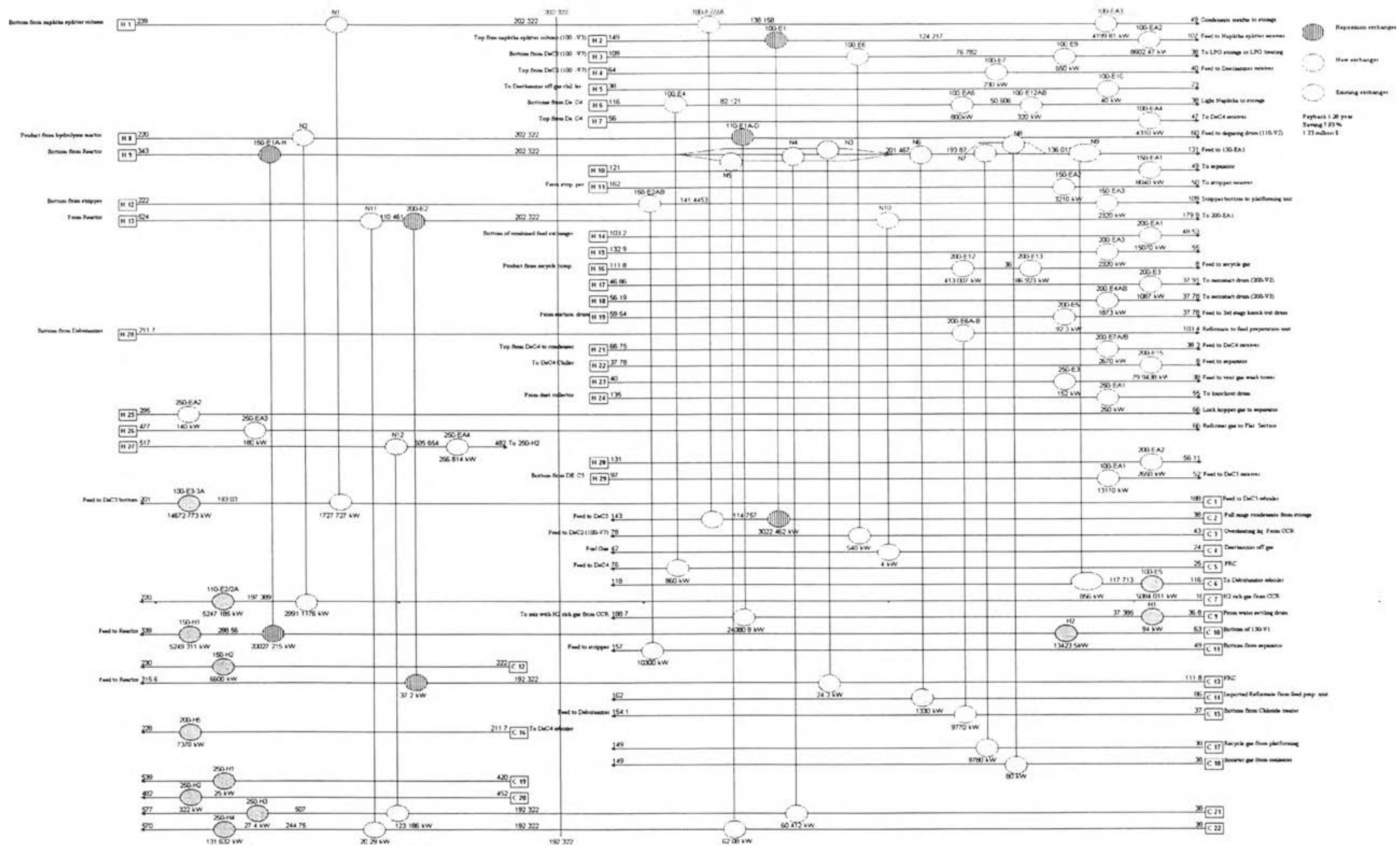


**Figure 4.6** Grid diagram of Design option A.

**Table 4.10** Calculation of investment cost for new area of exchangers for Design option A

| HEX | Area m$^2$ | Investment $10^3$ \$ |
|---|---|---|
| N1 | 127.33 | 123.868 |
| N2 | 297.29 | 213.173 |
| N3 | 1.34 | 34.453 |
| N4 | 2.20 | 34.963 |
| N5 | 2.26 | 34.998 |
| N6 | 39.14 | 49.294 |
| N7 | 288.09 | 113.377 |
| N8 | 2.36 | 35.052 |
| N9 | 110.24 | 70.144 |
| N10 | 0.05 | 33.495 |
| N11 | 0.16 | 33.835 |
| H52 | 1.87 | 34.775 |
| H53 | 102.62 | 109.366 |
| Total investment | | 920.792 |

Therefore the investment for extra area and new area is 1846.935 k$.

**Table 4.11** Calculation of utility savings for Design option A

| HEX | Old Q kW | New Q kW | Saved Q kW | Utility Type | annual cost $/kWyr | Savings 103 $/yr |
|---|---|---|---|---|---|---|
| 100-EA3 | 4060 | 4199.80 | -139.80 | AIR | 0.00 | 0.000 |
| 100-EA1 | 13110 | 13110.00 | 0.00 | AIR | 0.00 | 0.000 |
| 100-EA2 | 10470 | 8602.47 | 1867.53 | AIR | 0.00 | 0.000 |
| 100-E9 | 650 | 650.00 | 0.00 | CW | 21.04 | 0.000 |
| 100-E7 | 230 | 230.00 | 0.00 | CW | 21.04 | 0.000 |
| 100-E10 | 40 | 40.00 | 0.00 | RE | 0.00 | 0.000 |
| 100-EA4 | 4310 | 4310.00 | 0.00 | AIR | 0.00 | 0.000 |
| 100-EA5 | 800 | 800.00 | 0.00 | AIR | 0.00 | 0.000 |
| 100-E12AB | 320 | 320.00 | 0.00 | CW | 21.04 | 0.000 |
| 100-E3-3A | 16400 | 14672.27 | 1727.73 | HP | 214.51 | 370.614 |
| 100-E11 | 4 | 0.00 | 4.00 | LP | 200.00 | 0.800 |
| 100-E5 | 5940 | 5084.00 | 856.00 | LP | 200.00 | 171.200 |
| 110-EA1 | 2898 | 0.00 | 2898.00 | AIR | 0.00 | 0.000 |
| 110-E2/2A | 8238 | 5247.18 | 2990.82 | HP | 214.51 | 641.559 |
| 150-H1 | 6480 | 5249.31 | 1230.69 | POWER | 415.28 | 511.078 |
| 150-EA3 | 4150 | 2320.00 | 1830.00 | AIR | 0.00 | 0.000 |
| 150-EA1 | 8040 | 8040.00 | 0.00 | AIR | 0.00 | 0.000 |

**Table 4.11** (continued) Calculation of utility savings for Design option A

| HEX | Old Q kW | New Q kW | Saved Q kW | Utility Type | annual cost $/kWyr | Savings $10^3$ $/yr |
|---|---|---|---|---|---|---|
| 150-EA2 | 3210 | 3210.00 | 0.00 | AIR | 0.00 | 0.000 |
| 150-H2 | 6600 | 6600.00 | 0.00 | POWER | 415.28 | 0.000 |
| 200-EA1 | 15070 | 15070.00 | 0.00 | AIR | 0.00 | 0.000 |
| 200-E12 | 413.077 | 413.08 | 0.00 | CW | 21.04 | 0.000 |
| 200-E13 | 186.923 | 186.92 | 0.00 | RE | 0.00 | 0.000 |
| 200-EA2 | 2650 | 2650.00 | 0.00 | AIR | 0.00 | 0.000 |
| 200-E3 | 1087 | 1087.00 | 0.00 | CW | 21.04 | 0.000 |
| 200-EA3 | 2320 | 2320.00 | 0.00 | AIR | 0.00 | 0.000 |
| 200-E4AB | 1873 | 1873.00 | 0.00 | CW | 21.04 | 0.000 |
| 200-E5 | 92.3 | 92.30 | 0.00 | CW | 21.04 | 0.000 |
| 200-E7A/B | 2670 | 2670.00 | 0.00 | CW | 21.04 | 0.000 |
| 200-E15 | 79.9438 | 79.94 | 0.00 | RE | 0.00 | 0.000 |
| 200-E14 | 1330 | 0.00 | 1330.00 | MP | 207.63 | 276.142 |
| 200-H5 | 7370 | 7370.00 | 0.00 | POWER | 415.28 | 0.000 |
| 250-EA4 | 380 | 256.81 | 123.19 | AIR | 0.00 | 0.000 |
| 250-EA3 | 180 | 180.00 | 0.00 | AIR | 0.00 | 0.000 |
| 250-EA2 | 140 | 140.00 | 0.00 | AIR | 0.00 | 0.000 |
| 250-EA1 | 250 | 250.00 | 0.00 | AIR | 0.00 | 0.000 |
| 250-E3 | 152 | 152.00 | 0.00 | CW | 21.04 | 0.000 |
| 250-E1 | 9780 | 0.00 | 9780.00 | MP | 207.63 | 2030.575 |
| 250-H2 | 322 | 322.00 | 0.00 | POWER | 415.28 | 0.000 |
| 250-H1 | 25 | 25.00 | 0.00 | POWER | 415.28 | 0.000 |
| 250-H3 | 211 | 27.40 | 183.60 | POWER | 415.28 | 76.244 |
| 250-H4 | 214 | 131.63 | 82.37 | POWER | 415.28 | 34.206 |
| 250-E2 | 80 | 0.00 | 80.00 | MP | 207.63 | 16.610 |
| H1 | 0 | 94.00 | -94.00 | LP | 200.00 | -18.800 |
| H2 | 0 | 13423.17 | -13423.17 | HP | 214.51 | -2879.401 |
| | | | | | Total saving | 1230.827 |

The investment cost and saving give 1.5 year payback period with 7.93% energy saving (11.326 MW).

*4.1.5.2 Design Option B*

Tables 4.12 and 4.13 show the calculation of investment cost of existing exchangers with new area and new exchanger respectively. The utility saving calculation is shown in Table 4.14.

