Energy Recovery

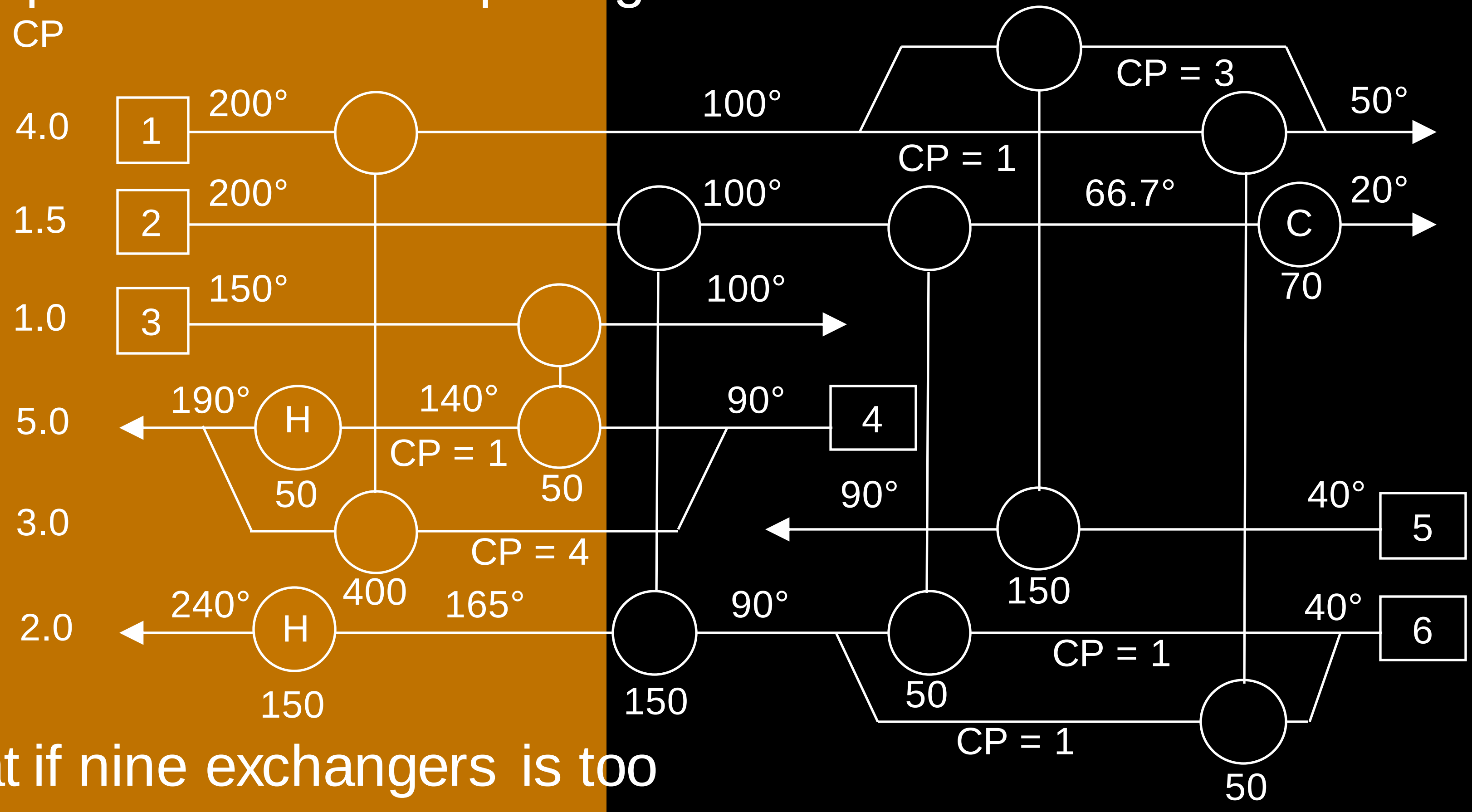
HEAT INTEGRATION

- Find the minimum number of units
- Paths
- Loops then Paths
- Estimating total area of network
- Capital costing

Energy Recovery

Heat Integration

Example from stream splitting lecture

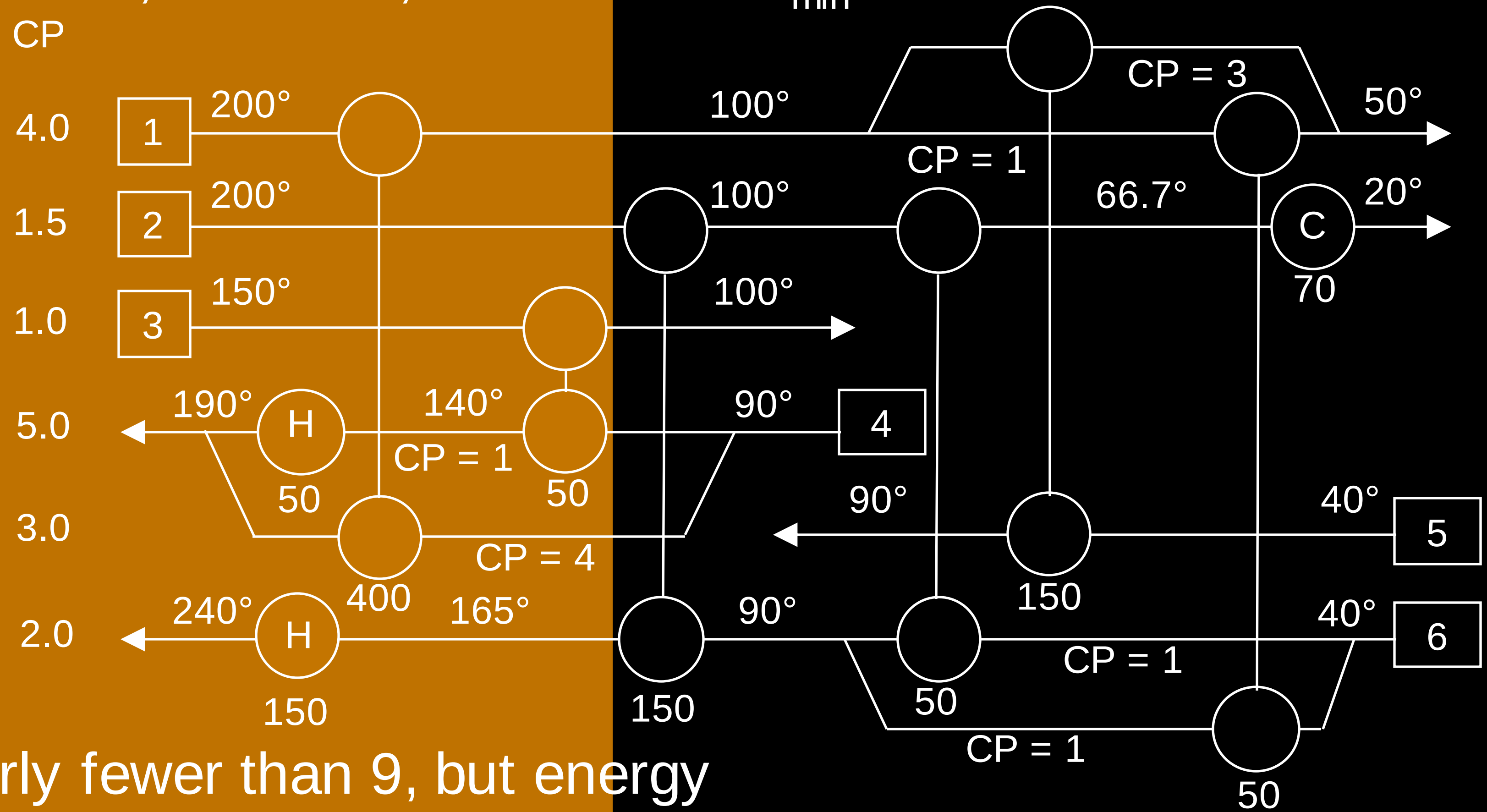


What if nine exchangers is too many?

Energy Recovery

Heat Integration

6 streams, 2 utilities, 1 subset so $U_{min} = 6 + 2 - 1 = 7$

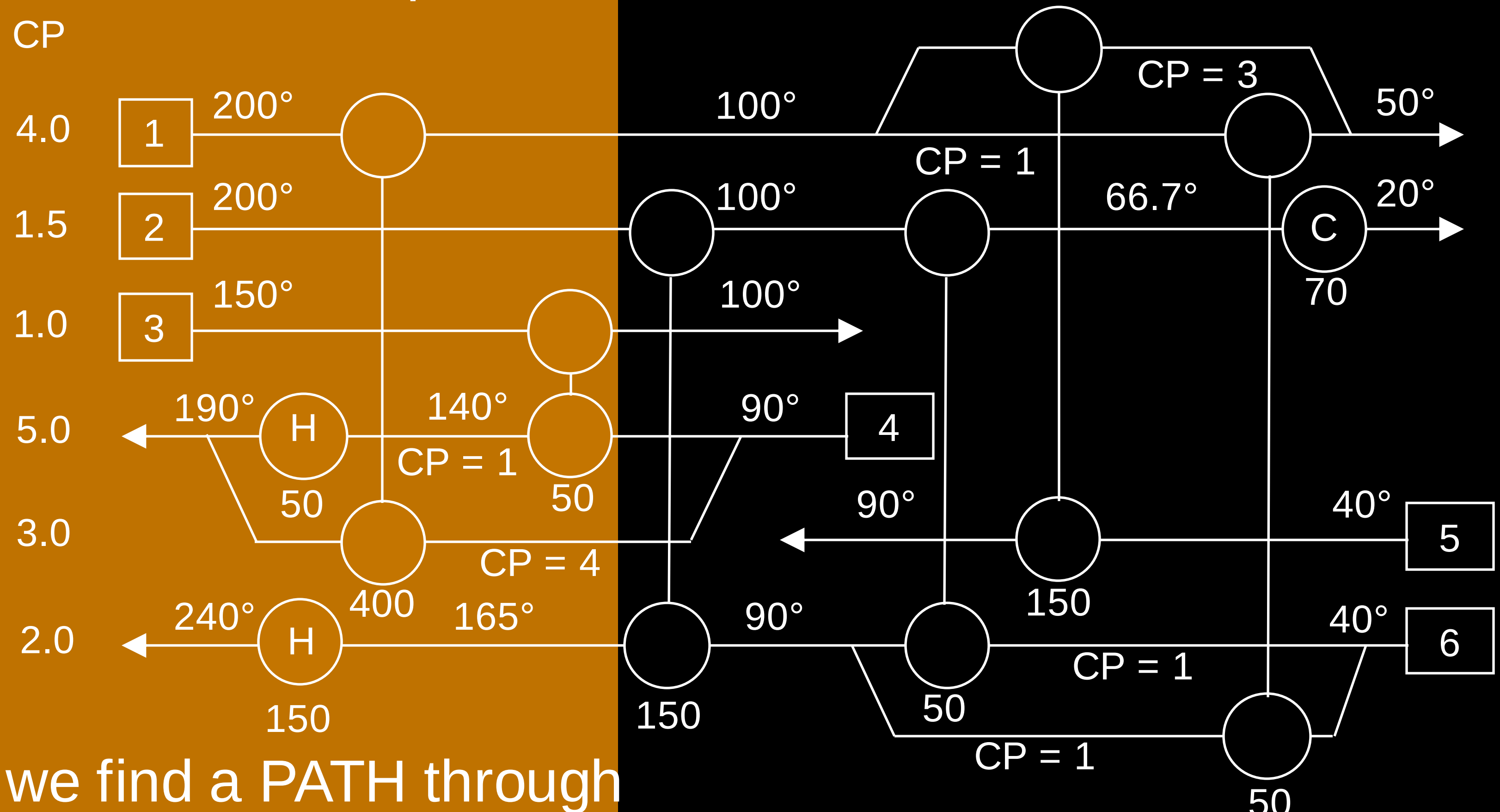


Clearly fewer than 9, but energy will exceed Q_{Hmin} and Q_{Cmin}

Energy Recovery

Heat Integration

APPROACH ONE - paths

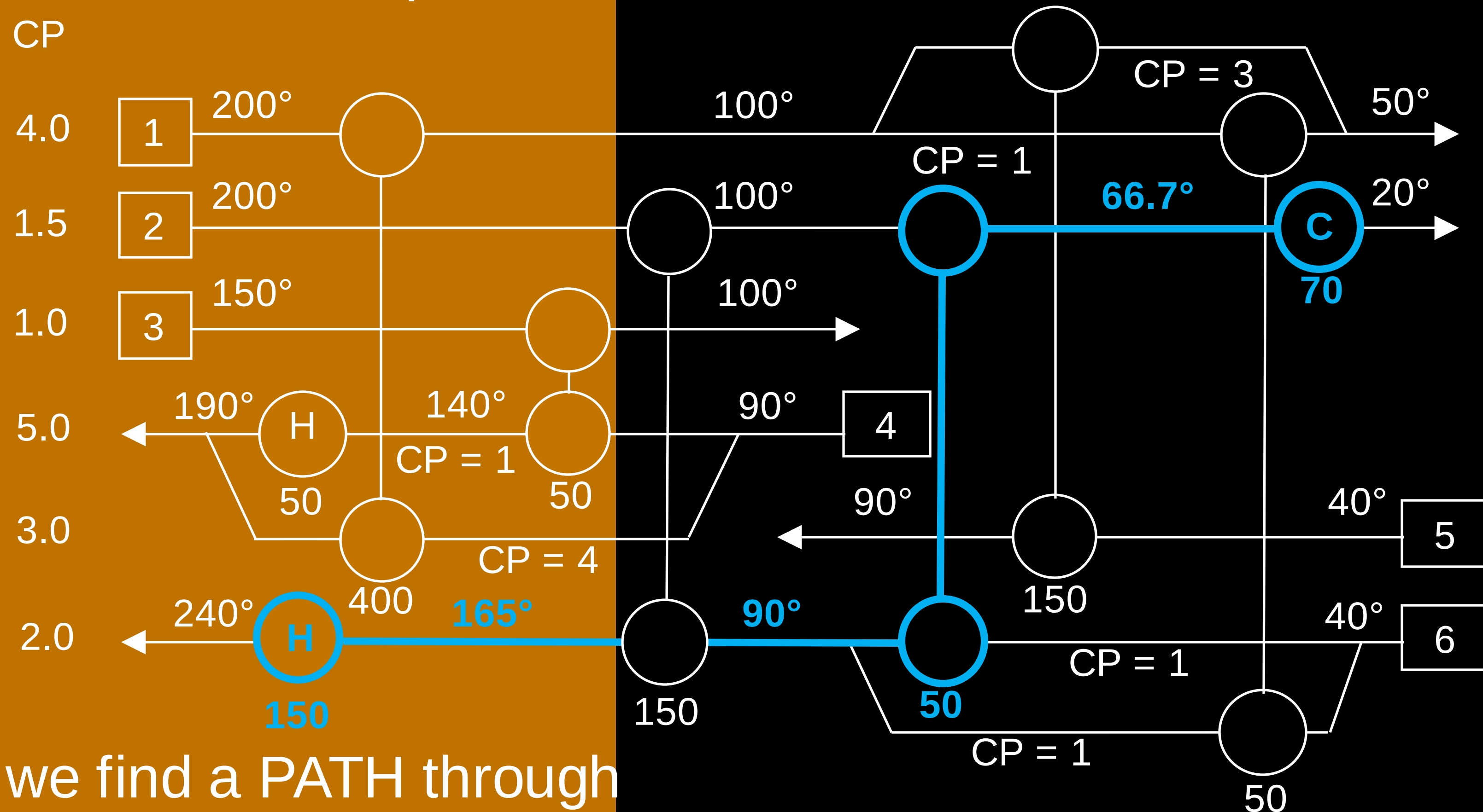


Can we find a PATH through network from hot to cold?

Energy Recovery

Heat Integration

APPROACH ONE - paths

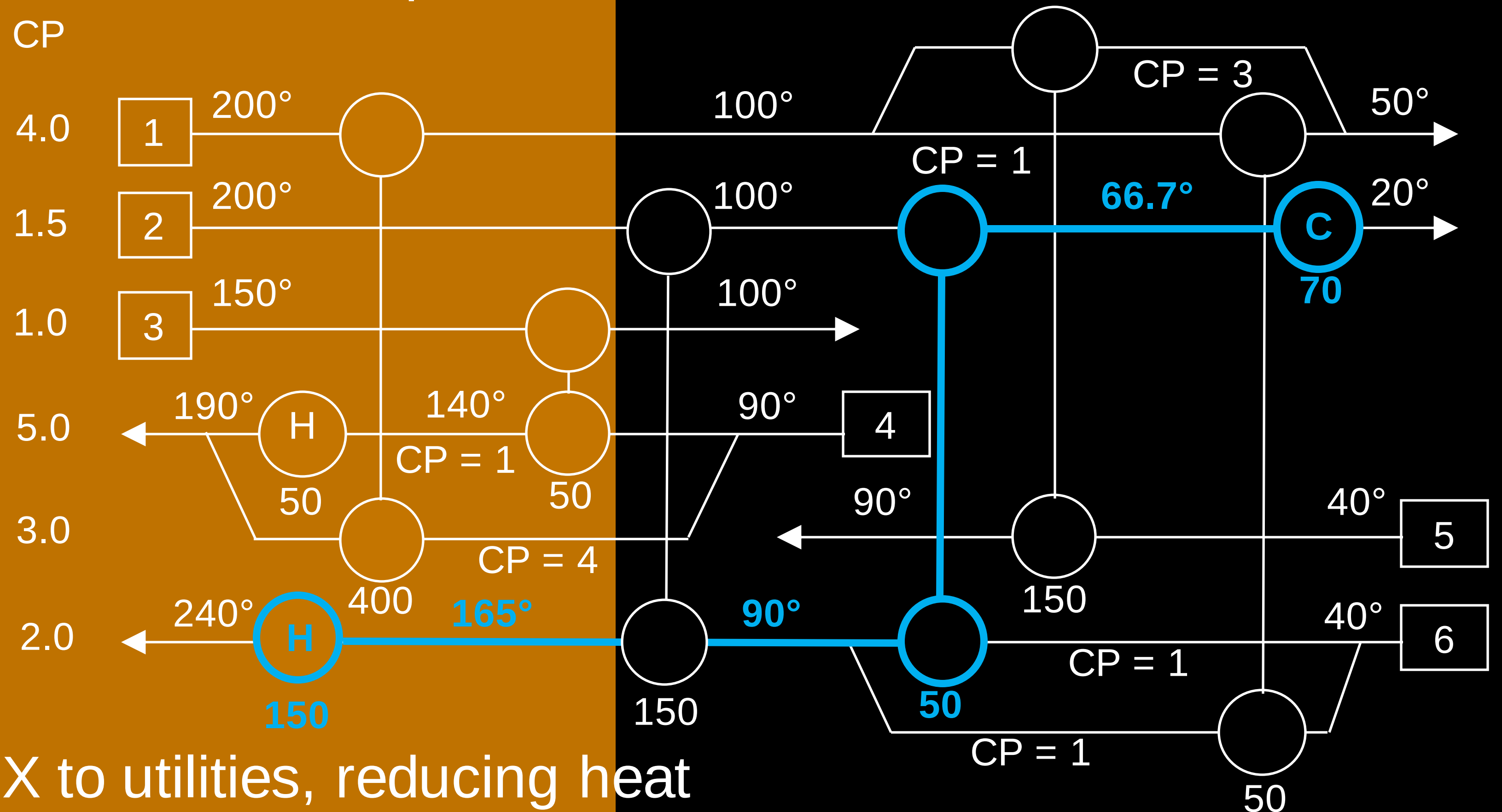


Can we find a PATH through network from hot to cold?