**Table 4.12** Calculation of investment cost of existing exchangers with extra area for Design option B

| HEX | U<br>kW/m$^{2o}$C | Old Area<br>m$^2$ | New Area<br>m$^2$ | Extra Area<br>m$^2$ | Investment<br>10$^3$ \$ |
|---|---|---|---|---|---|
| 100-E2/2A | 0.516 | 194.11 | 211.52 | 17.42 | 41.659 |
| 100-E1 | 0.473 | 489.67 | 878.69 | 389.02 | 135.399 |
| 100-E6 | 0.565 | 29.55 | 29.55 | 0.00 | 0.000 |
| 100-E4 | 0.619 | 39.92 | 39.92 | 0.00 | 0.000 |
| 110-E1A-D | 0.303 | 2238.11 | 4476.97 | 2238.86 | 454.290 |
| 150-E1A-H | 0.412 | 1258.17 | 1853.55 | 595.38 | 348.905 |
| 150-E2AB | 0.607 | 217.69 | 218.23 | 0.00 | 0.000 |
| 200-E2 | 0.315 | 1.56 | 3.13 | 1.57 | 35.998 |
| 200-E6A-B | 0.613 | 257.50 | 257.50 | 0.00 | 0.000 |
| | | | | Total investment | 1016.252 |

**Table 4.13** Calculation of investment cost for new exchangers for Design option B

| HEX | Area<br>m$^2$ | Investment<br>10$^3$ \$ |
|---|---|---|
| N1 | 30.01 | 61.477 |
| N2 | 14.48 | 34.586 |
| N3 | 0.36 | 34.194 |
| N4 | 911.78 | 236.721 |
| N5 | 0.16 | 33.835 |
| N6 | 2.67 | 37.371 |
| N7 | 6.37 | 37.068 |
| N8 | 0.98 | 35.171 |
| N9 | 1.93 | 36.463 |
| N10 | 8.34 | 63.226 |
| N11 | 0.05 | 33.495 |
| N12 | 0.79 | 34.900 |
| H1 | 1.87 | 34.775 |
| H2 | 7.56 | 37.613 |
| Total investment | | 704.544 |

Therefore the investment for extra area and new area is 1767.144 k\$.

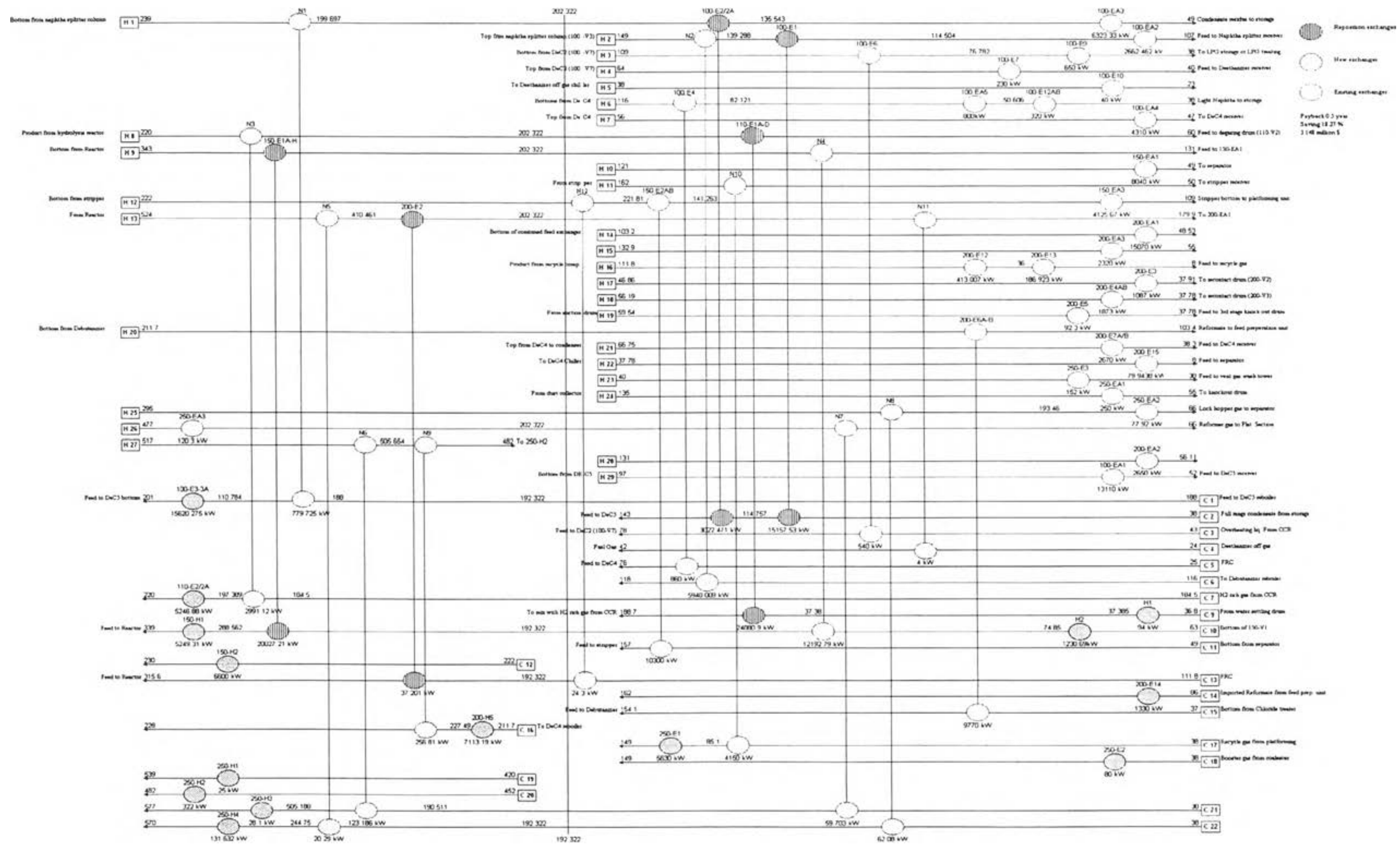


**Figure 4.7** Grid diagram of Design option B.

**Table 4.14** Calculation of utility savings for Design option B

| HEX | Old Q kW | New Q kW | Saved Q kW | Utility Type | annual cost $/kWyr | Savings $10^3$ $/yr |
|---|---|---|---|---|---|---|
| 100-EA3 | 4060 | 6323.33 | 2263.33 | AIR | 0.000 | 0.000 |
| 100-EA1 | 13110 | 13110.00 | 0.00 | AIR | 0.000 | 0.000 |
| 100-EA2 | 10470 | 2662.46 | 7807.54 | AIR | 0.000 | 0.000 |
| 100-E9 | 650 | 650.00 | 0.00 | CW | 21.040 | 0.000 |
| 100-E7 | 230 | 230.00 | 0.00 | CW | 21.040 | 0.000 |
| 100-E10 | 40 | 40.00 | 0.00 | RE | 0.000 | 0.000 |
| 100-EA4 | 4310 | 4310.00 | 0.00 | AIR | 0.000 | 0.000 |
| 100-EA5 | 800 | 800.00 | 0.00 | AIR | 0.000 | 0.000 |
| 100-E12AB | 320 | 320.00 | 0.00 | CW | 21.040 | 0.000 |
| 100-E3-3A | 16400 | 15620.28 | 779.73 | HP | 214.510 | 167.259 |
| 100-E11 | 4 | 0.00 | 4.00 | LP | 200.000 | 0.800 |
| 100-E5 | 5940 | 0.00 | 5940.00 | LP | 200.000 | 1188.000 |
| 110-EA1 | 2898 | 0.00 | 2898.00 | AIR | 0.000 | 0.000 |
| 110-E2/2A | 8238 | 5246.88 | 2991.12 | HP | 214.510 | 641.624 |
| 150-H1 | 6480 | 5249.31 | 1230.69 | POWER | 415.278 | 511.078 |
| 150-EA3 | 4150 | 4125.67 | 24.33 | AIR | 0.000 | 0.000 |
| 150-EA1 | 8040 | 8040.00 | 0.00 | AIR | 0.000 | 0.000 |
| 150-EA2 | 3210 | 0.00 | 3210.00 | AIR | 0.000 | 0.000 |
| 150-H2 | 6600 | 6600.00 | 0.00 | POWER | 415.278 | 0.000 |
| 200-EA1 | 15070 | 15070.00 | 0.00 | AIR | 0.000 | 0.000 |
| 200-E12 | 413.077 | 413.08 | 0.00 | CW | 21.040 | 0.000 |
| 200-E13 | 186.923 | 186.92 | 0.00 | RE | 0.000 | 0.000 |
| 200-EA2 | 2650 | 2650.00 | 0.00 | AIR | 0.000 | 0.000 |
| 200-E3 | 1087 | 1087.00 | 0.00 | CW | 21.040 | 0.000 |
| 200-EA3 | 2320 | 2320.00 | 0.00 | AIR | 0.000 | 0.000 |
| 200-E4AB | 1873 | 1873.00 | 0.00 | CW | 21.040 | 0.000 |
| 200-E5 | 92.3 | 92.30 | 0.00 | CW | 21.040 | 0.000 |
| 200-E7A/B | 2670 | 2670.00 | 0.00 | CW | 21.040 | 0.000 |
| 200-E15 | 79.9438 | 79.94 | 0.00 | RE | 0.000 | 0.000 |
| 200-E14 | 1330 | 1330.00 | 0.00 | MP | 207.625 | 0.000 |
| 200-H5 | 7370 | 7113.19 | 256.81 | POWER | 415.278 | 106.649 |
| 250-EA4 | 380 | 0.00 | 380.00 | AIR | 0.000 | 0.000 |
| 250-EA3 | 180 | 120.30 | 59.70 | AIR | 0.000 | 0.000 |
| 250-EA2 | 140 | 77.92 | 62.08 | AIR | 0.000 | 0.000 |
| 250-EA1 | 250 | 250.00 | 0.00 | AIR | 0.000 | 0.000 |
| 250-E3 | 152 | 152.00 | 0.00 | CW | 21.040 | 0.000 |
| 250-E1 | 9780 | 5630.00 | 4150.00 | MP | 207.625 | 861.645 |

**Table 4.14** (continued) Calculation of utility savings for Design option B

| HEX | Old Q kW | New Q kW | Saved Q kW | Utility Type | annual cost \$/kWyr | Savings $10^3$ \$/yr |
|---|---|---|---|---|---|---|
| 250-H2 | 322 | 322.00 | 0.00 | POWER | 415.278 | 0.000 |
| 250-H1 | 25 | 25.00 | 0.00 | POWER | 415.278 | 0.000 |
| 250-H3 | 211 | 18.11 | 192.89 | POWER | 415.278 | 80.102 |
| 250-H4 | 214 | 517.75 | -303.75 | POWER | 415.278 | -126.141 |
| 250-E2 | 80 | 80.00 | 0.00 | MP | 207.625 | 0.000 |
| H1 | 0 | 94.00 | -94.00 | LP | 200.000 | -18.800 |
| H2 | 0 | 1230.69 | -1230.6 | HP | 214.510 | -263.994 |
| | | | | | Total saving | 3148.22 |

The investment cost and saving give 0.561 year payback period (6.7 months) with 18.27% energy savings (26.1 MW).

## 4.2 Actual Case (as of October 10, 2003)

4.2.1 <u>Process Data</u>

The temperature and flow rate of streams can be measured by the instruments and are concluded in the Table 3.4 of Chapter III. The streams were assumed to have the same composition as in design case which results in the same heat capacity, dew point and bubble point temperature. The value of these data which some streams are adjusted for energy balance of heat exchanger was concluded in Table 4.15. The location and information of each stream are described in Appendix A-2.

**Table 4.15** Process data of actual case (hot streams)

| STREAM | stream in | | stream out | | phase | Tdew | Tbubble | flowrate | Cp in | Cp out | Cp avg | mCp | | Tin | Tout | Temp change for | total duty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | name | phase | name | phase | change | C | C | kg/hr | kWhr/kgC | kWhr/kgC | kWhr/kgC | sensible heat kW/C | latent heat kW/C | C | C | sensible heat (C) | MW |
| H1 | 346 | liq | 351 | liq | ✕ | - | - | 76160.0 | 0.000863 | 0.000611 | 0.000737 | 47.663 | | 241.48 | 57.51 | 241.478-57.51 | 8.769 |
| H2 | 306 | mixed | 310 | liq | ✓ | - | 111.02 | 215034.6 | 0.000571 | 0.000629 | 0.000600 | 129.009 | 627.595 | 133.45 | 95.21 | 111.023-95.209 | 0.000 |
| H3 | 540 | liq | 544 | liq | ✕ | - | - | 20374.1 | 0.001169 | 0.000728 | 0.000948 | 18.036 | | 107.84 | 35.61 | 107.84-35.61 | 1.303 |
| H4 | 606 | mixed | 604 | mixed | ✓ | - | - | 3476.8 | 0.000687 | 0.000887 | 0.000787 | 2.736 | 10.593 | 55.08 | 36.96 | - | 0.000 |
| H5 | 605 | mixed | 525 | mixed | ✓ | - | - | 772.2 | 0.000675 | 0.000824 | 0.000749 | 0.579 | 2.667 | 36.96 | 19.20 | - | 0.000 |
| H6 | 511 | liq | 565 | liq | ✕ | - | - | 28480.2 | 0.000786 | 0.000629 | 0.000707 | 20.106 | | 110.17 | 31.05 | 110.168-31.047 | 1.591 |
| H7 | 499 | vapor | 498 | mixed | ✓ | 53.93 | - | 47001.3 | 0.000562 | 0.000793 | 0.000678 | 31.843 | 613.075 | 55.14 | 45.85 | 55.136-53.925 | 0.000 |
| H8 | 006 | | 008 | | ✕ | - | - | 123979.9 | 0.000840 | 0.000608 | 0.000724 | 76.427 | | 190.88 | 60.00 | 190.876-60.002 | 10.002 |
| H9 | 131 | vapor | 132 | mixed | ✓ | 276.67 | - | 131970.9 | 0.000806 | 0.000682 | 0.000744 | 56.459 | 170.954 | 322.97 | 132.82 | 322.972-276.672 | 0.000 |
| H10 | 136 | mixed | 137 | mixed | ✓ | - | - | 139105.0 | 0.000668 | 0.000585 | 0.000627 | 87.171 | 111.667 | 132.82 | 51.01 | - | 0.000 |
| H11 | 307 | vapor | 309 | mixed | ✓ | 51.45 | - | 27959.7 | 0.000934 | 0.000829 | 0.000882 | 24.650 | 791.088 | 153.50 | 49.64 | 162-51.449 | 0.000 |
| H12 | 341 | liq | 399 | liq | ✕ | - | - | 129864.4 | 0.000838 | 0.000638 | 0.000738 | 100.884 | | 206.70 | 63.14 | 206.704-63.137 | 14.484 |
| H13 | 194 | vapor | 195 | vapor | ✕ | - | - | 187.3 | 0.000969 | 0.000722 | 0.000845 | 0.087 | | 510.93 | 62.13 | 510.925-62.133 | 0.039 |
| H14 | 167 | mixed | 181 | mixed | ✓ | - | - | 139684.4 | 0.000690 | 0.000902 | 0.000796 | 111.138 | 275.654 | 95.03 | 46.02 | - | 0.000 |
| H15 | 1204 | vapor | 1212 | mixed | ✓ | 61.71 | - | 20308.3 | 0.001340 | 0.001284 | 0.001312 | 26.638 | 30.571 | 130.28 | 54.49 | 130.28-61.71 | 0.000 |
| H16 | 1122 | vapor | 1123 | mixed | ✓ | 63.57 | - | 3219.2 | 0.001052 | 0.001276 | 0.001164 | 3.747 | 6.676 | 112.83 | 9.71 | 112.826-63.567 | 0.000 |
| H17 | 1164 | mixed | 1165 | mixed | ✓ | - | - | 137669.0 | 0.000945 | 0.000976 | 0.000961 | 132.281 | 121.453 | 43.71 | 36.71 | - | 0.000 |
| H18 | 1214 | mixed | 1215 | mixed | ✓ | - | - | 123456.5 | 0.001180 | 0.001262 | 0.001221 | 150.781 | 101.738 | 54.72 | 36.72 | - | 0.000 |
| H19 | 1254 | vapor | 1265 | mixed | ✓ | 44.58 | - | 2258.8 | 0.001680 | 0.001672 | 0.001676 | 3.786 | 4.286 | 67.30 | 32.53 | 67.305-44.854 | 0.000 |
| H20 | 1474 | liq | 1469 | liq | ✕ | - | - | 152420.0 | 0.000747 | 0.000593 | 0.000670 | 97.053 | | 207.29 | 118.90 | 207.288-118.902 | 8.578 |
| H21 | 1406 | mixed | 1409 | mixed | ✓ | - | - | 24948.4 | 0.000582 | 0.000750 | 0.000666 | 16.616 | 98.212 | 63.38 | 39.78 | 63.378-39.78 | 0.000 |
| H22 | 1411 | vapor | - | mixed | ✓ | 37.32 | - | 1270.0 | 0.000563 | 0.000650 | 0.000606 | 0.770 | 2.719 | 38.54 | 19.48 | 38.545-37.323 | 0.000 |
| H28 | 1154 | vapor | 1162 | mixed | ✓ | 69.39 | - | 26543.9 | 0.000123 | 0.001107 | 0.000615 | 16.320 | 115.108 | 138.81 | 57.70 | 138.81-69.391 | 0.000 |
| H29 | 170 | mixed | 173 | liq | ✓ | - | 68.66 | 115108.0 | 0.000575 | 0.000700 | 0.000638 | 73.413 | 454.858 | 80.53 | 51.69 | 68.662-51.69313 | 0.000 |

**Table 4.15** (Continued) Process data of actual case (Cold streams)

| STREAM | stream in | | stream out | | phase | Tdew | Tbubble | flowrate | Cp in | Cp out | Cp avg | mCp | | Tin | Tout | Temp change for | total duty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | sensible heat | latent heat | | | | |
| | name | phase | name | phase | change | C | C | kg/hr | kWhr/kgC | kWhr/kgC | kWhr/kgC | kW/C | kW/C | C | C | sensible heat (C) | MW |
| C1 | 131 | liq | 138 | mixed | ✔ | - | 192.32 | 151146.2 | 0.000769 | 0.000743 | 0.000756 | 114.242 | 1829.517 | 184.95 | 198.95 | 184.949-192.322 | 0.000 |
| C2 | 103 | liq | 110 | liq | ✕ | - | - | 252330.0 | 0.000573 | 0.000725 | 0.000649 | 159.692 | | 29.34 | 108.18 | 29.343-131.399 | 0.000 |
| | | | | | ✕ | - | - | 252330.0 | 0.000573 | 0.000725 | 0.000649 | 199.197 | | 108.18 | 131.40 | | |
| C3 | 517 | liq | 513 | liq | ✕ | - | - | 18040.7 | 0.000741 | 0.000864 | 0.000803 | 15.594 | | 42.97 | 71.78 | 42.974-71.778 | 0.449 |
| C4 | 525 | vapor | 527 | vapor | ✕ | - | - | 510.0 | 0.000665 | 0.000523 | 0.000594 | 0.303 | | 19.20 | 75.17 | 19.197-75.175 | 0.017 |
| C5 | 302 | liq | 305 | liq | ✕ | - | - | 43760.0 | 0.000700 | 0.000750 | 0.000725 | 31.800 | | 52.12 | 71.14 | 52.125-71.143 | 0.605 |
| C6 | 507 | liq | 508 | liq | ✕ | - | 116.01 | 183161.4 | 0.000791 | 0.000736 | 0.000763 | 139.828 | 2755.387 | 110.17 | 113.17 | 110.168-113.168 | 0.419 |
| C7 | | | | | ✕ | - | - | 123979.9 | 0.000764 | 0.000838 | 0.000801 | 99.304 | | 157.29 | 192.00 | 157.289-192.001 | 3.447 |
| C8 | | | | | ✕ | - | - | 129525.8 | 0.000764 | 0.000838 | 0.000801 | 103.747 | | 60.00 | 81.76 | 60.002-81.757 | 2.257 |
| C9 | | | 002 | | ✕ | - | - | 129514.3 | 0.000549 | 0.000765 | 0.000657 | 103.050 | | 97.89 | 157.29 | 36.8-188.7 | 6.121 |
| C10 | 112 | liq | 115 | vapor | ✔ | 288.98 | 263.48 | 139105.8 | 0.000579 | 0.000821 | 0.000700 | 108.023 | 499.122 | 81.87 | 324.81 | 81.865-263.482,288. | 0.000 |
| C11 | 151 | mixed | 306 | mixed | ✔ | - | - | 130147.9 | 0.000567 | 0.000717 | 0.000642 | 83.577 | 90.837 | 51.28 | 160.70 | - | 0.000 |
| C12 | 334 | liq | 338 | liq | ✕ | - | 222.00 | 264064.0 | 0.000838 | 0.000730 | 0.000784 | 207.027 | 825.000 | 206.70 | 213.16 | 220-230 | 0.000 |
| C13 | 190 | vapor | 193 | vapor | ✕ | - | - | 94.5 | 0.001051 | 0.001228 | 0.001139 | 0.607 | | 112.83 | 177.00 | 111.8-315.6 | 0.039 |
| C14 | 1720 | liq | 1405-1420 | liq | ✕ | - | - | 40519.5 | 0.000671 | 0.000797 | 0.000734 | 29.750 | | 35.00 | 127.32 | 86-162 | 2.747 |
| C15 | 1438 | liq | 1420 | liq | ✕ | - | - | 116891.3 | 0.000502 | 0.000652 | 0.000577 | 71.154 | | 36.98 | 157.54 | 37-154.1 | 8.578 |
| C16 | 1449 | liq | 1451 | mixed | ✔ | - | 213.72 | 149998.6 | 0.000747 | 0.000659 | 0.000703 | 105.487 | 501.580 | 207.29 | 230.55 | 211.7-213.715 | 0.000 |