Energy Recovery

Heat Integration

APPROACH ONE - paths

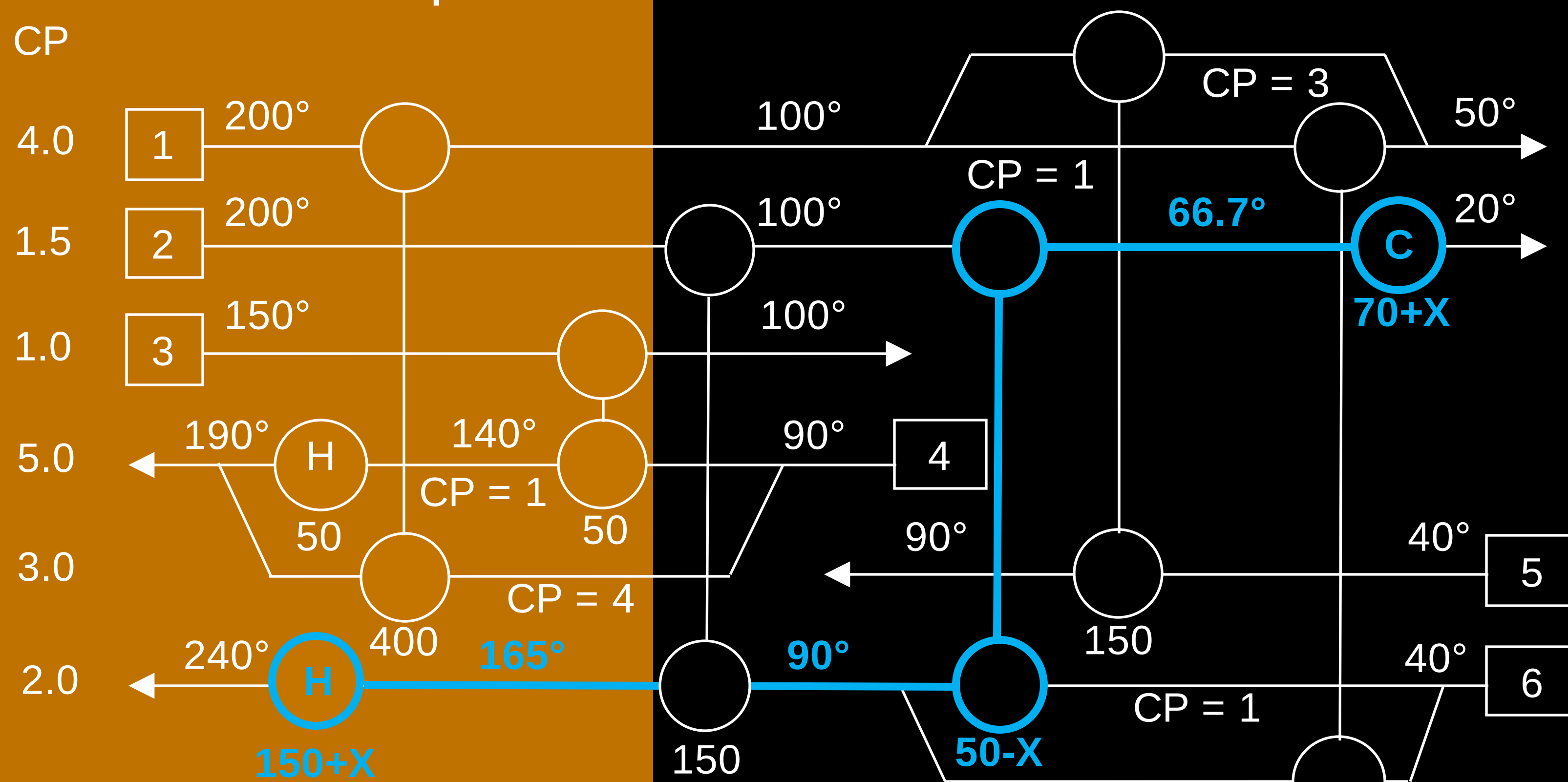


Add X to utilities, reducing heat exchange by X elsewhere

Energy Recovery

Heat Integration

APPROACH ONE - paths

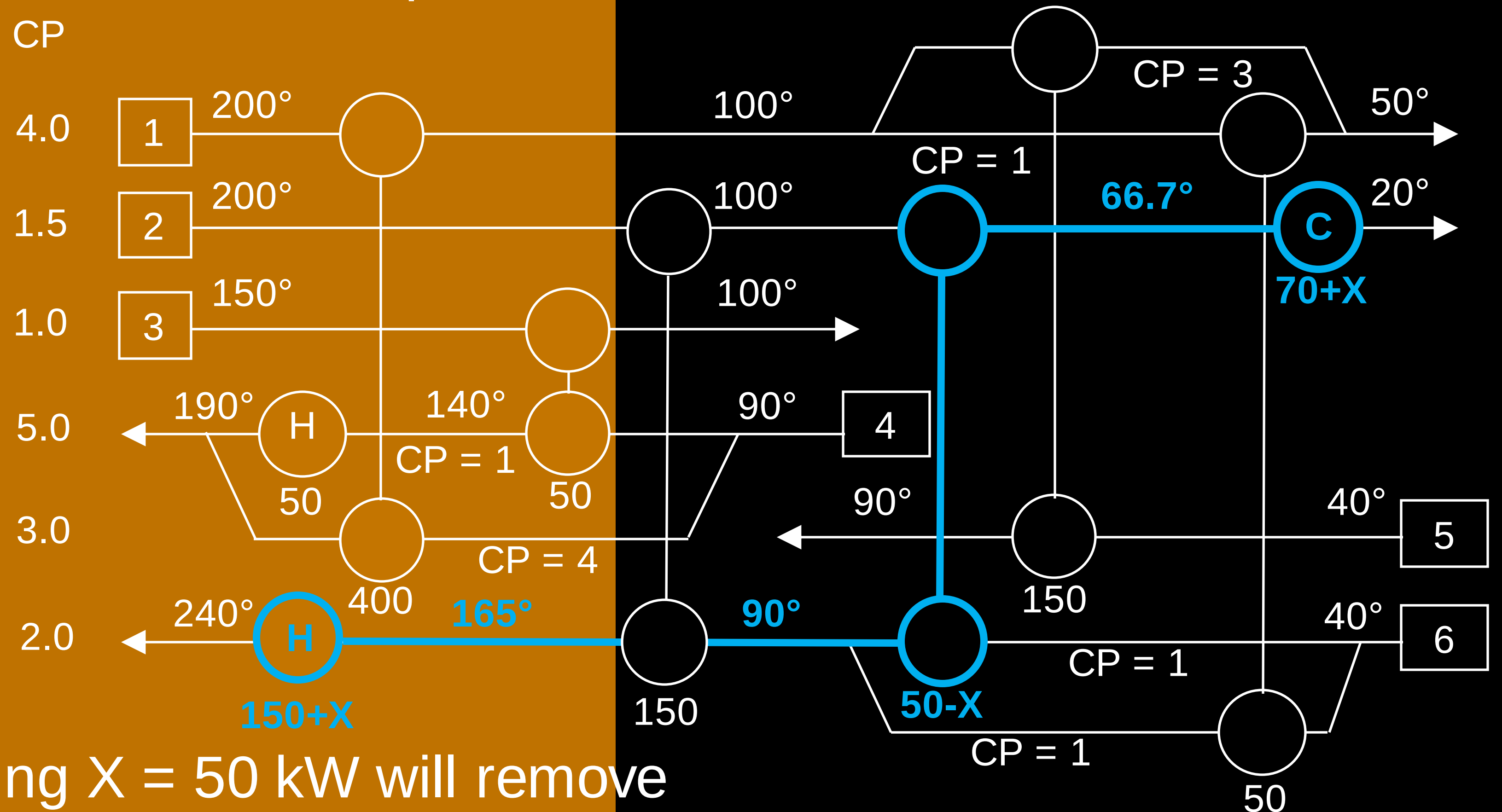


Add X to utilities, reducing heat exchange by X elsewhere

Energy Recovery

Heat Integration

APPROACH ONE - paths

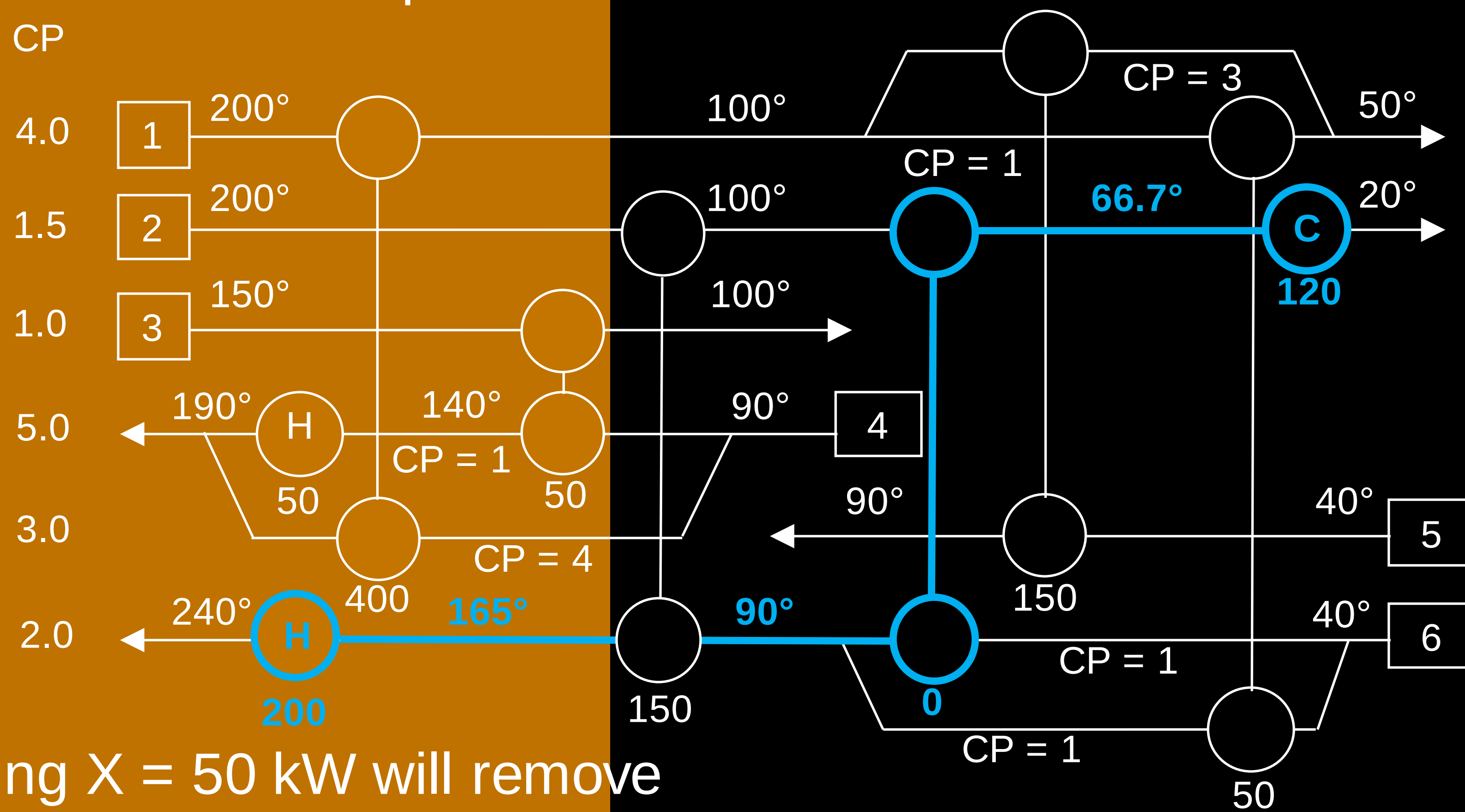


Making X = 50 kW will remove one exchanger and break the path

Energy Recovery

Heat Integration

APPROACH ONE - paths



Making X = 50 kW will remove one exchanger and break the path

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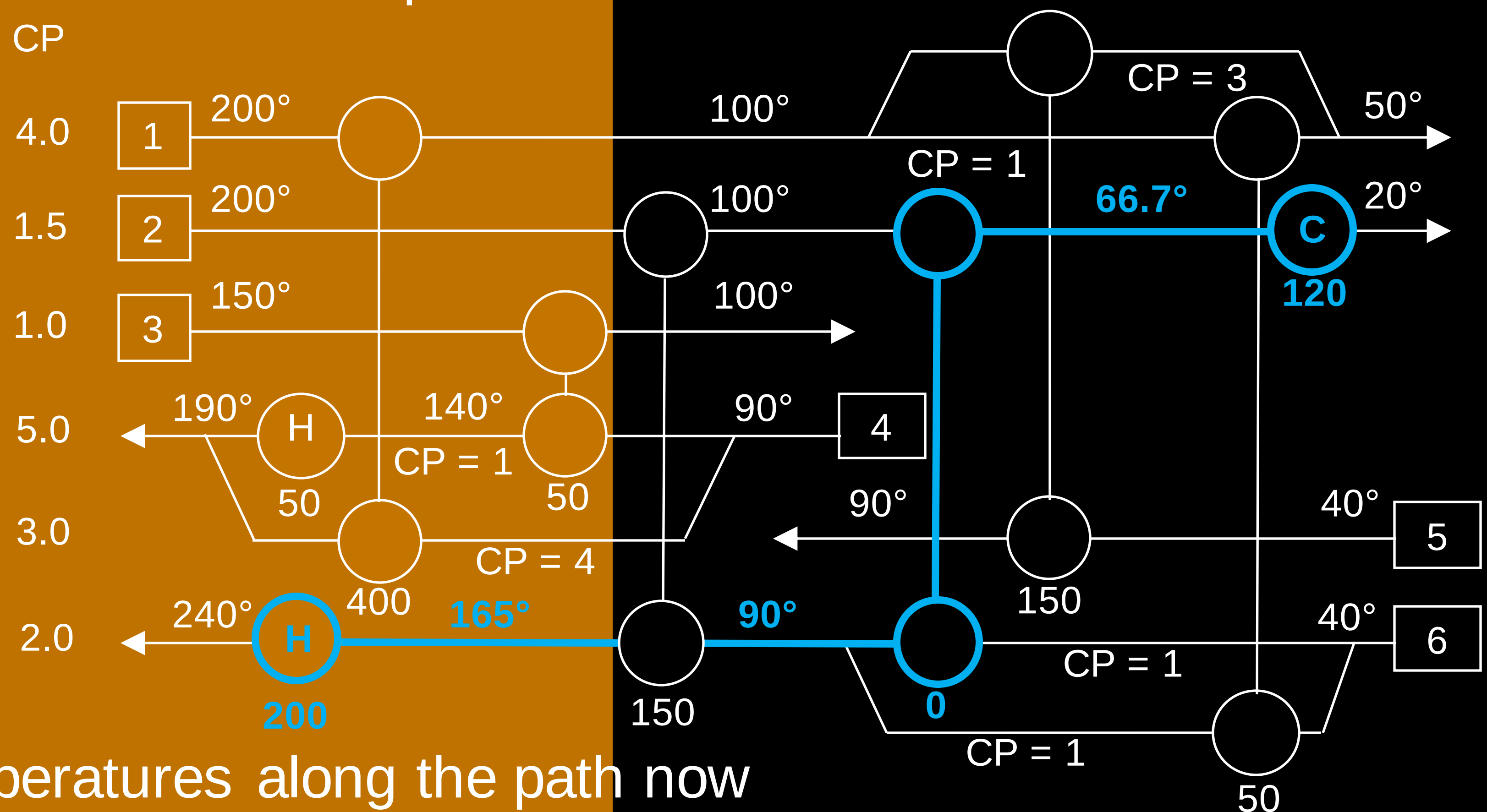
Energy Recovery