### 4.2.2 Energy Target

The problem table analysis and grand composite curves at any minimum approach temperatures had been done as in the procedure in section 3.4. The data extracted from grand composite curve will give the minimum utility requirement which results in minimum total cost and minimum heat exchanger capital investment cost at any $\Delta T_{min}$. The problem table algorithm (PTA) for any $\Delta T_{min}$ can be done as in actual case and the result of PTA is shown in Table 4.16.

**Table 4.16** Result of PTA at various $\Delta T_{min}$

| $\Delta T_{min}$ C | $Q_{Hmin}$ MW | $Q_{Cmin}$ MW | pinch C |
|---|---|---|---|
| 5 | 30.507 | 51.976 | 194.822 |
| 10 | 28.825 | 54.959 | 197.322 |
| 20 | 32.325 | 57.660 | 196.704 |
| 30 | 34.750 | 60.984 | 199.949 |
| 40 | 36.937 | 62.271 | 204.949 |
| 51.034 | 41.322 | 66.656 | 123.409 |

The actual case of existing plant uses 66.656 MW of hot utility and 41.322 MW cold utility of cold utility in the process. The reduced utility is from removing some exchangers that can not be modified. These values of both utilities tell that $\Delta T_{min}$ of the process is 51.034 °C. The $\Delta T_{min}$ of this process, comparing with the similar process in many literatures which is about 10-20 °C (Linnhoff, 1998), is very high. This can be concluded that the utility usage in the process is too high and can be reduced by recovering process to process energy.

### 4.2.3 Area Target

The surface area of over all and each of existing heat exchanger is shown in Table 4.17. The hot and cold composite curves for calculating minimum area at any $\Delta T_{min}$ are shown in Figure 4.8. The procedure to construct the curves as in section 3.5 is shown in Appendix C-2. The result from this analysis is in Table 4.18.

**Table 4.17** Surface area of existing heat exchangers in the process

| HEX | Stream | surface area $m^2$ |
|---|---|---|
| 100-E1 | H2 | 661 |
| | C2 | |
| 100-E2/2A | H1 | 202.700 |
| | C2 | |
| 100-E4 | H6 | 76.700 |
| | C5 | |
| 100-E6 | H3 | 32.700 |
| | C3 | |
| 110-E1A-D | H8 | 2768.000 |
| | C9 | |
| 150-E1A-H | H9 | 1944.000 |
| | C10 | |
| 150-E2AB | H12 | 231.600 |
| | C11 | |
| 200-E2 | H13 | 6.977 |
| | C13 | |
| 200-E6A/B | H20 | 265.400 |
| | C15 | |
| | total area | 6189.077 $m^2$ |

**Table 4.18** Result from area targeting at various $\Delta T_{min}$

| ΔTmin C | $A_{ideal}$ $m^2$ |
|---|---|
| 5 | 7093.461 |
| 10 | 5429.980 |
| 20 | 3983.7413 |
| 30 | 3378.9582 |
| 40 | 2959.0727 |
| 51.034 (existing case) | 2357.4488 |

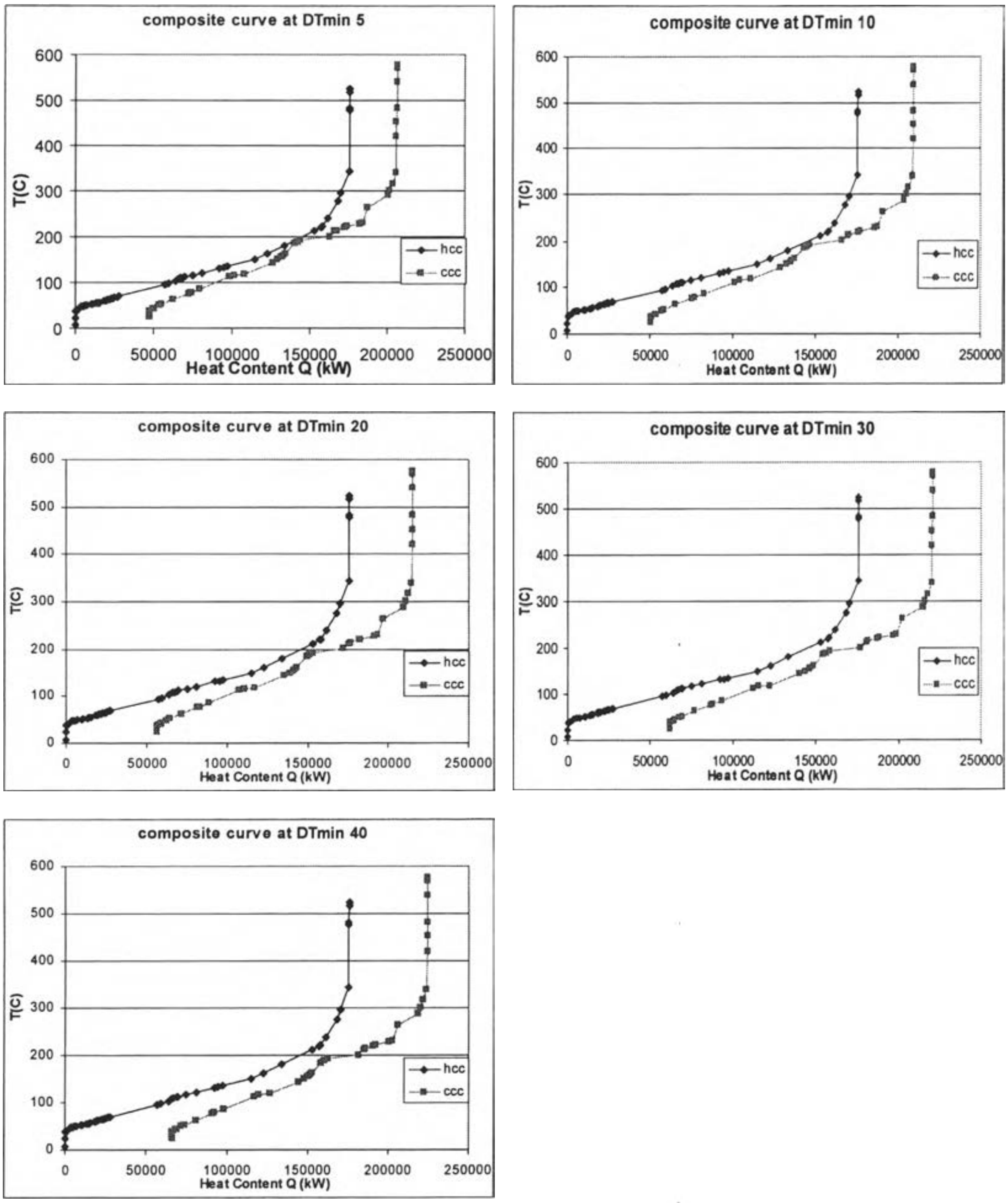



**Figure 4.8** Hot and Cold composite curves at various $\Delta T_{min}$.

4.2.4 Setting Retrofit Targets

Step1. Calculation of Area Targets for Various Energy Levels and Area Efficiency of Existing network

The existing HEN has an area efficiency of 0.380905, where the existing area ($A_{existing}$) and target area ($A_{ideal}$) for the existing energy recovery are 6187.01 and 2357.45 $m^2$, respectively.

Step 2. Calculation of the Retrofit Curve

The utility demands and area requirement for each global $\Delta T_{min}$ which were calculated in sections 4.2.2 and 4.2.3 are concluded in Table 4.19 and the area-energy plot is in Figure 4.9.

**Table 4.19** Area-Energy data for various $\Delta T_{min}$

| ΔTmin C | $Q_{cu,min}$ kW | $Q_{hu,min}$ kW | $A_{ideal}$ m2 | $A_{max,retr}$ Δα=1 | $A_{max,retr}$ Δα=0.4365 |
|---|---|---|---|---|---|
| 5 | 51975.8 | 26641.5 | 7093.46 | 10925.09 | 18622.66 |
| 10 | 54059.1 | 28724.8 | 5429.98 | 9261.61 | 14255.48 |
| 20 | 57659.5 | 32325.2 | 3983.74 | 7815.37 | 10458.63 |
| 30 | 60083.8 | 34749.5 | 3378.96 | 7210.59 | 8870.87 |
| 40 | 62270.8 | 36936.5 | 2959.07 | 6790.70 | 7768.54 |
| 51.034 | 66656.0 | 41321.7 | 2357.45 | 6189.08 | 6189.08 |