Heat Integration

APPROACH ONE - paths

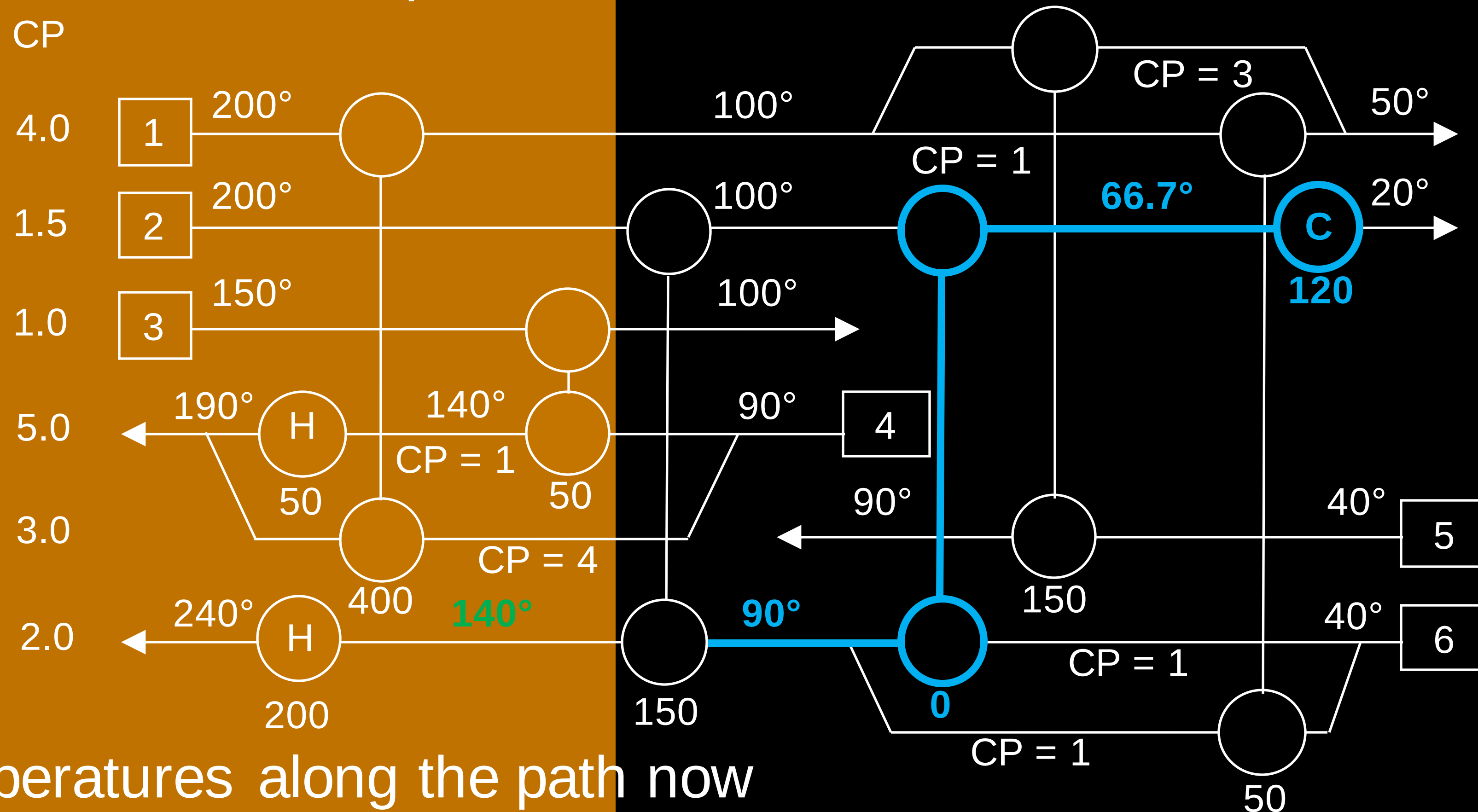


Temperatures along the path now need amending

Energy Recovery

Heat Integration

APPROACH ONE - paths

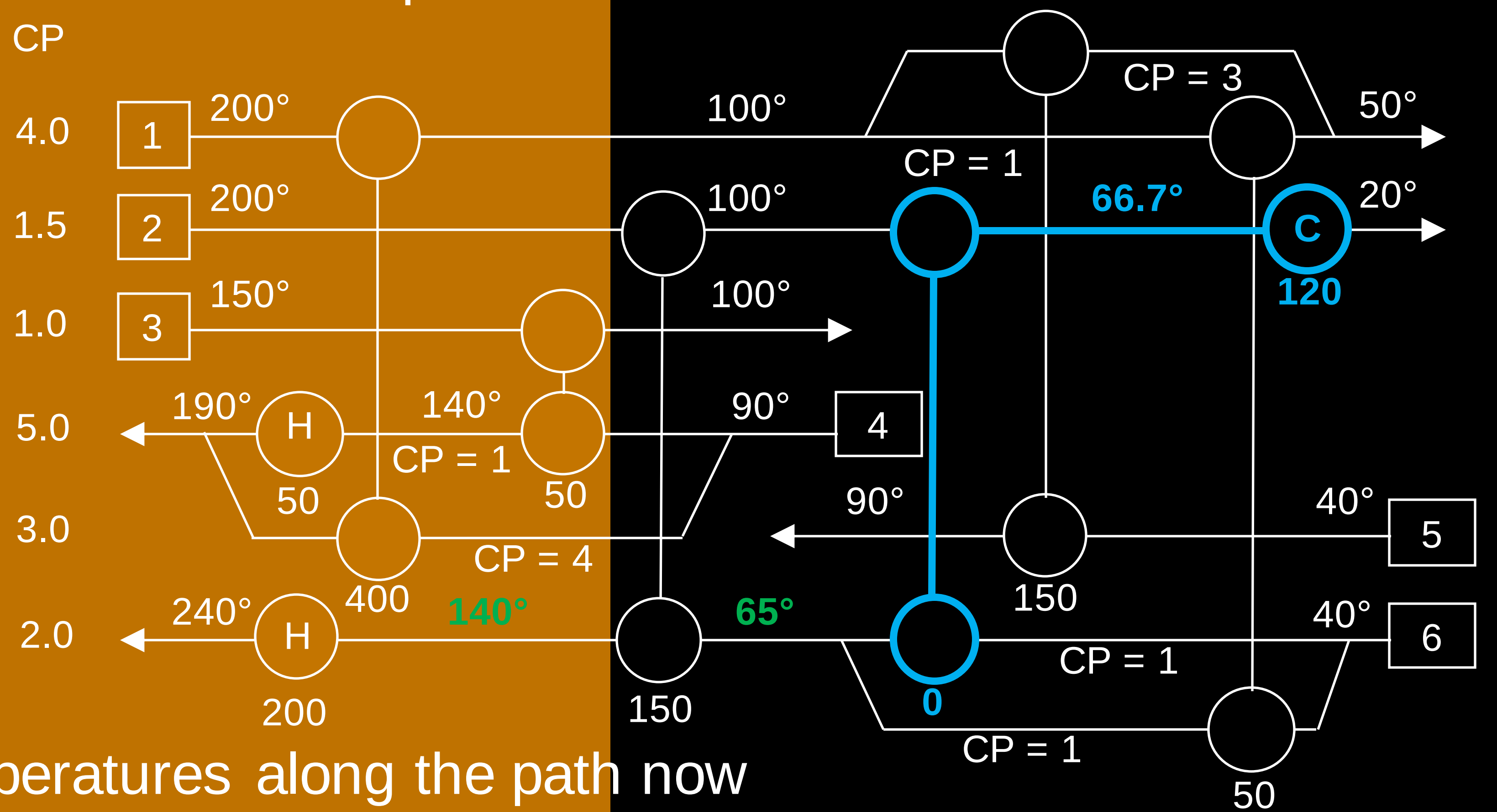


Temperatures along the path now need amending

Energy Recovery

Heat Integration

APPROACH ONE - paths

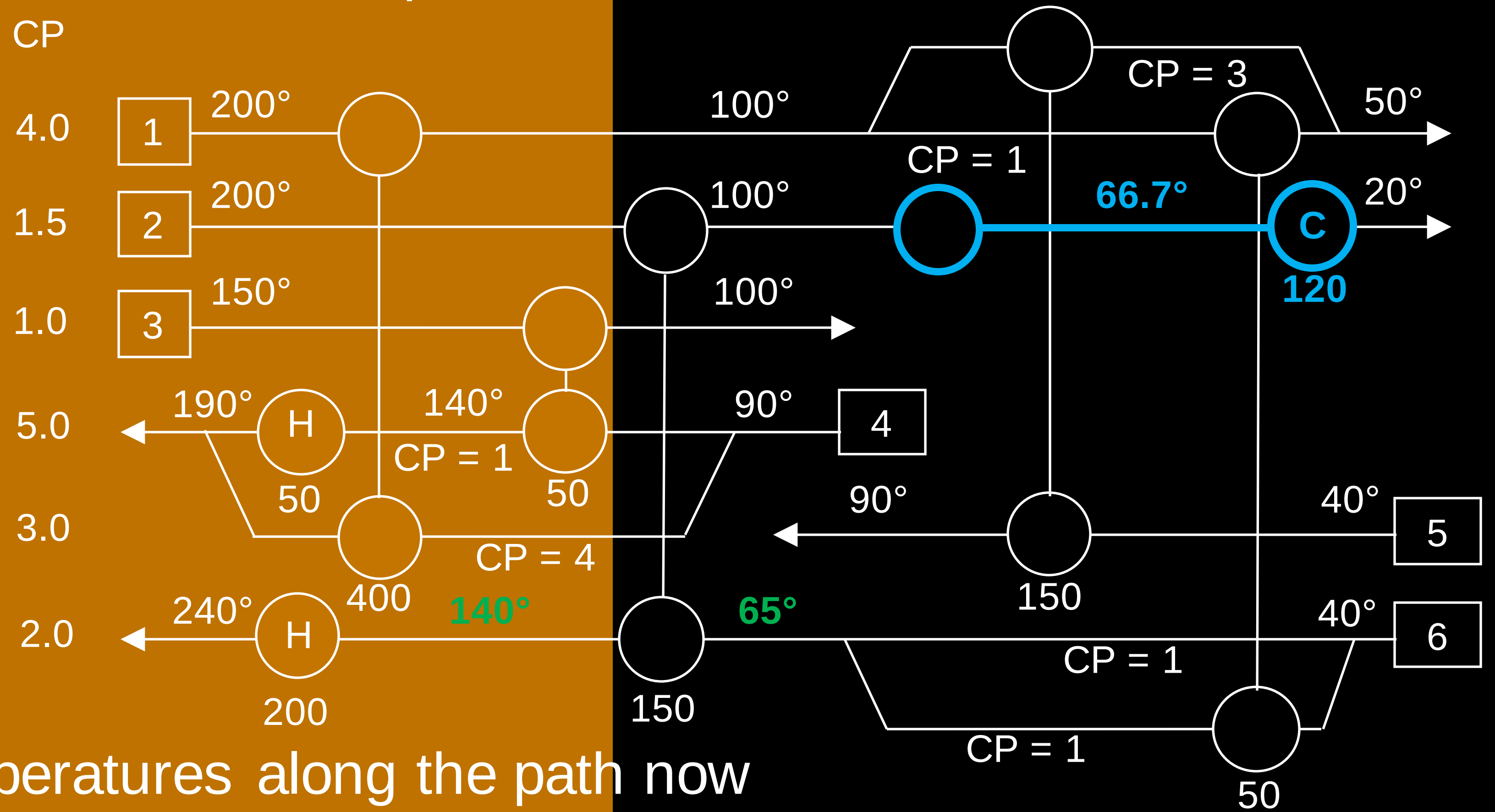


Temperatures along the path now need amending

Energy Recovery

Heat Integration

APPROACH ONE - paths



Temperatures along the path now need amending

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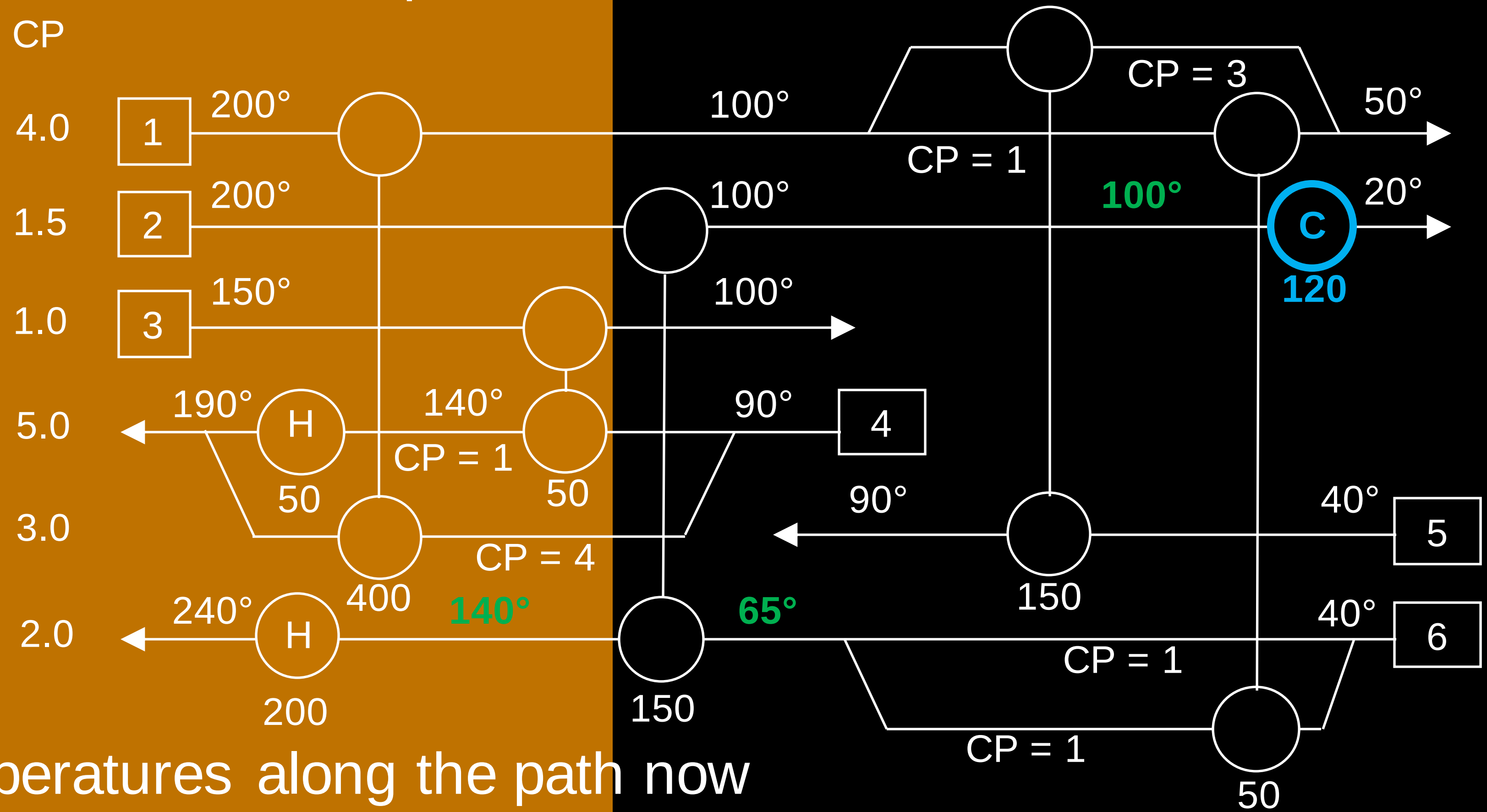
Energy Recovery