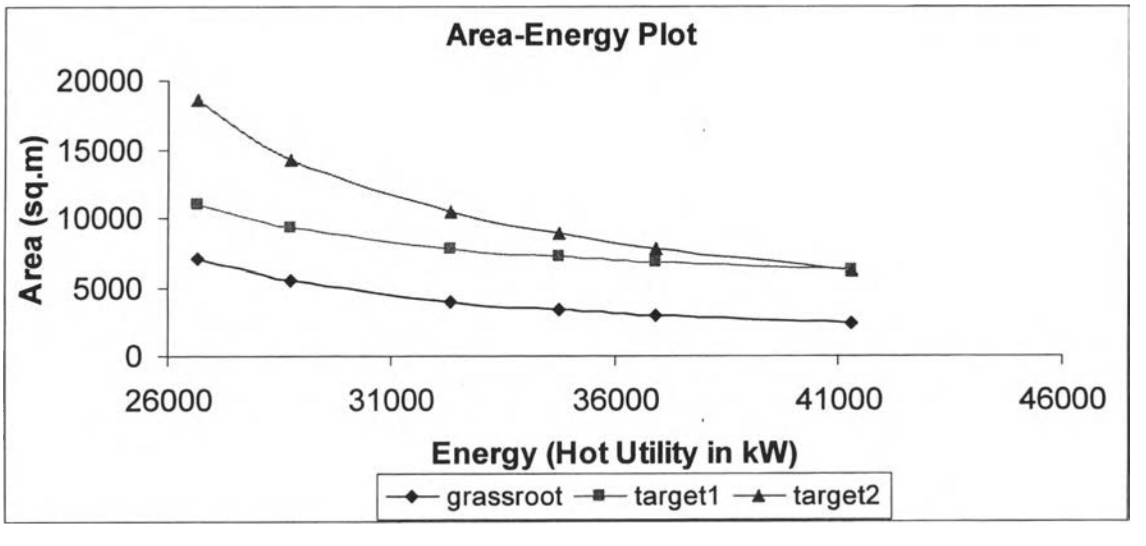



**Figure 4.9** Retrofit Curve on Area-Energy Plot.

Step3. Calculation of Energy Saving and Extra Area Required

Before calculation of the energy saving, the utility usage for multiple utility levels is required and doing Problem Table Analysis will be very useful in this step as shown in Appendix D-2. The data of target utility usage for various $\Delta T_{min}$ was concluded in the Table 4.20 where

| Annual cost of utilities in $/(kWyr) for : | | |
|---|---|---|
| | Medium Pressure steam | 207.62527 |
| | High Pressure steam | 214.50967 |
| | Refrigerant | 0 |
| | Power | 415.278 |
| | Cooling Water | 21.04 |
| | Air | 0 |
| | Low Pressure steam | 200 |

**Table 4.20** Data of target utility usage for multiple utilities

| utility i | Current uility usage | | Target utility required | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ΔTmin=5 | | ΔTmin=10 | | ΔTmin=20 | | ΔTmin=30 | | ΔTmin=40 | |
| | in kW | in $ | in kW | in $ | in kW | in $ | in kW | in $ | in kW | in $ | in kW | in $ |
| MP | 2747 | 570266 | | | | | | | | | | |
| HP | 5704 | 1223587 | 25919 | 5559919 | 27462 | 5890929 | 29983 | 6431558 | 31327 | 6719859 | 33082 | 7096495 |
| RE | 243 | 0 | 6381 | 0 | 31048 | 0 | 17538 | 0 | 20548 | 0 | 43833 | 0 |
| POWER | 19468 | 8084794 | | | | | | | | | | |
| CW | 6776 | 142577 | 20042 | 421691 | 17511 | 368434 | 17150 | 360841 | 20984 | 441504 | 4165 | 87638 |
| AIR | 59637 | 0 | 25552 | 0 | 5500 | 0 | 22971 | 0 | 18552 | 0 | 14272 | 0 |
| LP | 436 | 87286 | | | | | | | | | | |
| total | | 10108509 | | 5981610 | | 6259363 | | 6792399 | | 7161363 | | 7184133 |

Step4. Economic Analysis of Investment vs. Savings

The calculated data for energy saving cost and investment cost is in Table 4.21. The investment-saving plot is in Figure 4.10.

**Table 4.21** Calculated data for energy saving cost and investment cost

| ΔTmin | Energy Savings | Extra Area Δα=1 | Extra Area Δα=0.4365 | Savings | ΔN Δα=1 | ΔN Δα=0.4365 | Investment Δα=1 | Investment Δα=0.4365 | payback |
|---|---|---|---|---|---|---|---|---|---|
| C | kW | m2 | m2 | k$/yr | | | k$ | k$ | yr |
| 5 | 14680.2 | 10925.09 | 18622.66 | 4126.899 | 46 | 78 | 1538.123 | 2608.117 | 0.632 |
| 10 | 12596.9 | 9261.61 | 14255.48 | 3849.146 | 39 | 60 | 1304.061 | 2006.248 | 0.521 |
| 20 | 8996.5 | 7815.37 | 10458.63 | 3316.110 | 33 | 44 | 1103.437 | 1471.248 | 0.444 |
| 30 | 6572.2 | 7210.59 | 8870.87 | 2947.146 | 30 | 37 | 1003.119 | 1237.182 | 0.420 |
| 40 | 4385.2 | 6790.70 | 7768.54 | 2924.376 | 29 | 33 | 969.692 | 1103.440 | 0.377 |

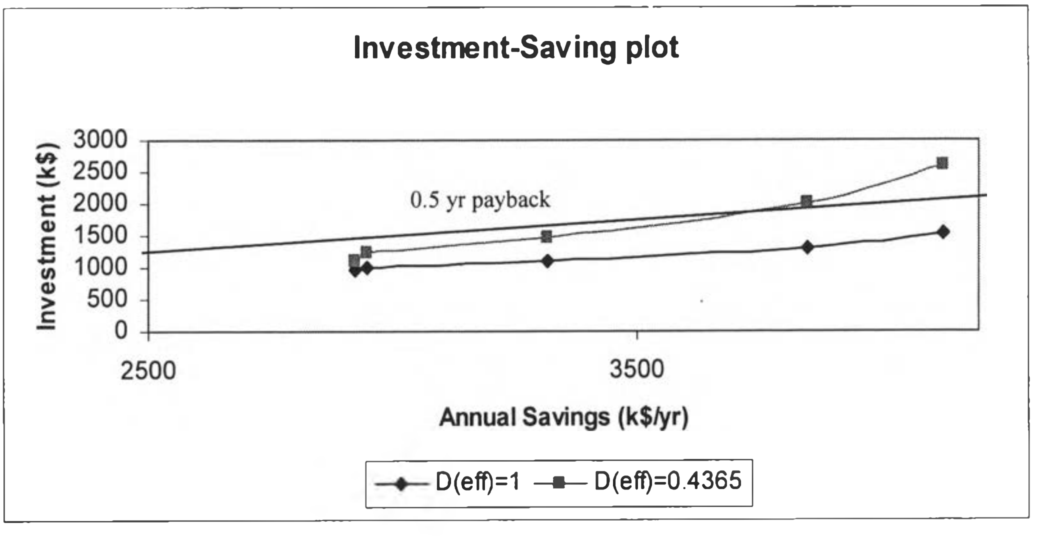



**Figure 4.10** Investment-Saving plot.

Step5. Identification of Target $\Delta T_{min}$

Based on the specified payback period (2 years), the required target is the point where the investment is twice the savings. But from the table above at any $\Delta T_{min}$ , payback period is less than 2 years. Therefore, the payback period is now chosen to be 0.5 year which corresponds to $\Delta T_{min}$ 12.736 $^{o}$C.

### 4.2.5 Design Procedure

As in design case the network is analysed to determine the heat exchanger units that transfer heat across pinch and inappropriate utility placement. The grid for existing network (using $\Delta T_{min}$ identified in the targeting stage) was shown in the Figure 4.11 and the heat exchangers crossing the pinch are reported in Table 4.22.

**Table 4.22** Heat exchangers, heater and cooler which transfer heat across the Pinch

| HEX no. | HEX name | Hot stream | Cold stream | Heat load (kW) |
|---|---|---|---|---|
| 2 | 100-E2/2A | 1 | 2 | 4624.400 |
| 3 | 100-E3/3A | HP | 1 | 12966.200 |
| 5 | 100-E5 | LP | 6 | 419.485 |
| 10 | 100-E11 | LP | 4 | 16.945 |
| 18 | 110-E2 | HP | 8 | 2257.050 |
| 19 | 110-E2A | HP | 7 | 3447.060 |
| 21 | 150-E1A-H | 9 | 10 | 27205.900 |
| 22 | 150-E2AB | 12 | 11 | 9939.380 |
| 28 | 200-E2 | 13 | 13 | 38.979 |
| 32 | 200-E6AB | 20 | 15 | 8578.160 |
| 36 | 200-E14 | MP | 14 | 2746.610 |