Heat Integration

APPROACH ONE - paths

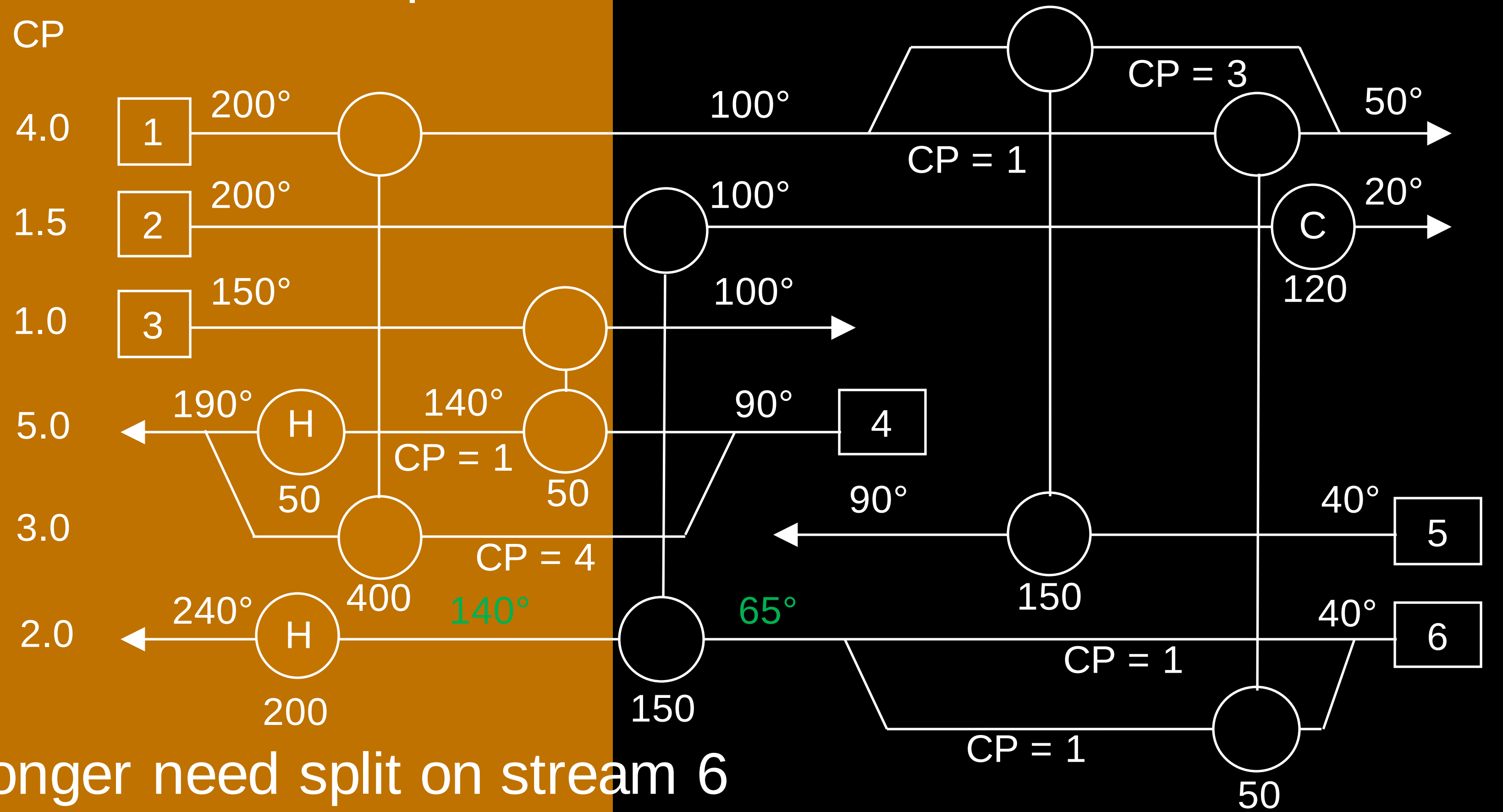


Temperatures along the path now need amending

Energy Recovery

Heat Integration

APPROACH ONE - paths

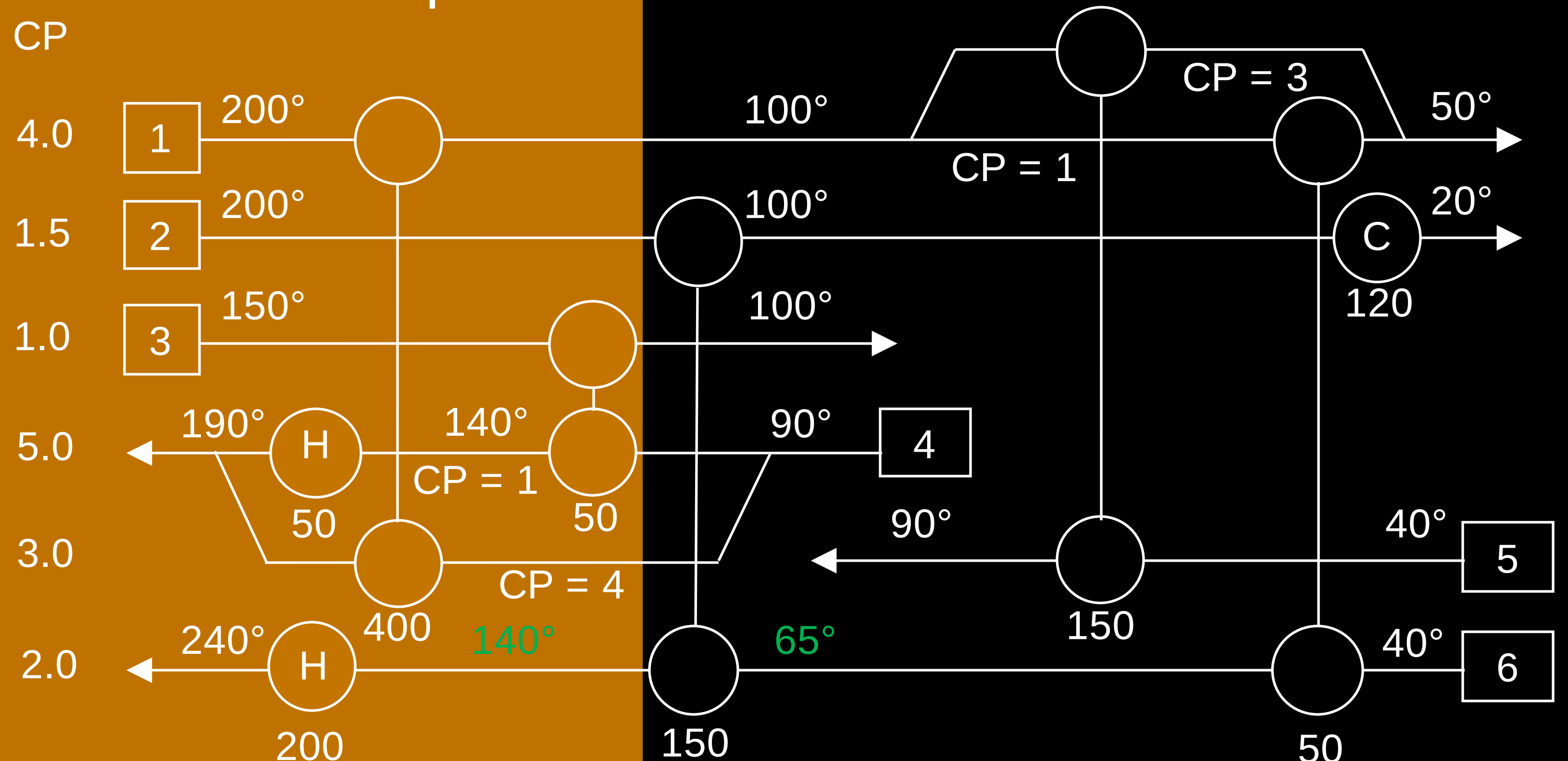


No longer need split on stream 6

Energy Recovery

Heat Integration

APPROACH ONE - paths

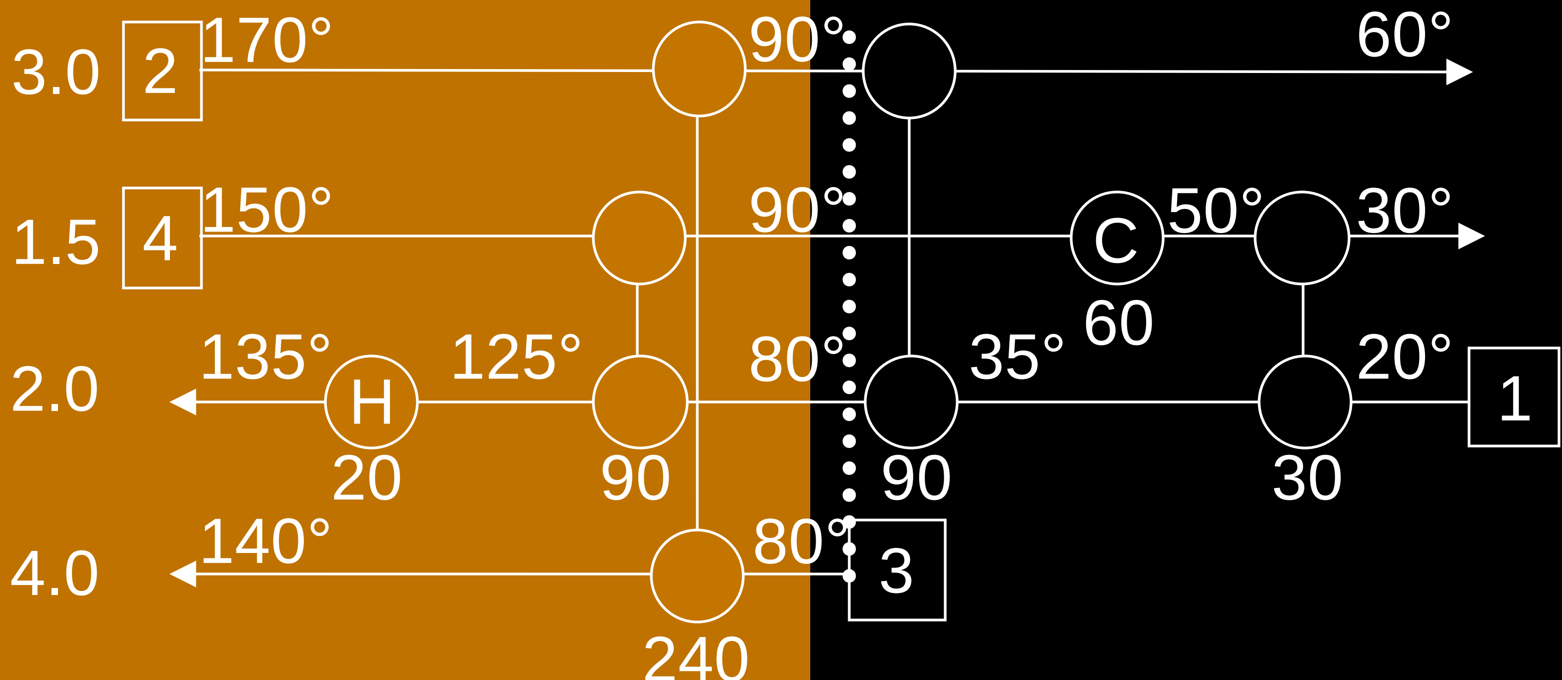


ΔT_{min} of 10° not violated, U = 8, simpler network, but utility demand higher

Energy Recovery

Heat Integration

APPROACH TWO: Example from earlier lecture, $U_{min/MER} = 6$



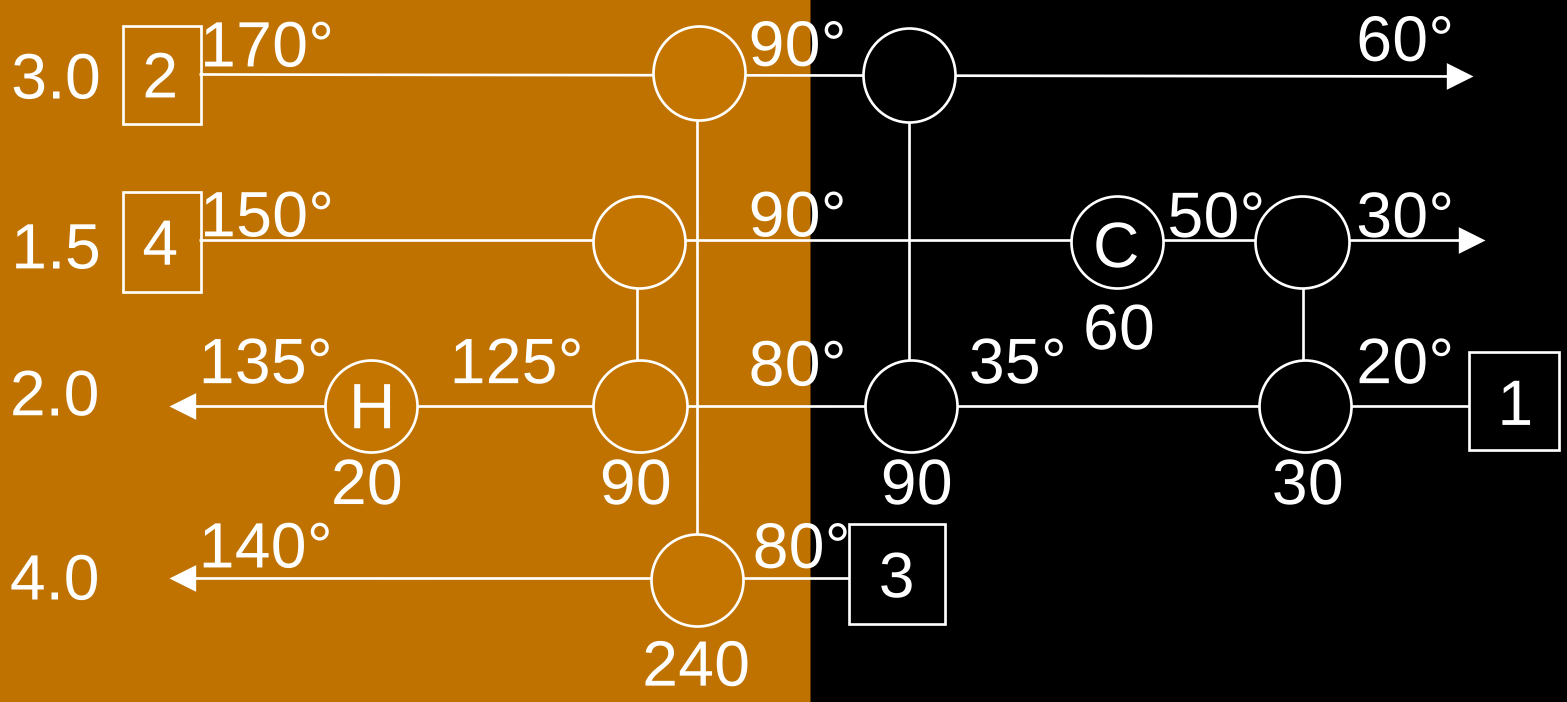
What if six exchangers is too many?

Relax pinch constraint; will discarding MER mean lower U_{min}?

Energy Recovery

Heat Integration

Without pinch, number of streams = 6 (including utilities)



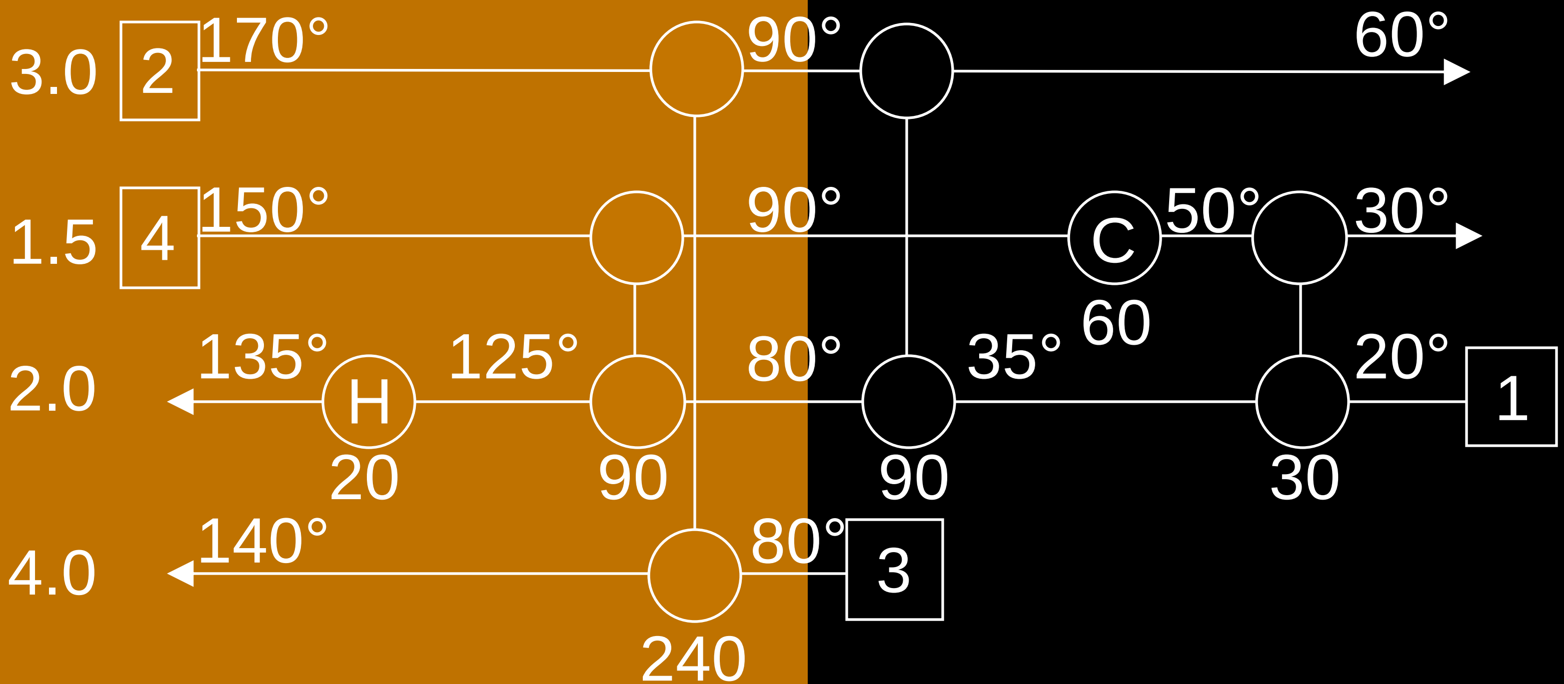
$U_{min} = 6 - 1 = 5$

ie. we could lose an exchanger, but which?

Energy Recovery

Heat Integration

Approach number two – eliminate LOOPS

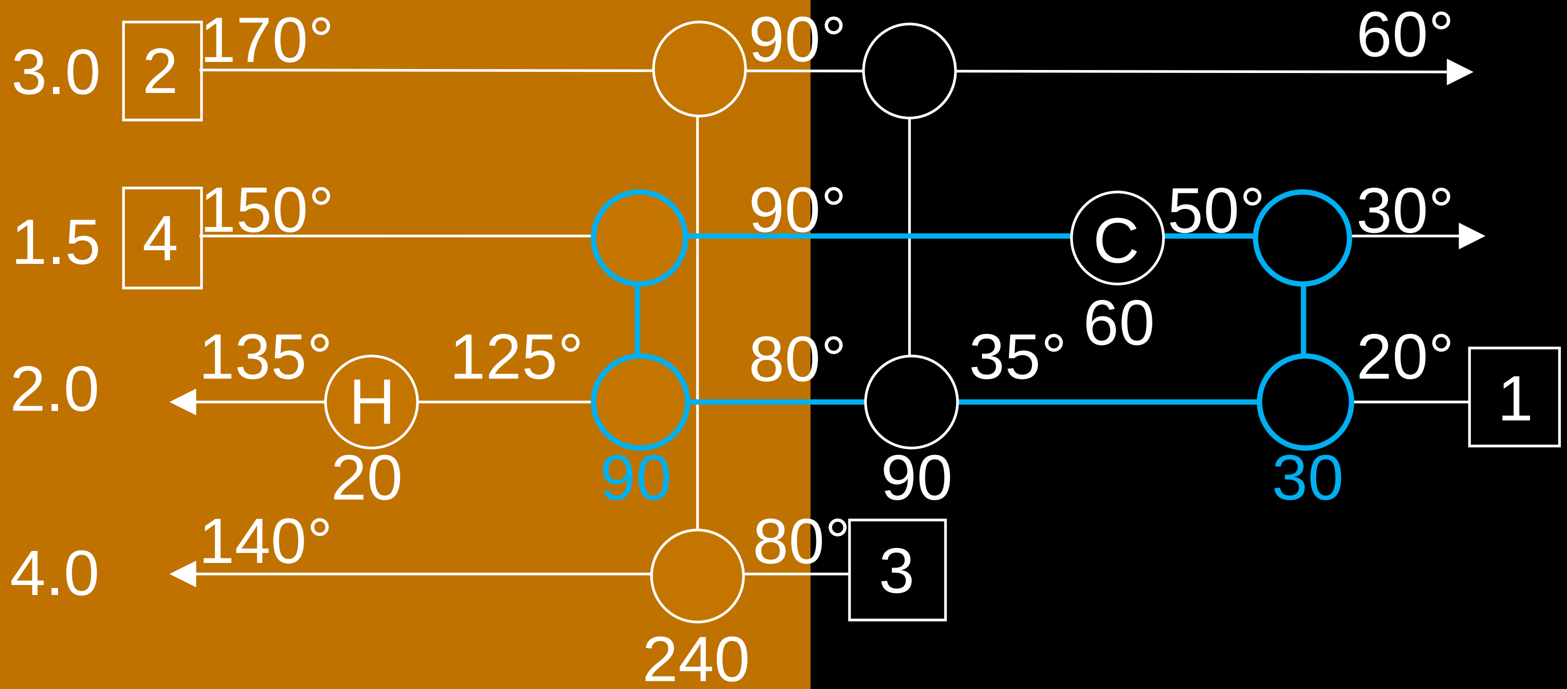


Can we start at an exchanger and move around the network until we are back where we started?

Energy Recovery

Heat Integration

Approach number two – eliminate LOOPS

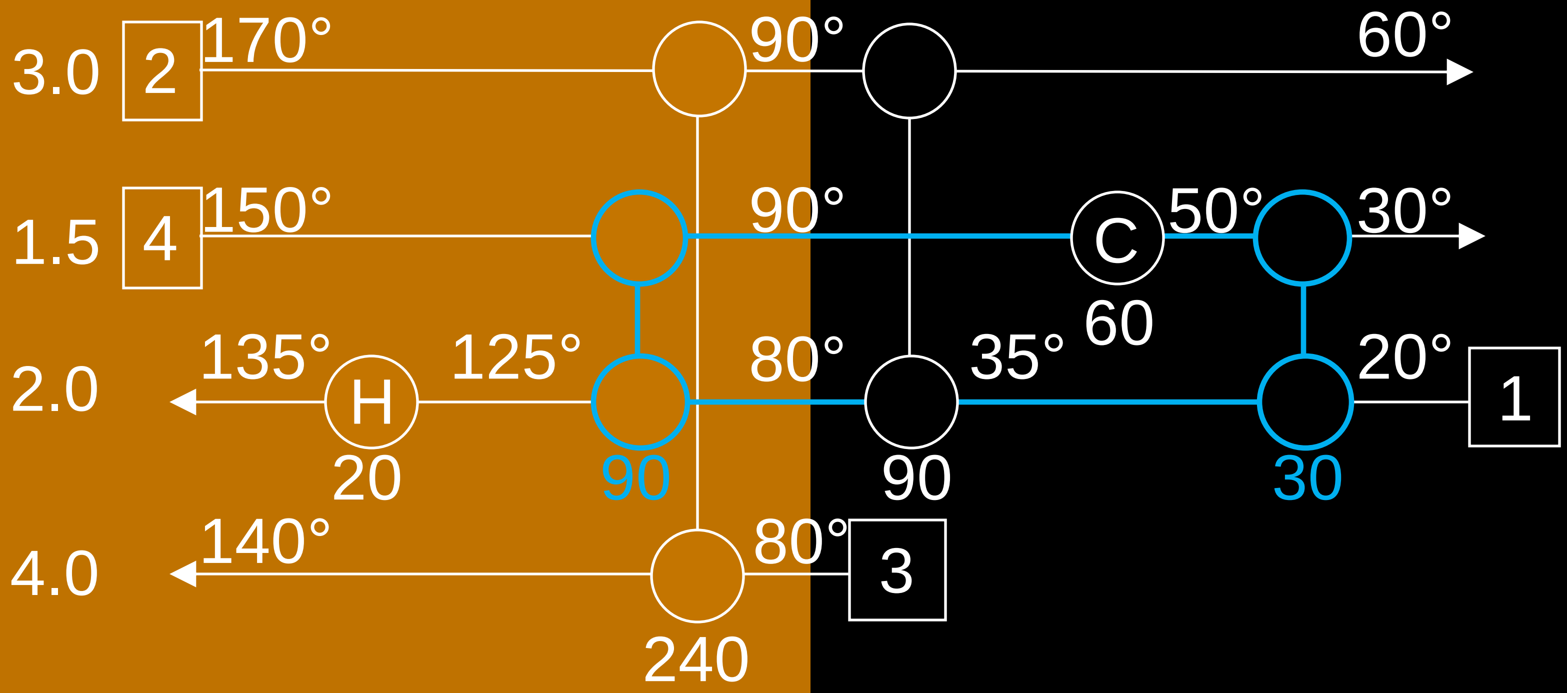


Can we start at an exchanger and move around the network until we are back where we started?