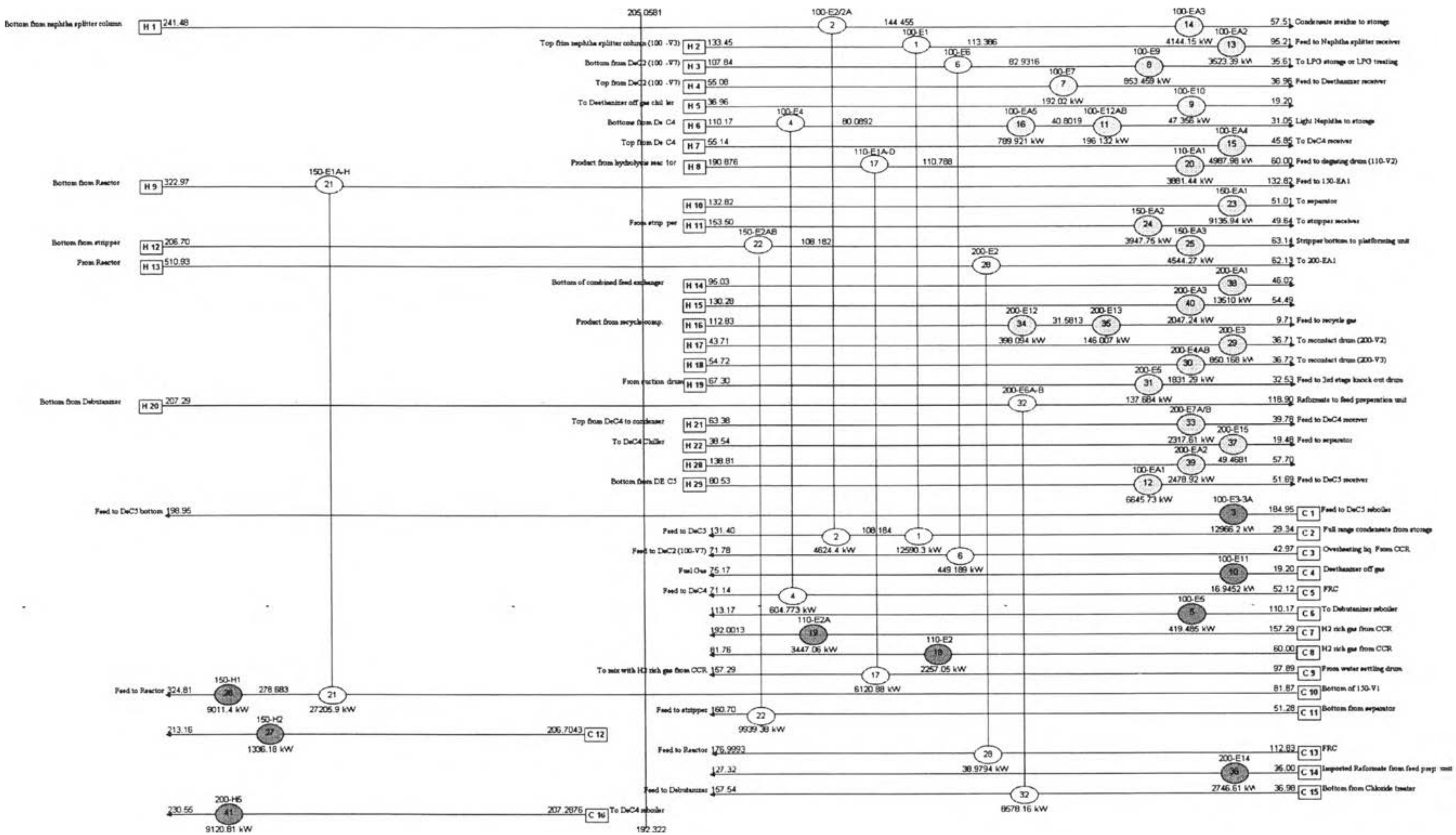


**Figure 4.11** Grid diagram of existing plant with pinch temperature.

A summary of the heat flow violation of the pinch is given in Table 4.23. The process-to-process heat exchangers transfer significant amounts of heat, especially HEX 2. Also hot utility units HEX 18, 19 and 36 also transfer considerable amounts. But no cold utility unit transfers heat across pinch.

**Table 4.23** Summary of pinch design violation of existing network

| HEX no. | HEX name | Heat flow across pinch (kW) | cold utility above pinch (kW) | Hot utility below pinch (kW) |
|---|---|---|---|---|
| 2 | 100-E2/2A | 1735.874 | | |
| 3 | 100-E3/3A | | | 842.325 |
| 5 | 100-E5 | | | 419.485 |
| 10 | 100-E11 | | | 16.945 |
| 18 | 110-E2 | | | 2257.050 |
| 19 | 110-E2A | | | 3447.060 |
| 21 | 150-E1A-H | 417.386 | | |
| 22 | 150-E2AB | 166.045 | | |
| 28 | 200-E2 | 26.580 | | |
| 32 | 200-E6AB | 216.419 | | |
| 36 | 200-E14 | | | 2746.610 |

At the targeting stage, the potential for energy savings is set by the economics of the process. The optimum energy recovery corresponds to a minimum approach temperature of 12.736°C, and the minimum energy consumption of the process is given by the composite curves.

Unlike the design case retrofit which the cross pinch exchangers were eliminated and the network was completed with the new and reused exchanger, only exchangers that transfer the significant amount of heat will be considered.

In the diagnosis stage, inspection for topology changes, which increases energy savings by shifting heat from below to above the network pinch, are carried out. The modifications considered include resequencing, repiping and the addition of new heat exchangers. Split heuristics modifications are implemented whenever the network pinch and process pinch coincides. With these modification methods the across pinch exchanger will be eliminated and the heat flow across pinch will be reduced.

*4.2.5.1 Diagnosis Stage*

The purpose of this stage is to identify design options that overcome the network pinch and increases the energy recovery of the network. The inspection for potential topology changes is sequential. At each step resequencing is considered first, followed by repiping, and finally by adding of a new heat exchanger. As the area efficiency method was used for targeting, the optimum value of the minimum approach temperature obtained from it, 12.736°C was used for the retrofit design in this study. The design objective in the diagnosis stage was set for minimum energy consumption. A summary of the steps taken in the diagnosis stage for the different design options is shown in Figure 4.12.

Design Option A

1) There is no beneficial resequencing modifications, repiping was considered. The inspection gives two beneficial options: repiping of HEX 2's cold stream to C1 and repiping of HEX 2's cold stream to C12. The first option with more energy savings was chosen while the second option will be used in design option D since more utility saving cost was obtained. This gives MP steam duty savings of HEX 3 about 1.458 MW.

2) The next modifications for this design option is the addition of new heat exchanger. Since repiping of HEX 2, the stream C2 now need heating with the hot stream having high enough temperature and this results in addition of HEX 42 between H12 and C2.

3) The modification continues with the addition of new heat exchanger HEX 43. The best few options identified are H1-C8, H1-C14 and H10-C8. The first two options will save the MP steam duty while the third option will save the HP steam duty. But the third option is not considered as it will be explored in design option B. Then the match between H1-C14 with more energy savings is selected which gives 2.746 MW energy savings

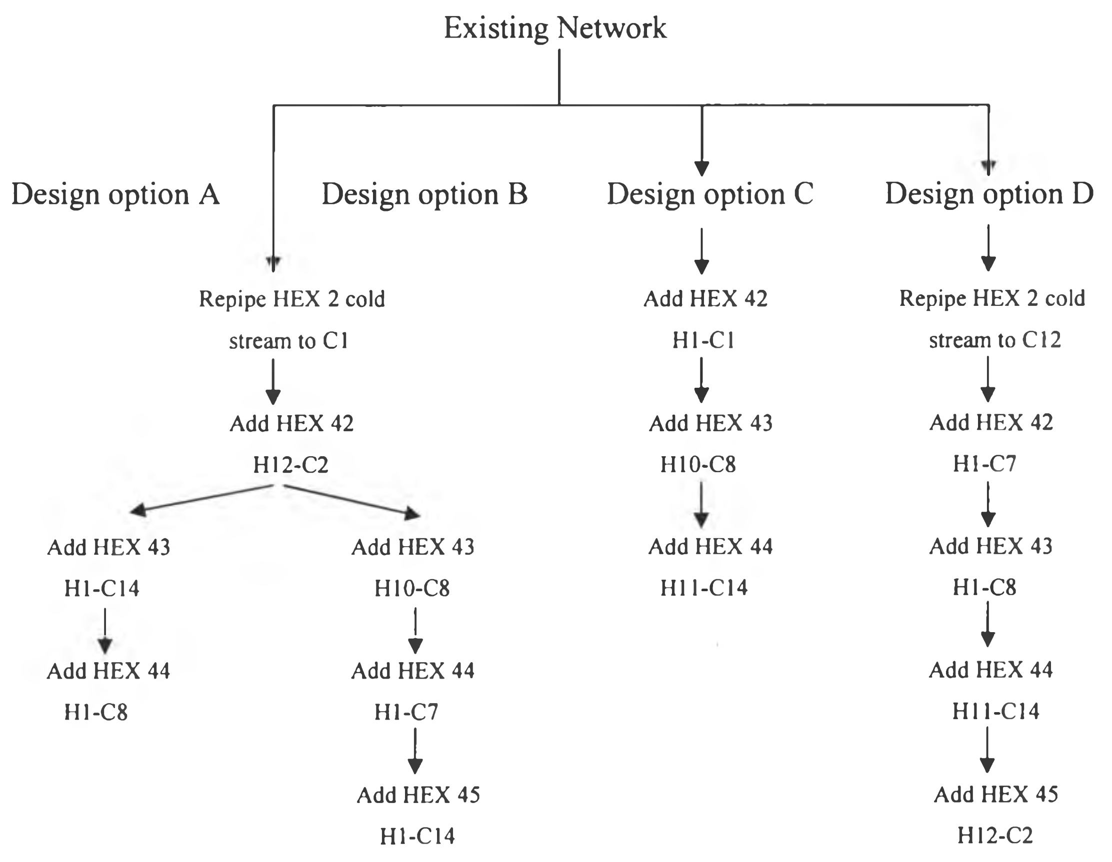



**Figure 4.12** The design solution search tree for diagnosis stage of HEN.

4) No beneficial modifications are found for repiping and resequencing. The addition of new heat exchanger HEX 44 between H1-C8 gives the best energy recovery.

At this stage the inspection is stopped. There are a number of modifications made and now there is no match that gives significant energy savings.

*Design Option B*

1) As mentioned above in design option A the first two modifications are the same as design option A. The third modification is the addition of HEX 43 between H10-C8 that gives 2.257 MW of energy savings.

2) Since stream H1 has high temperature enough to exchange heat with cold stream C7, the addition of HEX 44 between H1-C7 is selected and 1.947 MW of HP steam duty could be saved.

3) Further modification is addition of HEX 45 between H1-C14, which give the best energy recovery.

*Design Option C*

1) This search begins with the addition of new heat exchangers. The first modification should reduce heat transferring across pinch of HEX 2. Therefore the match of HEX 42 between H1-C1 is selected. But this action will change the duty and area of HEX 1 and HEX 2. To minimize the investment cost of added area of these two heat exchangers, the same area of HEX 2 is used, resulting in 4.366 MW of energy savings.

2) The next modification is the addition of HEX 43 which gives two options with maximum energy recovery of stream C8. The two matches are H1-C8 and H10-C8. The match of H10-C8 is selected as in this case since there is large driving force or else low new area with 4.514 MW.

3) The addition of new heat exchanger HEX 44 also gives two options. The first option with the maximum energy recovery is the match between H11 and C14. Although the second option, the match between H28 and C14, saves less energy, the stream match is in the same unit (unit 200) which gives less piping costs. In this design the first option is selected because of the higher utility cost savings. This option gives 5.493 MW of energy savings.

*Design Option D*

1) As mentioned in design option A, the first modification is repiping HEX 2's cold stream toC12 with the heating duty saving of 1.050 MW.

2) The next modification is the addition of new heat exchanger HEX 42 between H1 and C7 since the hot stream, H1, has high temperature enough to exchange heat with cold stream C7. This modification saves HP steam duty of 2.355 MW.

3) The next modification is the addition of new heat exchanger HEX 43 between H1-C8 with the maximum energy recovery of cold stream C8, which saves energy about 2.257 MW.