Energy Recovery

Heat Integration

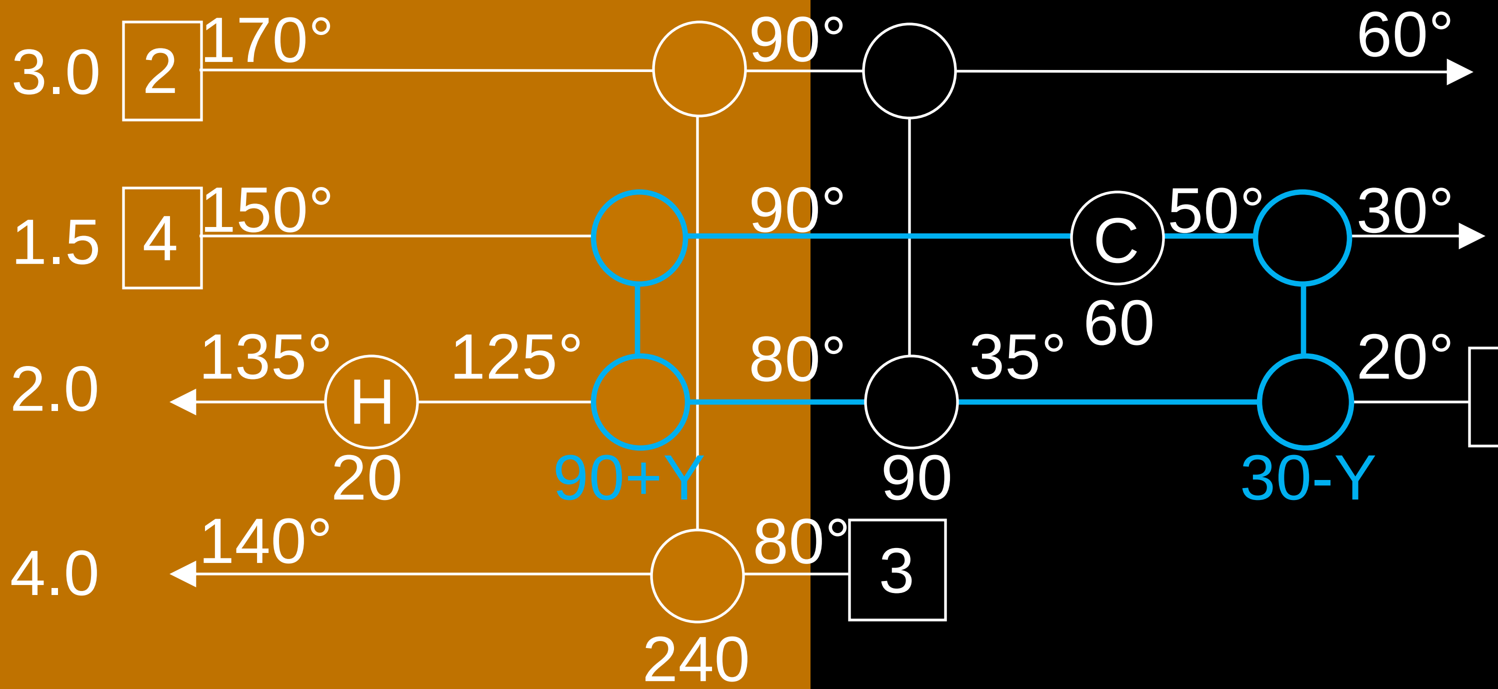
If left hand exchanger had Y added to duty



Energy Recovery

Heat Integration

If left hand exchanger had Y added to duty



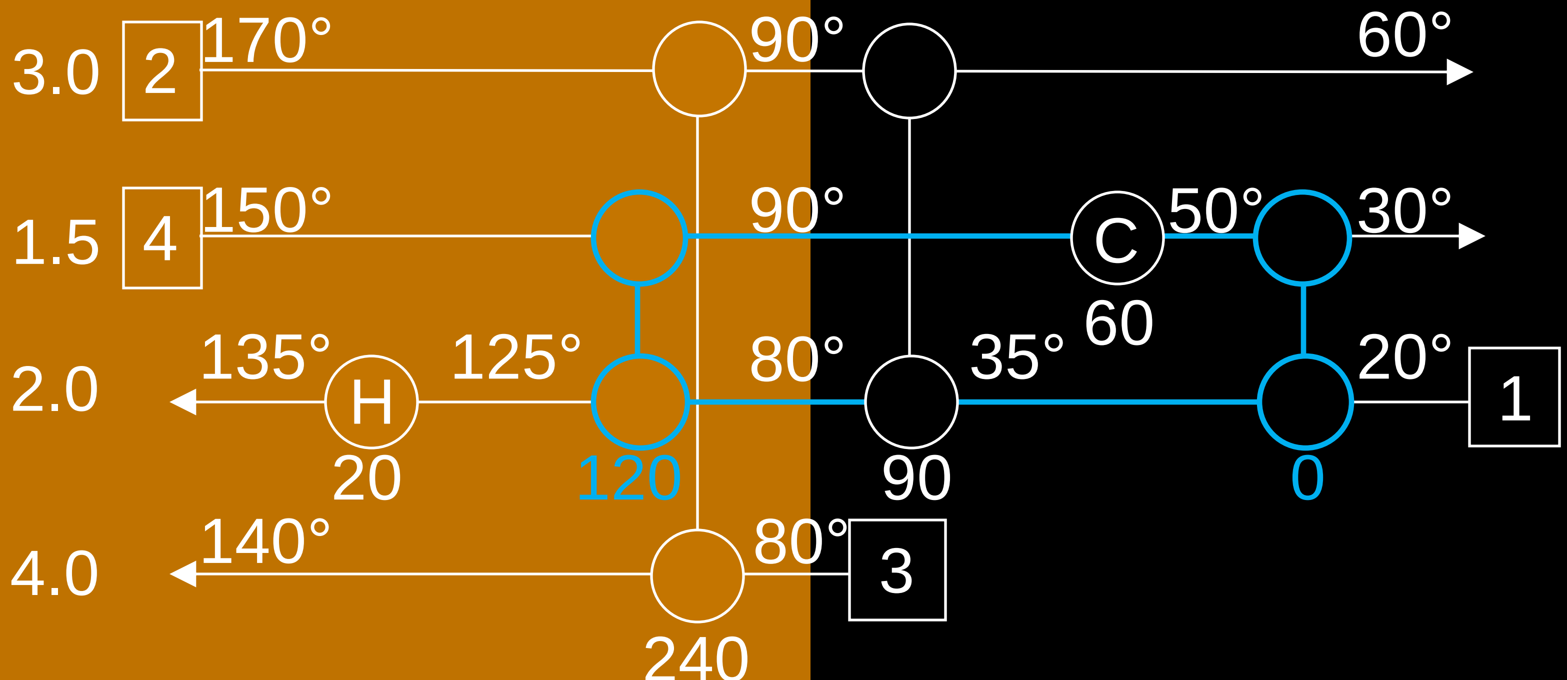
To remove loop entirely, let Y = duty of its smallest exchanger

Here, Y = 30

Energy Recovery

Heat Integration

If left hand exchanger had X added to duty



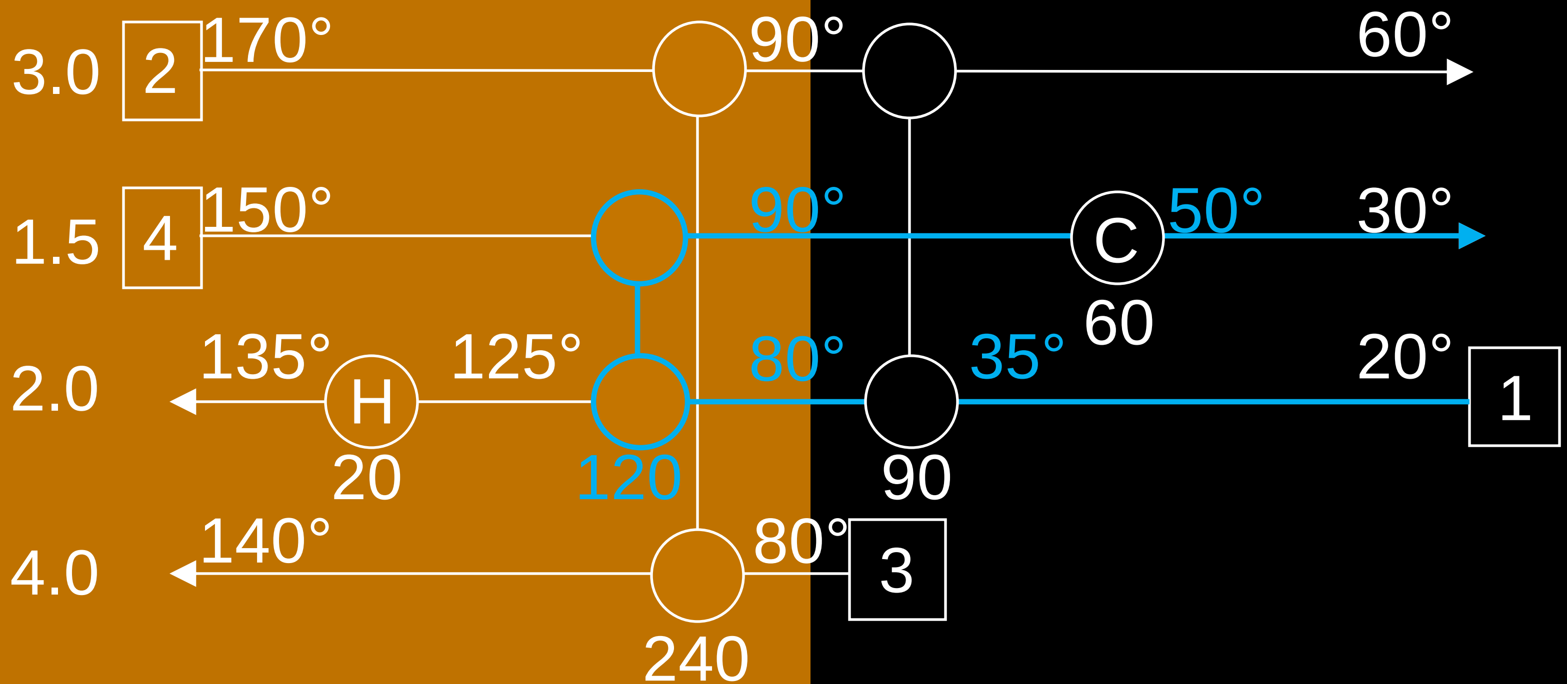
To remove loop entirely, let Y = duty of its smallest exchanger

Here, Y = 30

Energy Recovery

Heat Integration

Temperatures on streams 1 and 4 now need review

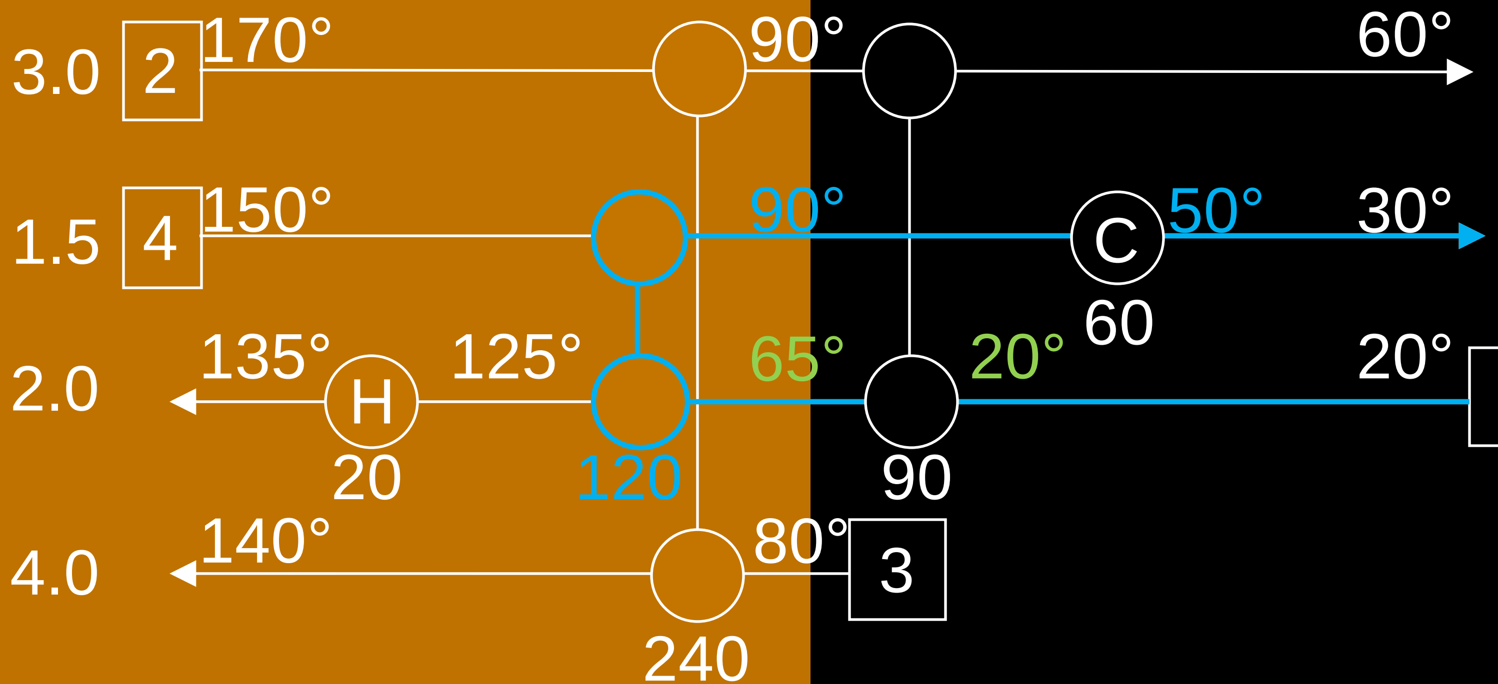


Stream 1 @ 2.0 kW °C^{-1}: 120 kW adds 60° rather than 45°

Energy Recovery

Heat Integration

Temperatures on streams 1 and 4 now need review



Stream 1 @ 2.0 kW °C^{-1} : 120 kW adds 60° rather than 45°

Stream 4 @ 1.5 kW °C^{-1} : 120 kW removes 80° not 60°

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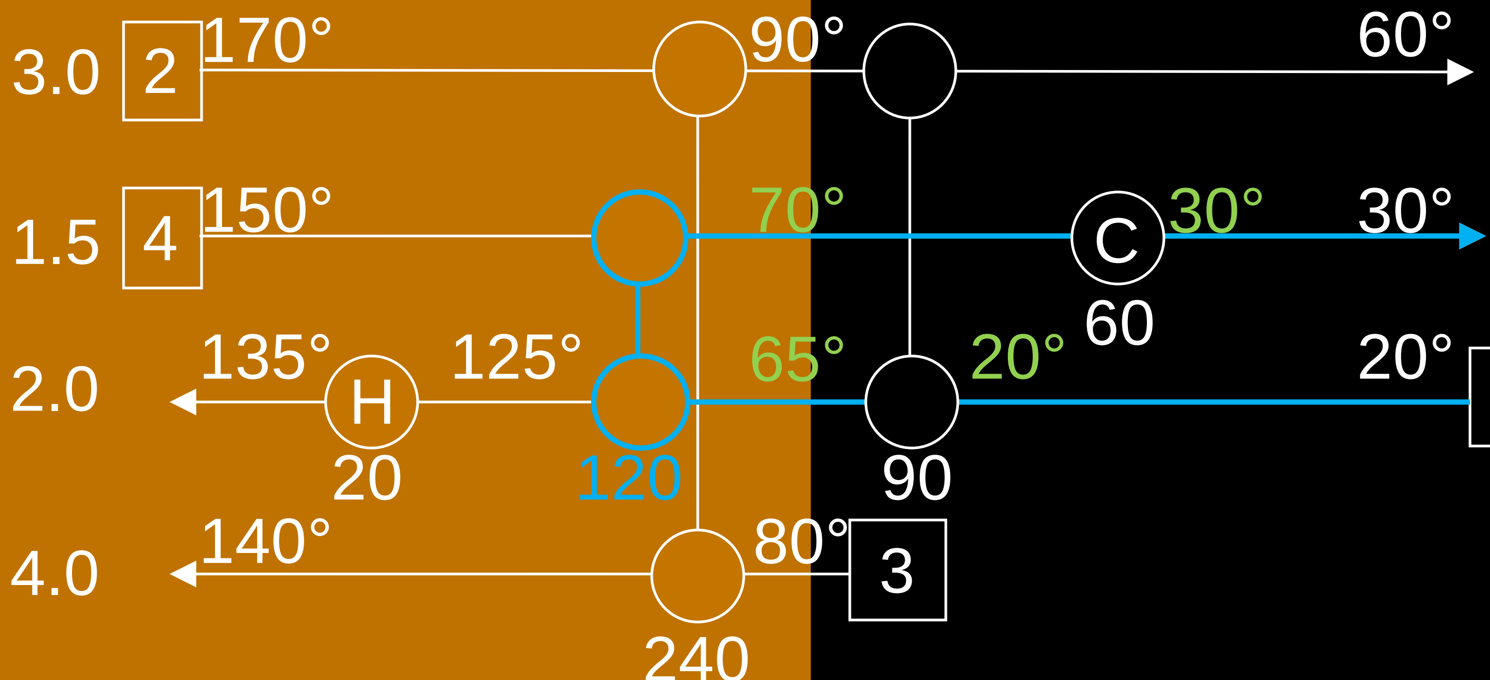
Energy Recovery

Heat Integration

Temperatures on streams 1 and 4 now need review



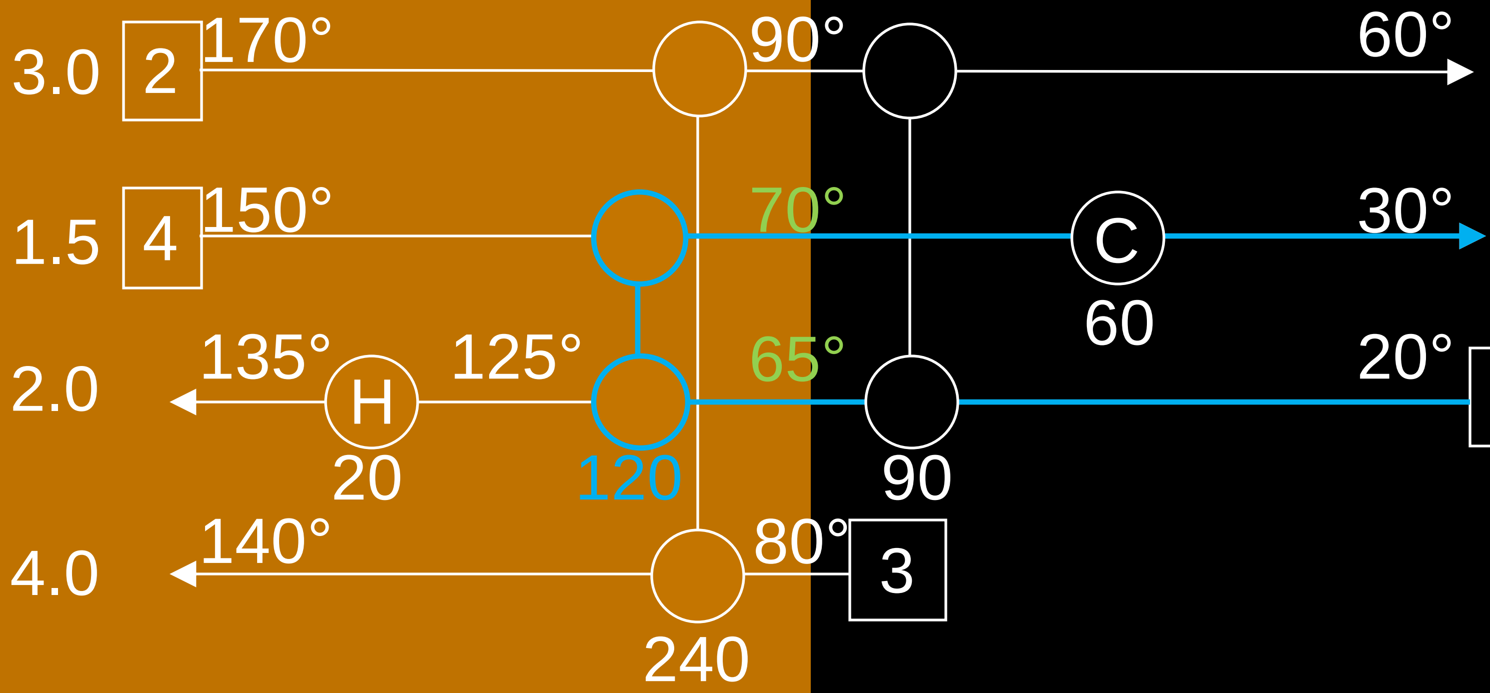
Stream 1 @ 2.0 kW °C^{-1}: 120 kW adds 60° rather than 45°

Stream 4 @ 1.5 kW °C^{-1}: 120 kW removes 80° not 60°

Energy Recovery

Heat Integration

Problem is that 120 kW exchanger violates ΔT_{min} = 10°C

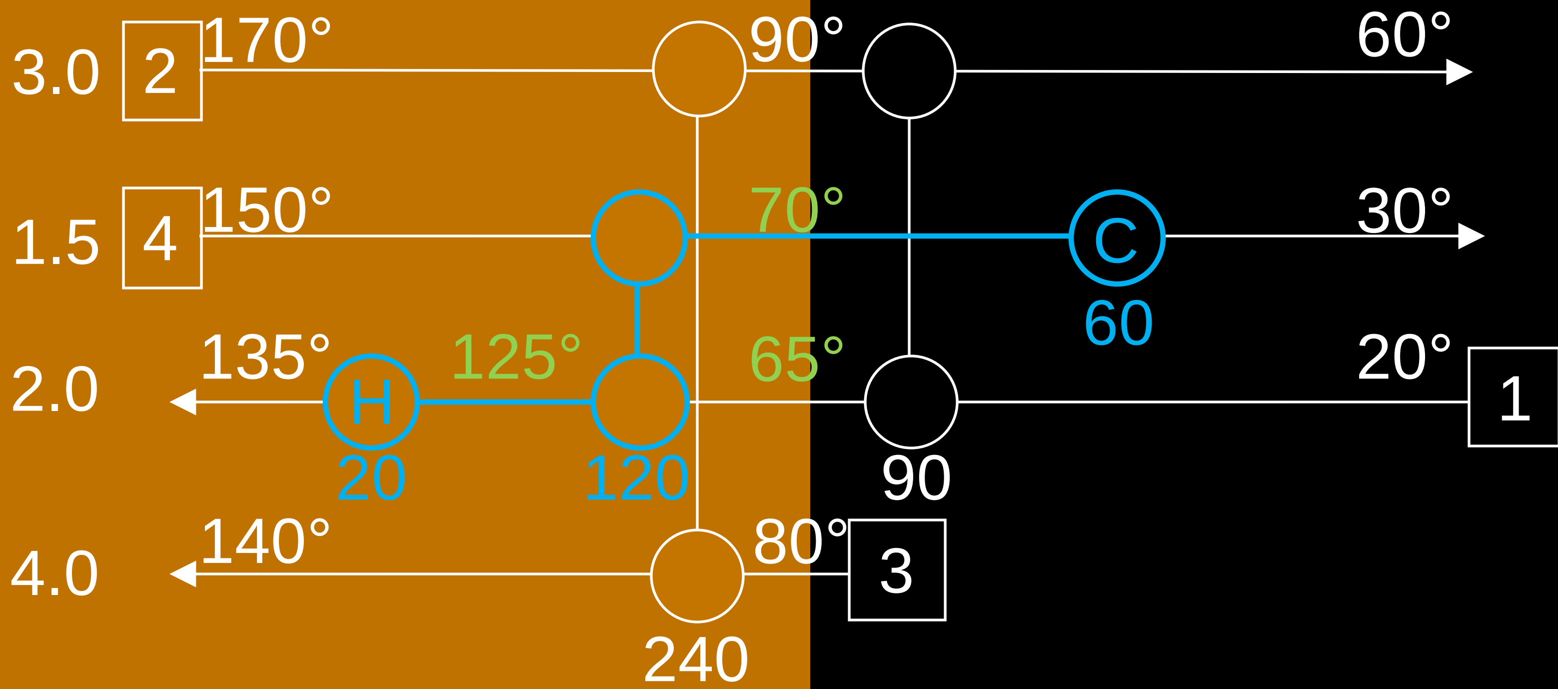


Second step – find a PATH between hot and cold utilities that travels through 120 kW exchanger

Energy Recovery

Heat Integration

Problem is that 120 kW exchanger violates ΔT_{min} = 10°C

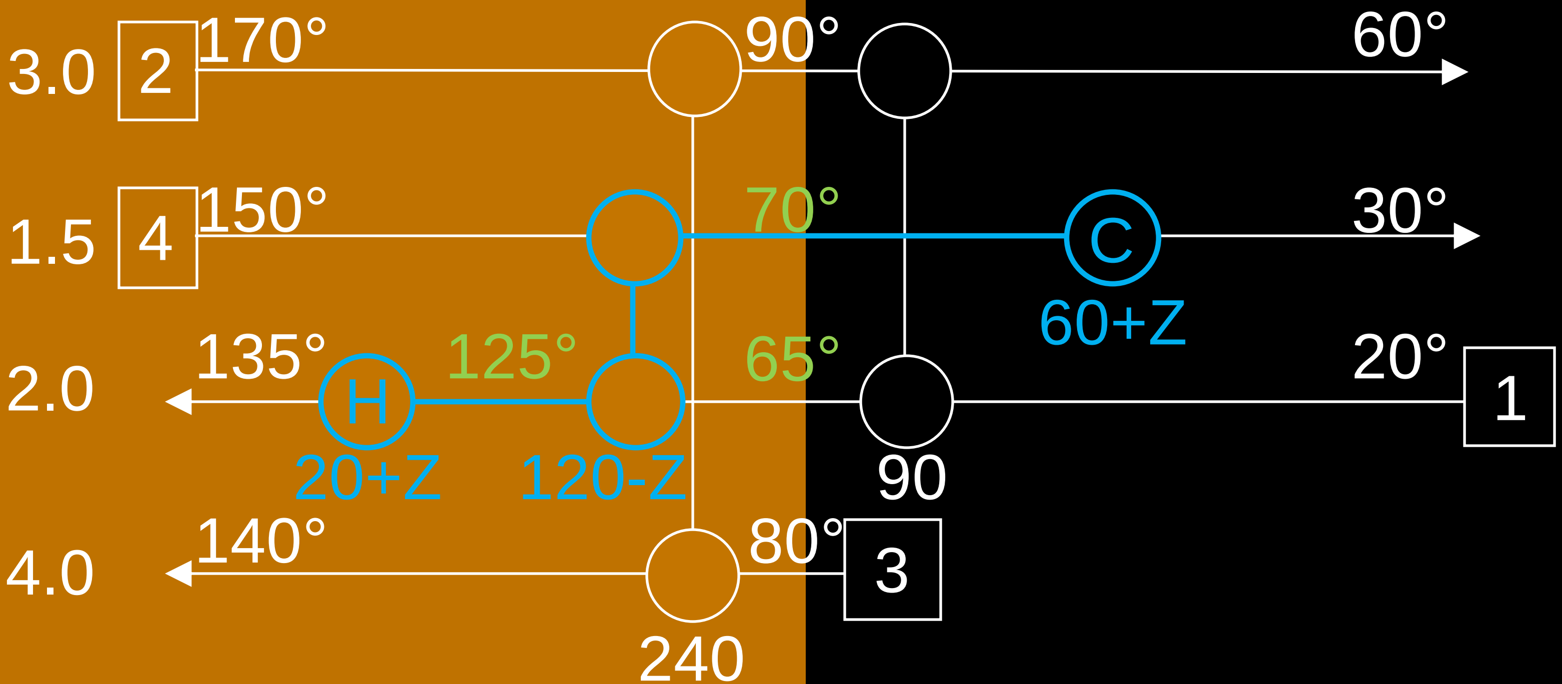


Second step – find a PATH between hot and cold utilities that travels through 120 kW exchanger

Energy Recovery

Heat Integration

If 120kW exchanger conveys Z less heat, utilities compensate



Stream 4 needs to leave exchanger at 75°C

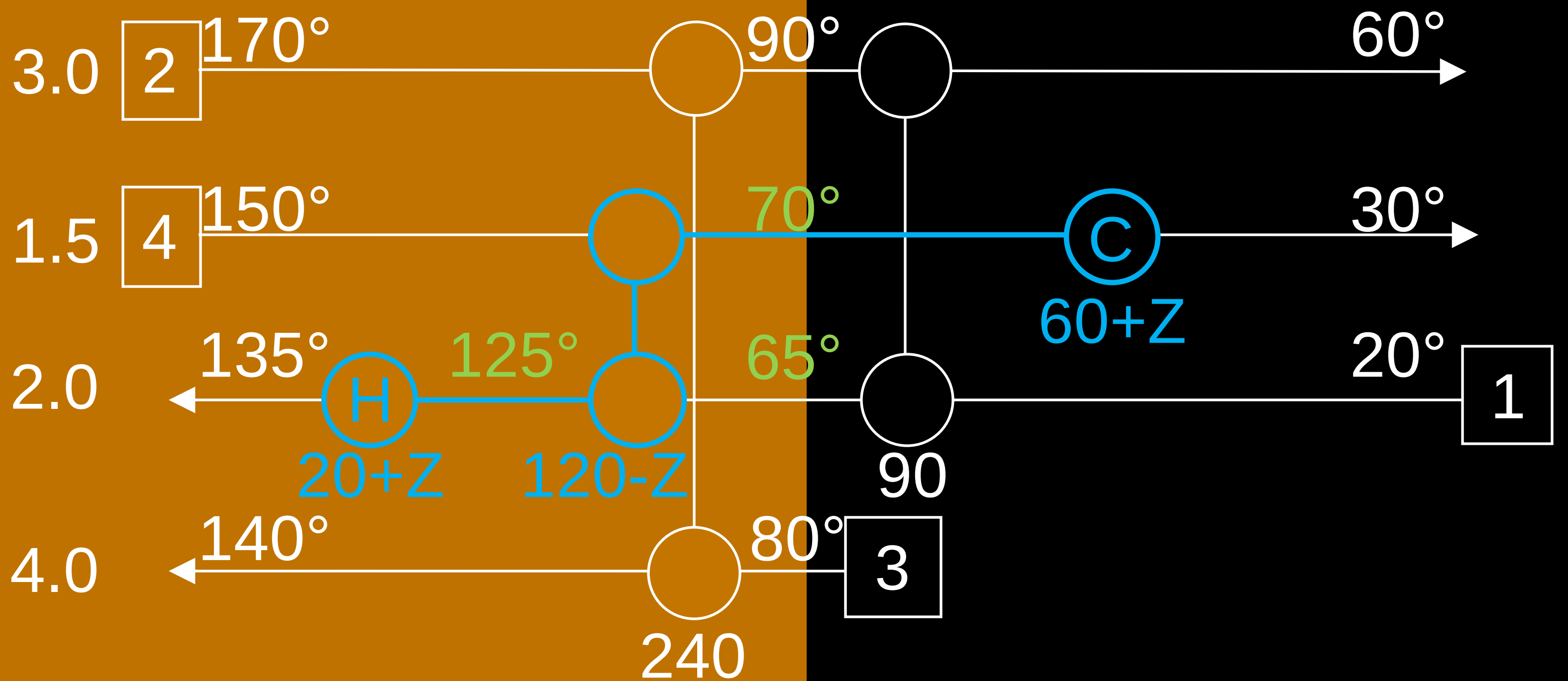
ie. 60+Z kW cools from 75°C to 30°C

Energy Recovery

Heat Integration

$$1.5 = \frac{60 + Z}{75 - 30}$$

ie. Z = 7.5 kW



Also means that 120 – 7.5 = 112.5 kW added to stream 1

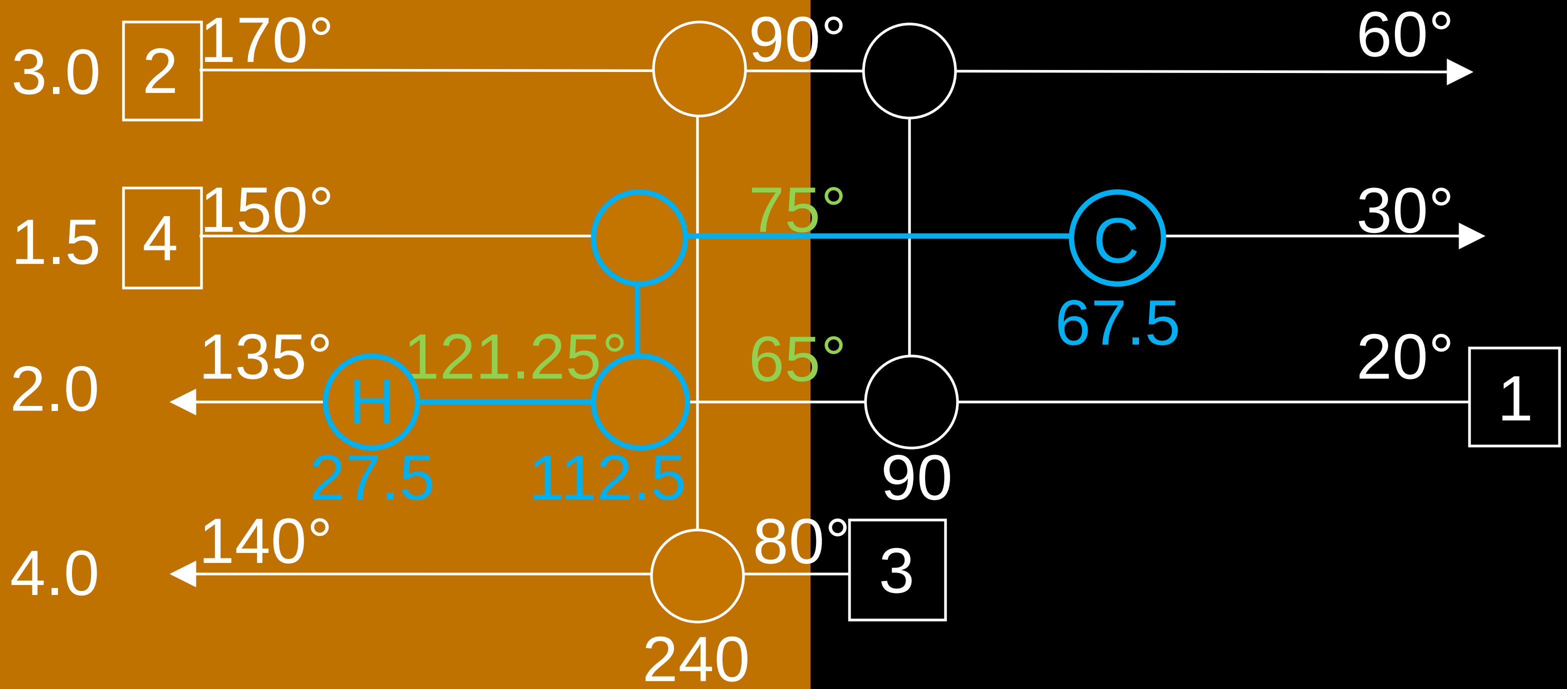
ie. temperature increases by 56.25°, not 60°