4) The further modification is the addition of new heat exchanger HEX 44 between H11-C14 with the maximum energy recovery of cold stream C14. This modification gives 5.493 MW of energy savings.

5) The last modification for this design option is the addition of new heat exchanger. Due to the repiping of HEX 2, the stream C2 is heated with the hot stream that has high temperature. And as in design option A the addition of HEX 42 between H12 and C2 is selected.

*4.2.5.2 Optimized Design Options Results*

After all the modifications of each design option have been completed, grid diagrams of the modified network of design options A, B, C and D are generated, and shown in Figures 4.13, 4.14, 4.15 and 4.16, respectively. The retrofit network cost report of all design options are in Appendix E. A summary of the design options modifications are :

Design Option A

- 12.95 MW of energy savings correspond to a utility cost saving about 1.367 M US$ and investment cost of 0.48946 M US$ gives a payback period of 0.358 year.
- Two hot utility units using MP steam and HP steam are removed. The duty of other hot utility unit using HP steam is reduced.

Design Option B

- 16.691 MW of energy savings corresponding to a utility cost saving about 1.752 M US$ and investment cost of 0.6304 M US$ giving a payback period of 0.36 year.
- Two hot utility units using MP steam and HP steam are removed. The duty of other hot utility units using HP steam are reduced.