Energy Recovery

Heat Integration

$$1.5 = \frac{60 + X}{75 - 30}$$

ie. X = 7.5 kW



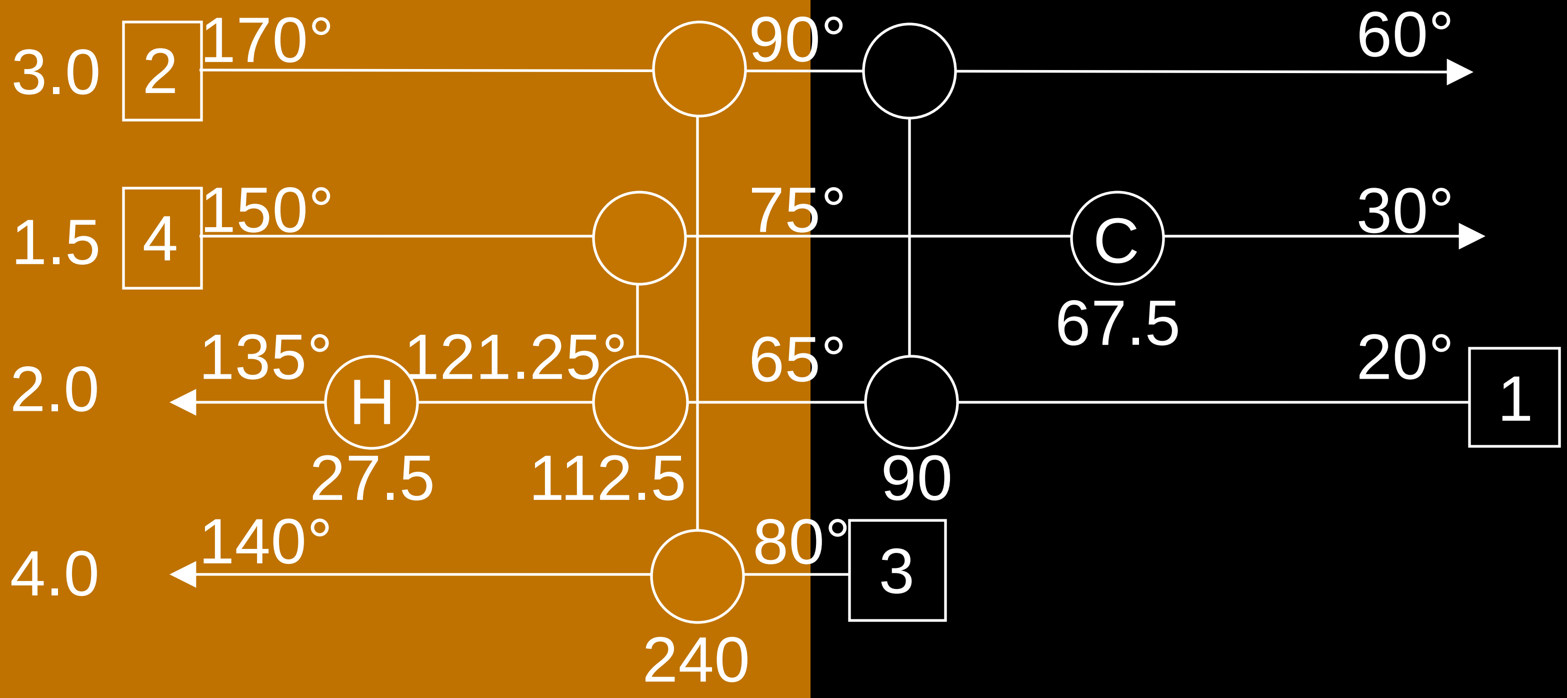
Also means that 120 – 7.5 = 112.5 kW added to stream 1

ie. temperature increases by 56.25°, not 60°

Energy Recovery

Heat Integration

So 5 units, Q_H = 27.5 kW, Q_C = 67.5 kW



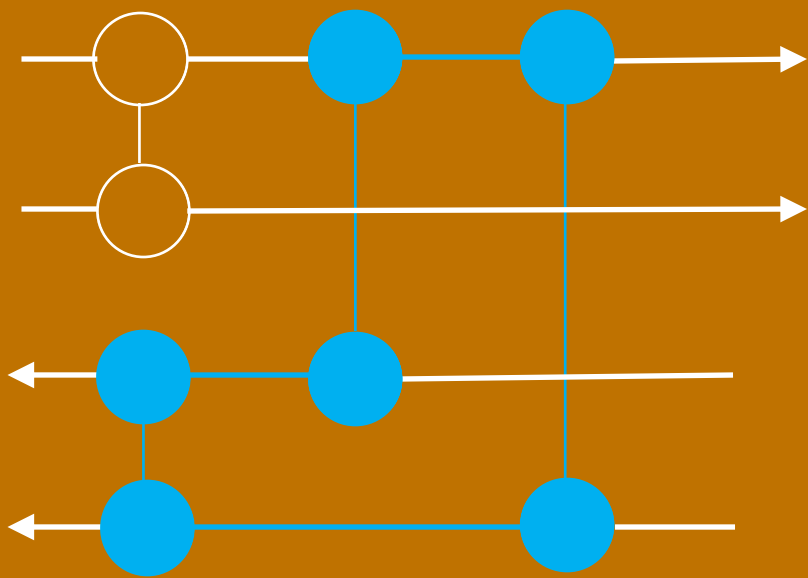
Examine extra 7.5 kW of both utilities versus capital saving on exchangers – three of which are bigger

Energy Recovery

Heat Integration

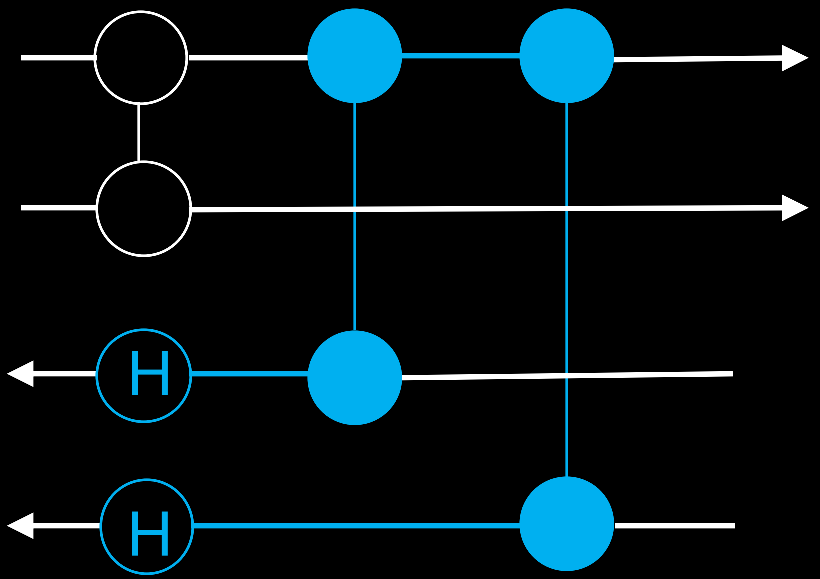
NOTE

Loops can include more than two exchangers



NOTE

Loops can include going back to same utility

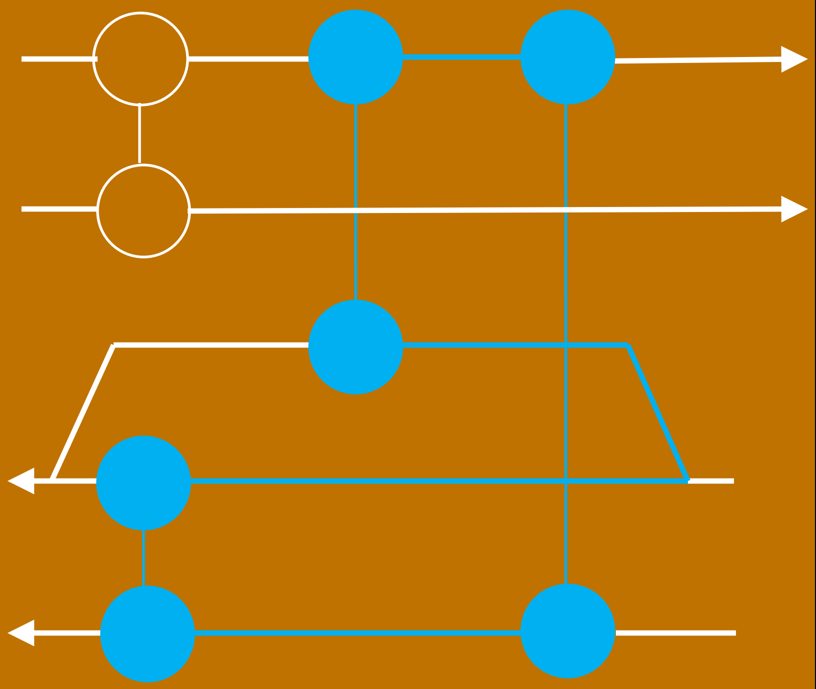


Energy Recovery

Heat Integration

NOTE

Loops can include split streams



Path method removed a 50 kW exchanger but added 50 kW to both utilities

Loop method removed 30 kW exchanger with 7.5 kW penalty

Loop method more complicated but more efficient

Still need a path to correct after loop-breaking, so it will never remove the last surplus exchanger

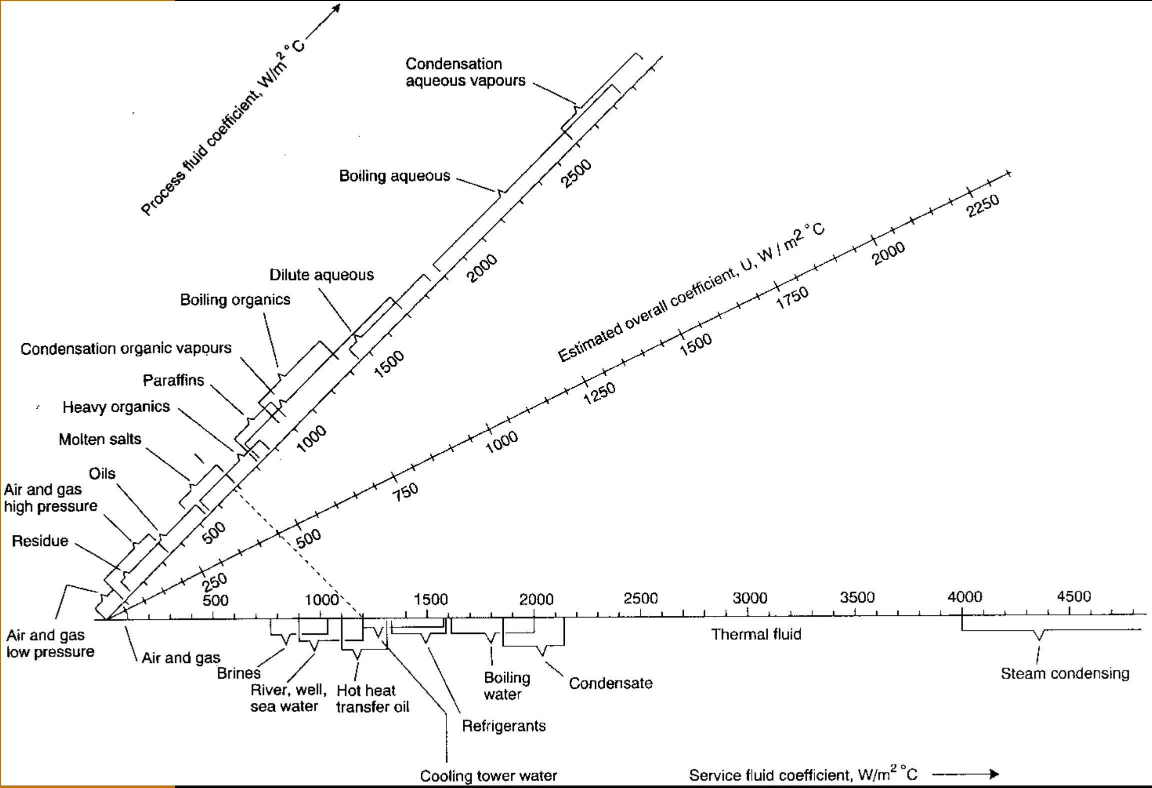
Energy Recovery

Heat Integration

Also the possibility of looking at exchanger area

Ultimately interested in installed capital cost, which is function of area

Take ideal case for each exchanger



- Counter-current flow
- Design achieves “typical” h-value for both fluids

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Energy Recovery

Heat Integration

Let’s look at stream properties more closely:

Stream ID	CP (kW °C^{-1})	kg s^{-1}	Cp (J kg^{-1}K^{-1})
1: Dilute aqueous	2.0	0.5	4000
2: Low pressure gas	3.0	1.5	1000
3: Paraffin	4.0	2.0	2000
4: Heavy organic	1.5	0.75	2000

Predicting h with chart:

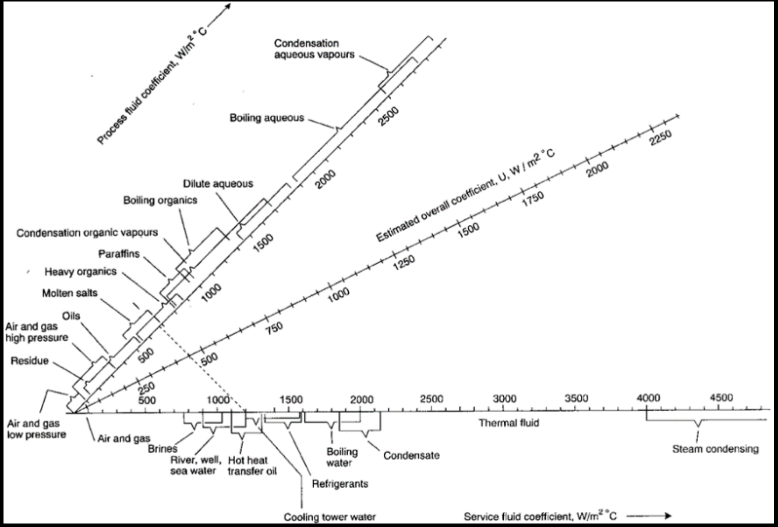
$h_1 = 1800$ W m^{-2}K^{-1}

$h_2 = 50$ W m^{-2}K^{-1}

$h_3 = 1000$ W m^{-2}K^{-1}

$h_4 = 800$ W m^{-2}K^{-1}

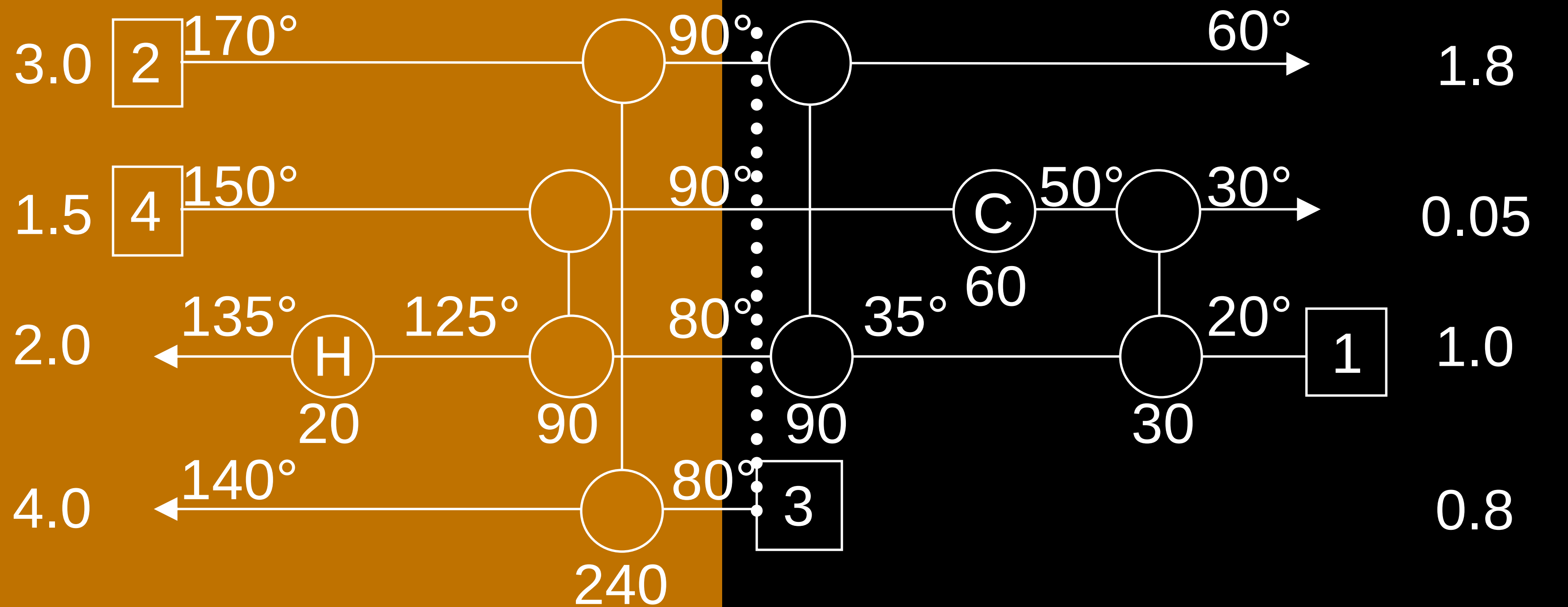
$h_H = 4000$, $h_C = 1600$ W m^{-2}K^{-1}



Energy Recovery

Heat Integration

Original network was this:

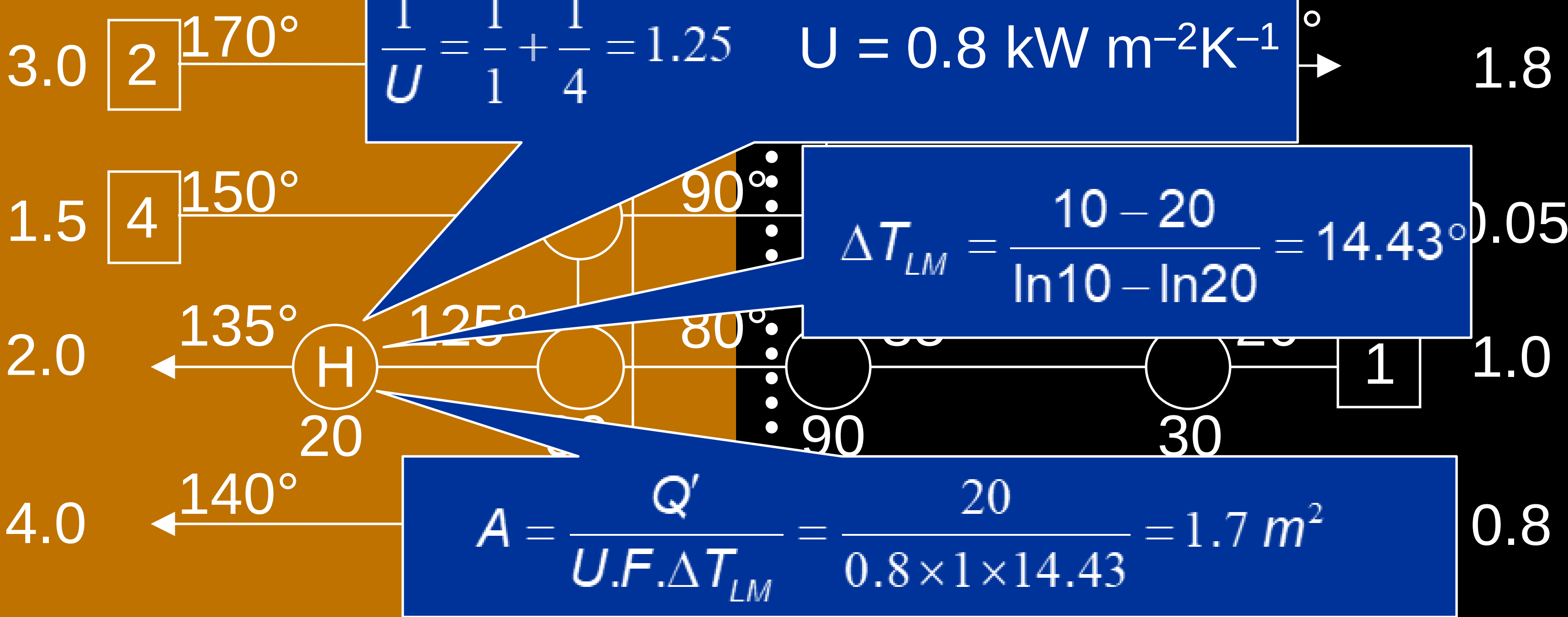


Take utilities as 145° at 4 kW m^{-2}K^{-1}, 40° at 1.6 kW m^{-2}K^{-1}

Energy Recovery

Heat Integration

Original network was this:



$$\frac{1}{U} = \frac{1}{1} + \frac{1}{4} = 1.25 \qquad U = 0.8 \text{ kW m}^{-2}\text{K}^{-1}$$

$$\Delta T_{LM} = \frac{10 - 20}{\ln 10 - \ln 20} = 14.43°$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{20}{0.8 \times 1 \times 14.43} = 1.7\ m^2$$