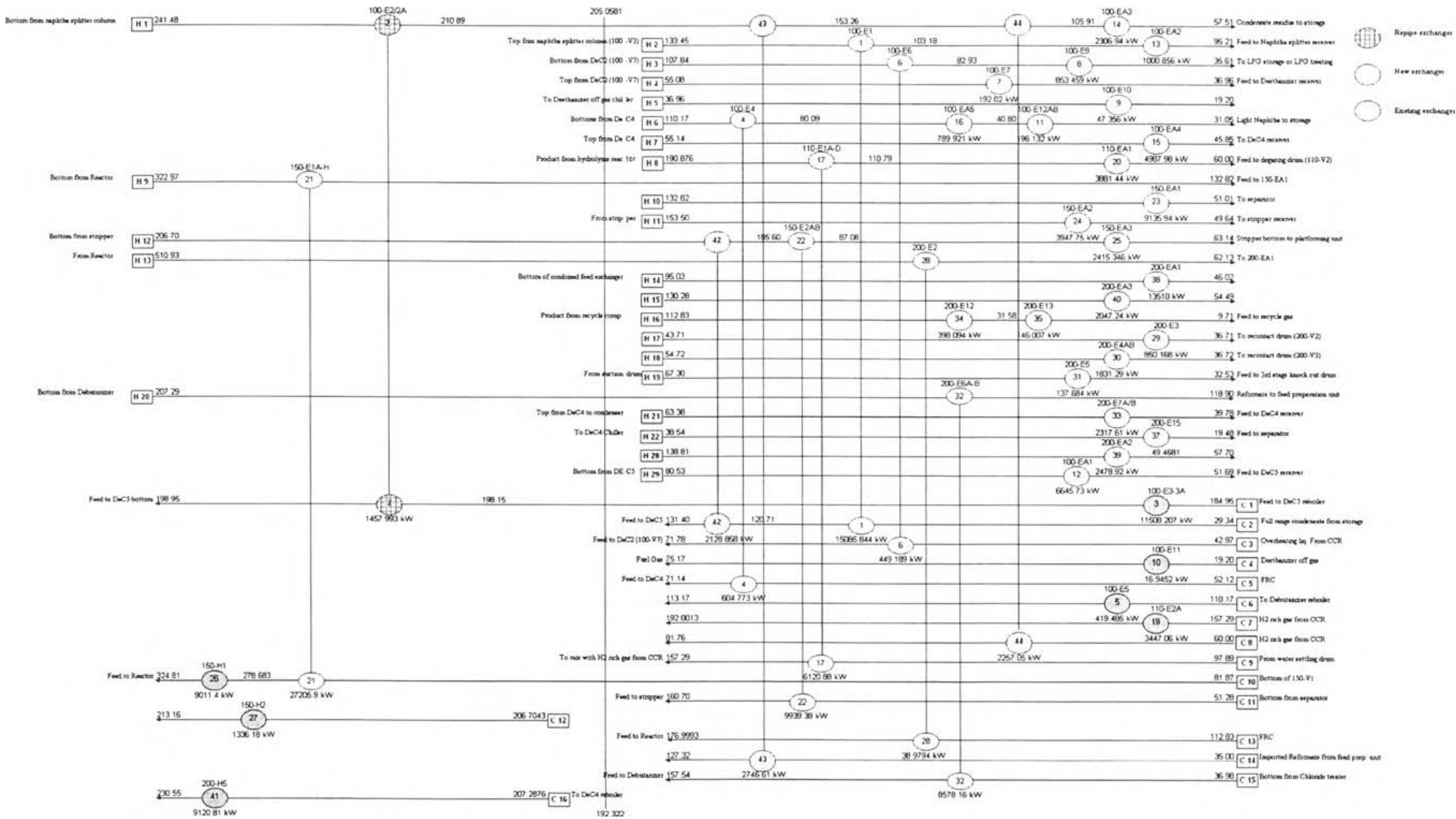


**Figure 4.13** Grid diagram for actual case of design option A.

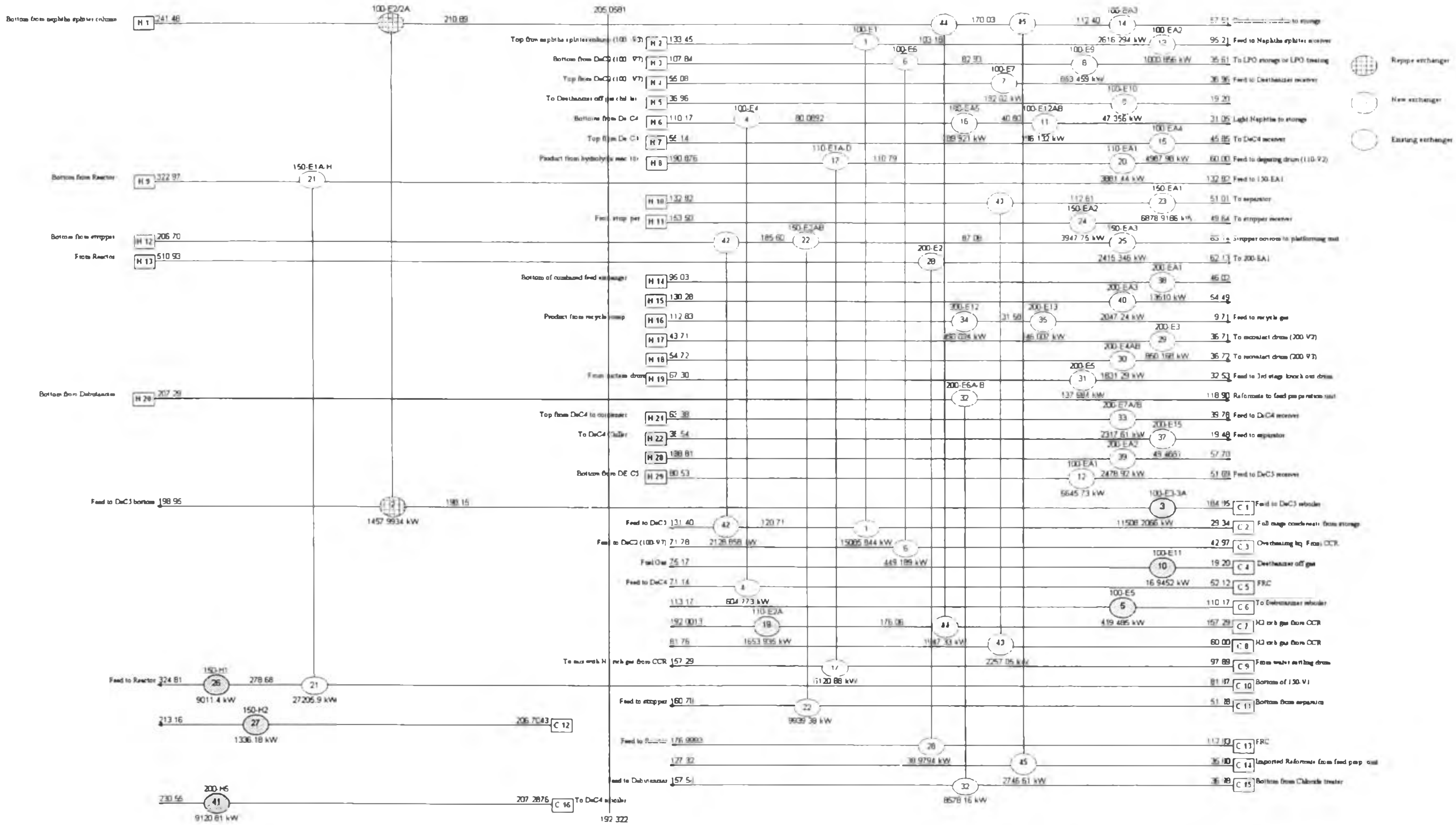


**Figure 4.14** Grid diagram for actual case of design option B.

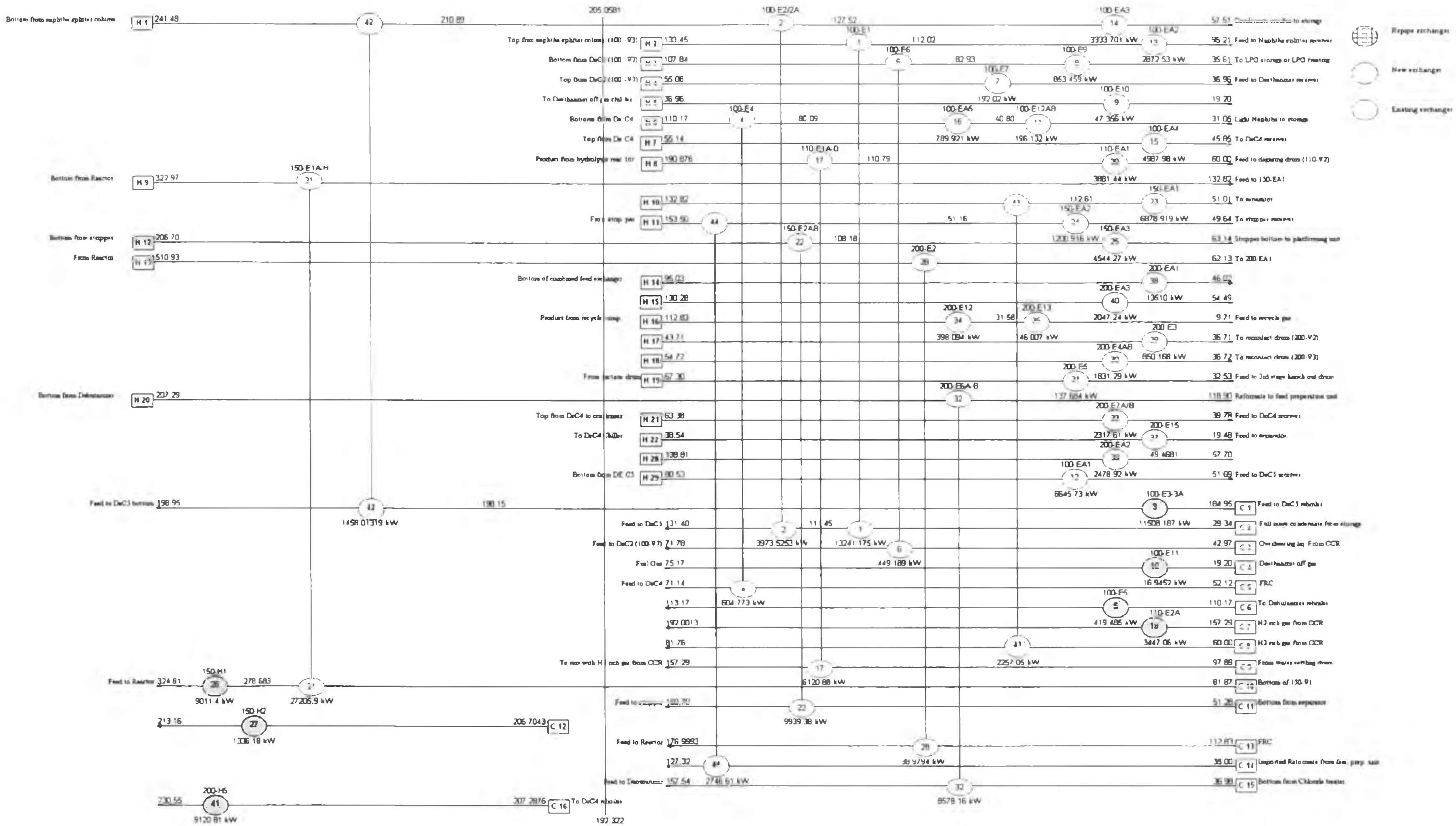


**Figure 4.15** Grid diagram for actual case of design option C.

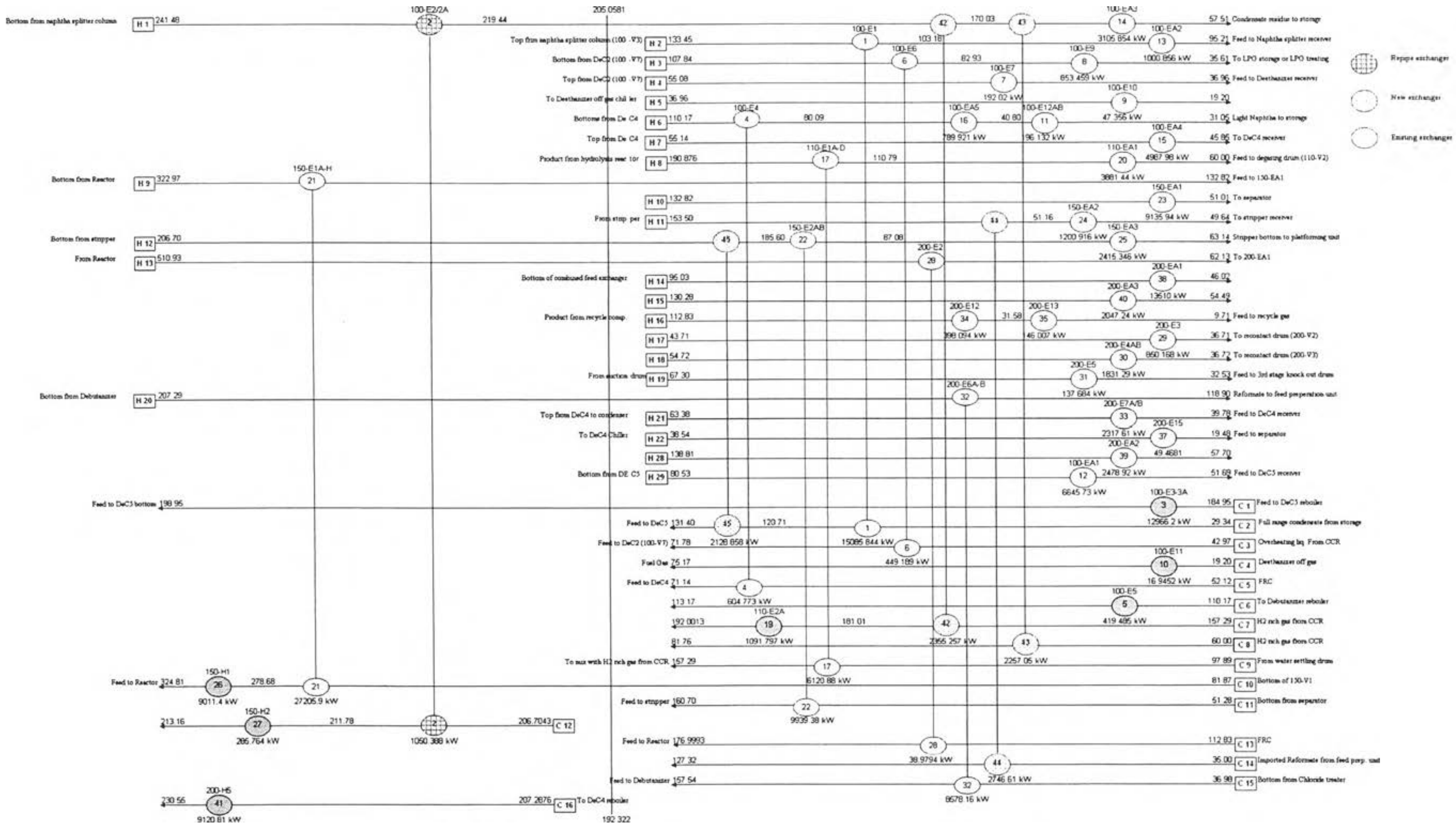


**Figure 4.16** Grid diagram for actual case of design option D.

*Design Option C*

- 12.92 MW of energy savings correspond to a utility cost saving about 1.3672 M US$ and investment cost of 0.3632 M US$ gives a payback period of 0.266 year.
- Two hot utility units using MP steam and HP steam are removed. The duty of other hot utility unit using HP steam is reduced.

*Design Option D*

- 16.846 MW of energy savings correspond to a utility cost saving about 1.996 M US$ and investment cost of 0.6791 M US$ gives a payback period of 0.340 year.
- Two hot utility units using MP steam and HP steam are removed. The duty of other hot utility unit using HP steam is reduced.

For all the design options, the utility units are reduced to zero load. Two design options had three new heat exchangers added to them but other two design options had four new heat exchangers. The number of extra units was limited to keep investment costs low. A number of modifications identified for the different design options are similar. There were two repiping options identified, which is repiping of HEX 2 which transfers a large amount of heat across the pinch. The repiping of HEX 2 moves heat from below to above the pinch and reduced the utility cost significantly since it also reduced the amount of MP steam or power. The rest of the modifications are the addition of new exchangers. The new exchangers include matches between hot streams and cold streams that violate the pinch. The impact on the cost depends on type of hot utility mediums.

The energy savings achieved at each modification step in the diagnosis stage are shown in Figure 4.17. Design D seems to give a good energy saving overall. The comparison of the results of the design options together with the existing design is given in Table 4.24. They all give payback period under 0.5 year.

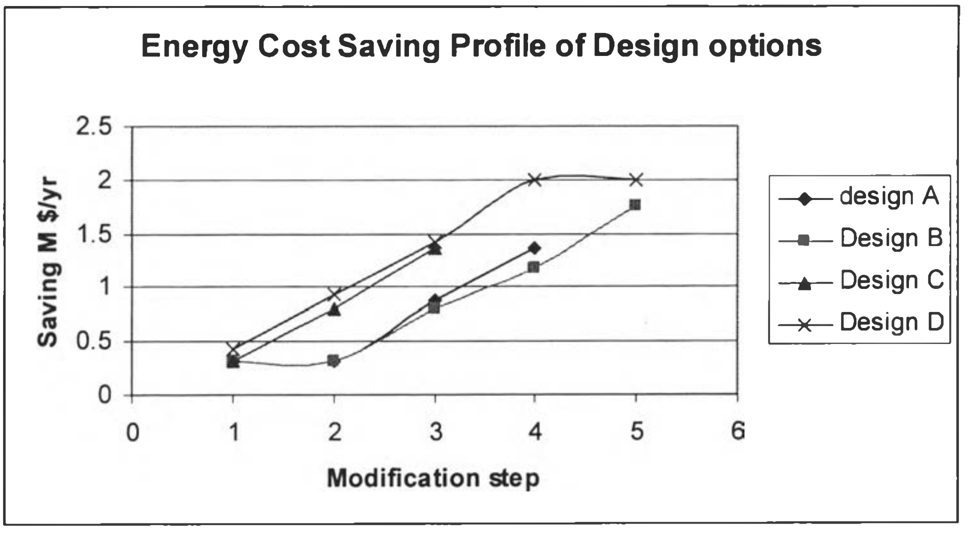



**Figure 4.17** Comparison of energy savings for the different design options.

**Table 4.24** Comparison of design option parameter with existing design

| Design | Utility cost (M$/y) | Area ($m^2$) | ΔA ($m^2$) | no. of units | Payback (y) |
|---|---|---|---|---|---|
| Existing | 10.109 | 6189.08 | | 41 | |
| Option A | 8.741 | 7139.18 | 950.105 | 44 | 0.36 |
| Option B | 8.357 | 7365.11 | 1176.03 | 45 | 0.36 |
| Option C | 8.741 | 6779.35 | 590.265 | 44 | 0.27 |
| Option D | 8.113 | 7533.41 | 1344.33 | 45 | 0.34 |