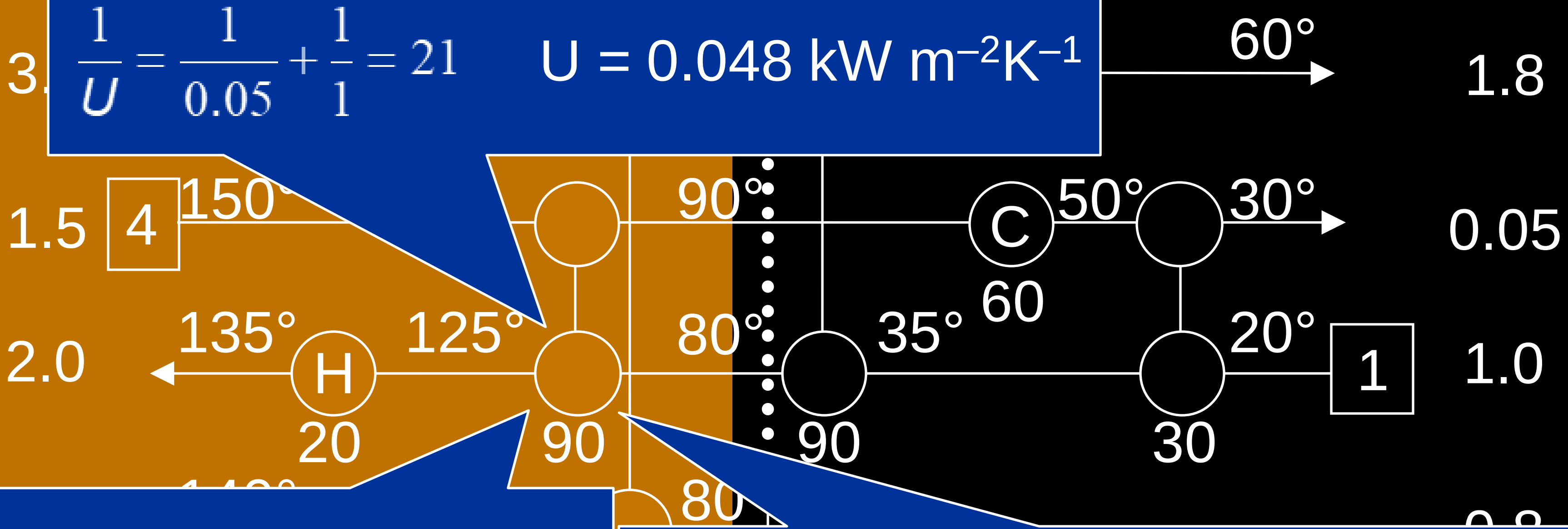
Take utilities as 145° at 4 kW m^{-2}K^{-1}, 40° at 1.6 kW m^{-2}K^{-1}

Total area = 1.7 + …

Energy Recovery

Heat Integration

Original network was this:



$$\frac{1}{U}=\frac{1}{0.05}+\frac{1}{1}=21$$

U = 0.048 kW m^{-2}K^{-1}

$$\Delta T_{LM}=\frac{25-10}{\ln 25-\ln 10}=16.37^{\circ}$$

$$A=\frac{Q'}{U.F.\Delta T_{LM}}=\frac{90}{0.048\times 1\times 16.37}=114.5\ m^2$$

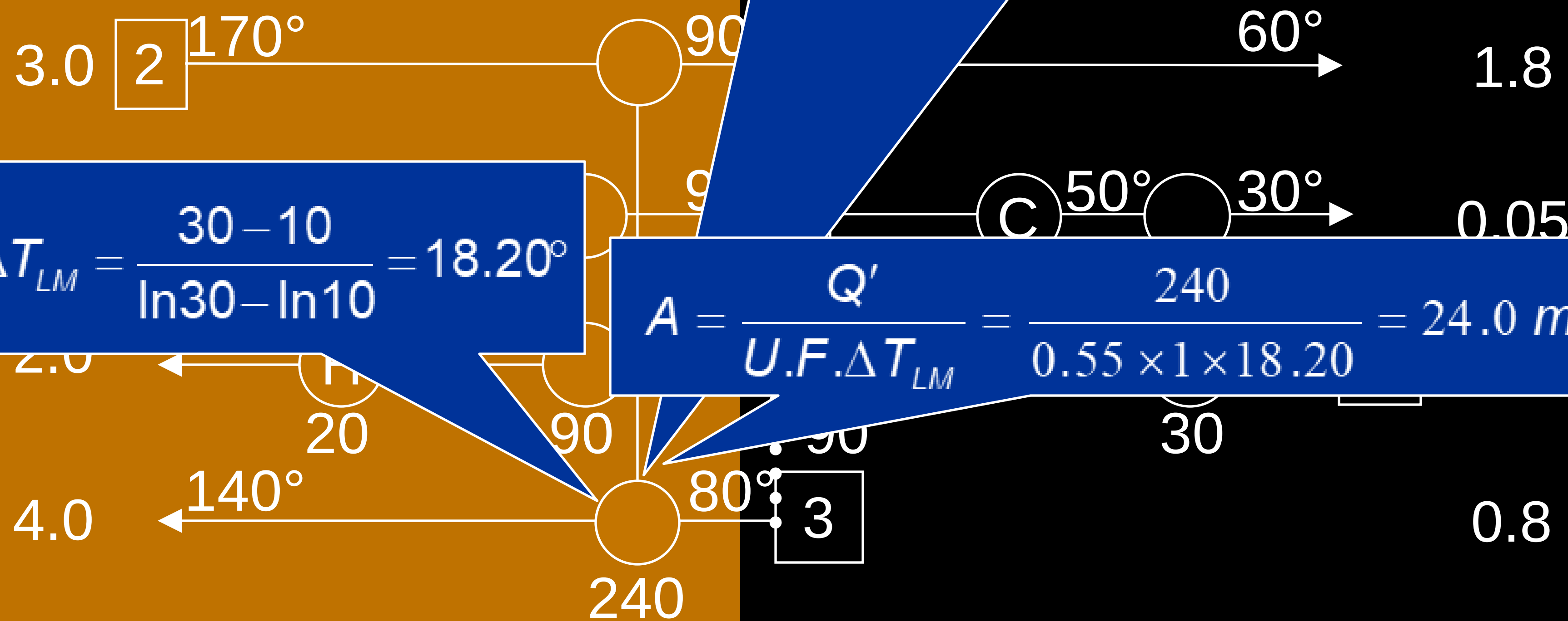
Total area = 1.7 + 114.5 + …

Energy Recovery

Heat Integration

Original network was …

$$\frac{1}{U}=\frac{1}{1.8}+\frac{1}{0.8}=1.805 \qquad U = 0.55\ \text{kW m}^{-2}\text{K}^{-1}$$



$$\Delta T_{LM}=\frac{30-10}{\ln 30-\ln 10}=18.20°$$

$$A=\frac{Q'}{U.F.\Delta T_{LM}}=\frac{240}{0.55\times 1\times 18.20}=24.0\ m^2$$

Take utilities as 145° at 4 kW m^{-2}K^{-1}, 40° at 1.6 kW m^{-2}K^{-1}

Total area = 1.7 + 114.5 + 24.0 + …

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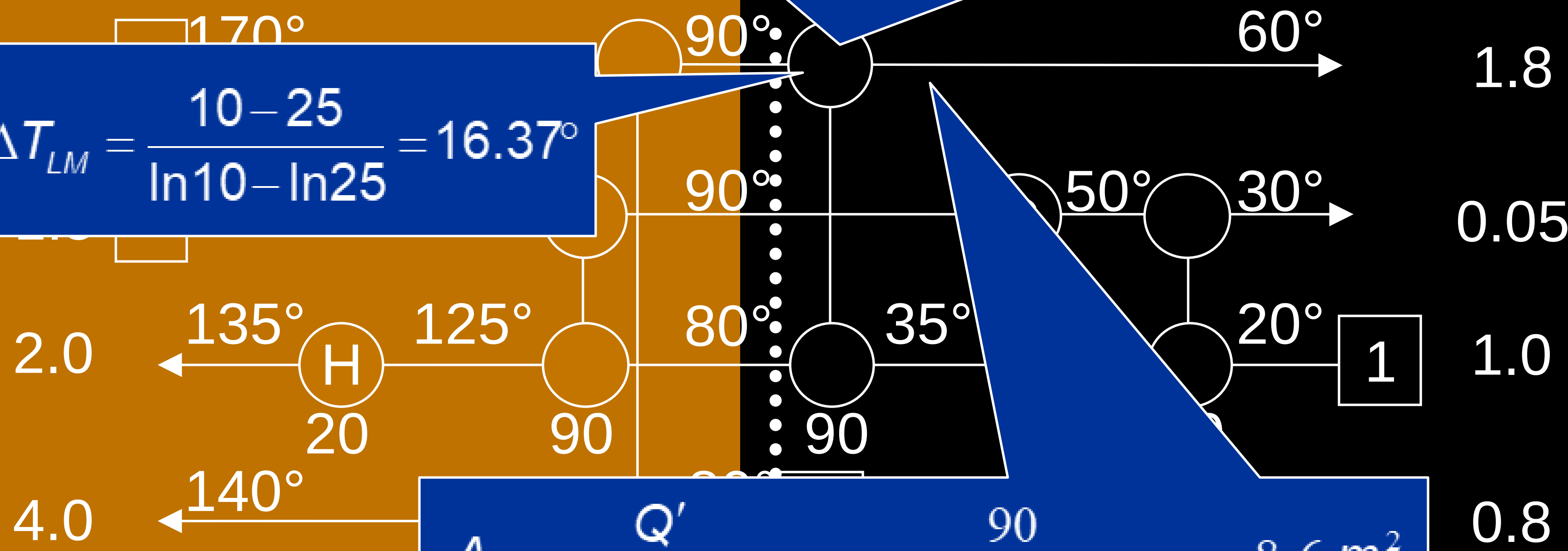
Energy Recovery

Heat Integration

Original network was t

$$\frac{1}{U} = \frac{1}{1.8} + \frac{1}{1} = 1.556 \quad U = 0.643\ \text{kW m}^{-2}\text{K}^{-1}$$

$$\Delta T_{LM} = \frac{10 - 25}{\ln 10 - \ln 25} = 16.37^{\circ}$$



$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{90}{0.643 \times 1 \times 16.37} = 8.6\ m^2$$

Take utilities as 145° at 4 kW m^{-2}K^{-1}, 40° at 1.6 kW m^{-2}K^{-1}

Total area = 1.7 + 114.5 + 24.0 + 8.6 + …

Energy Recovery

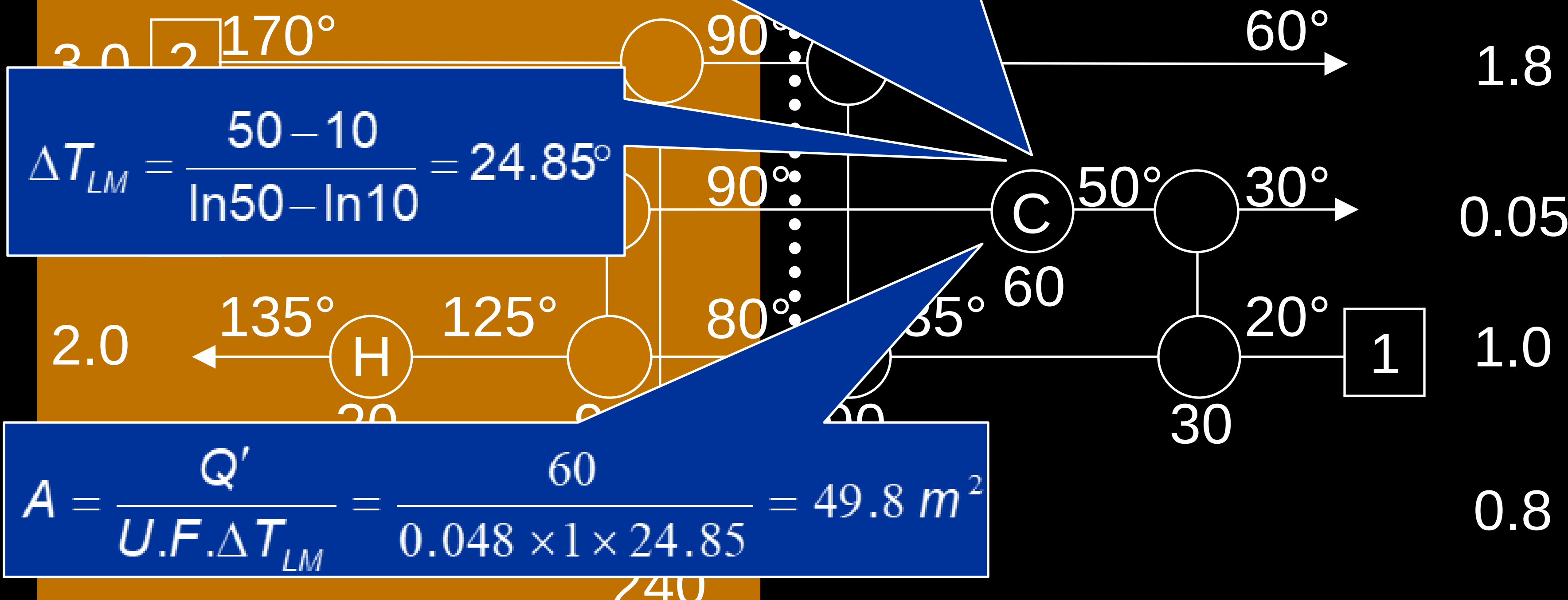
Heat Integration

Original network w

$$\frac{1}{U} = \frac{1}{0.05} + \frac{1}{1.6} = 20.625 \qquad U = 0.048 \text{ kW m}^{-2}\text{K}^{-1}$$

$$\Delta T_{LM} = \frac{50-10}{\ln 50 - \ln 10} = 24.85^{\circ}$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{60}{0.048 \times 1 \times 24.85} = 49.8\ m^2$$



Take utilities as 145° at 4 kW m^{-2}K^{-1}, 40° at 1.6 kW m^{-2}K^{-1}

Total area = 1.7 + 114.5 + 24.0 + 8.6 + 49.8 + …

Energy Recovery

Heat Integration

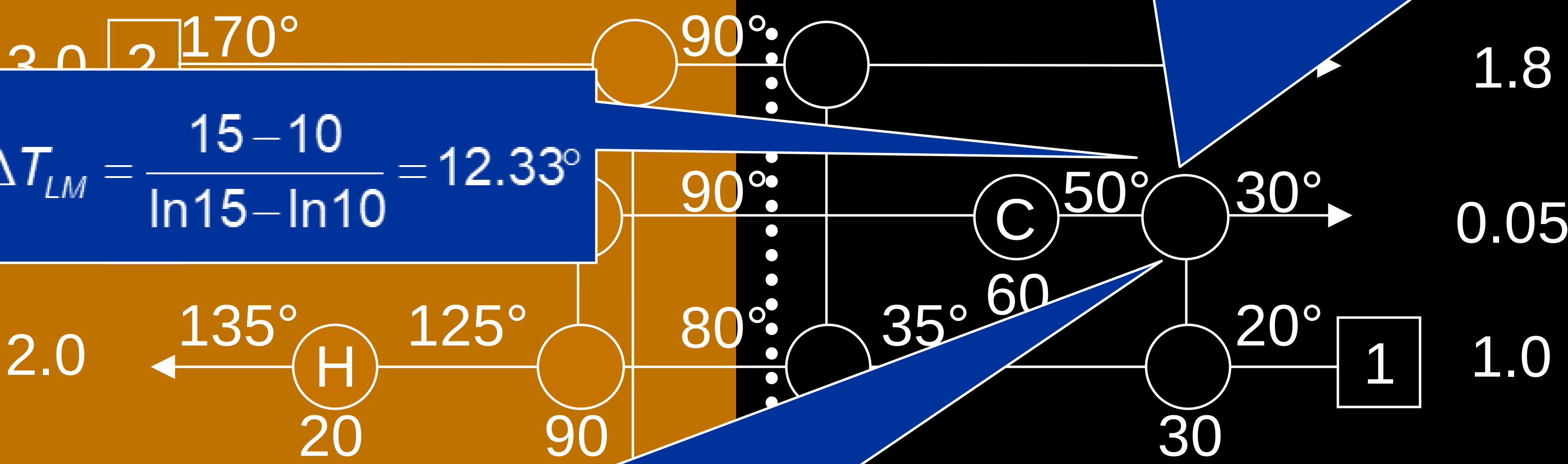
Original network w

$$\frac{1}{U} = \frac{1}{0.05} + \frac{1}{1} = 21$$

U = 0.048 kW $m^{-2}K^{-1}$

$$\Delta T_{LM} = \frac{15 - 10}{\ln 15 - \ln 10} = 12.33^{\circ}$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{30}{0.048 \times 1 \times 12.33} = 50.7\ m^2$$



Take utilities as 145° at 4 kW $m^{-2}K^{-1}$, 40° at 1.6 kW $m^{-2}K^{-1}$

Total area = 1.7 + 114.5 + 24.0 + 8.6 + 49.8 + 50.7 = 249.3 m^2

Energy Recovery

Heat Integration

Estimated cost of exchangers when 20 < A < 500 m^2 per shell:

$$\text{Installed cost (\$)} = \left(\frac{I_{MS}}{280}\right) 474.7 A^{0.65} \left(2.29 + F_C\right)$$

I_{MS} = Marshall and Swift index (2171.6 in 2020)

Shell / tubes	F_M	Design type	F_D	Pressure (bar)	F_P
CS / CS	1.00	Kettle	1.35	<10	0.00
CS / brass	1.30	Floating head	1.00	20	0.10
CS / Monel	2.15	U-tube	0.85	30	0.25
CS / SS	3.75	Fixed tubesheet	0.80	60	0.52
SS / SS	3.75			>75	0.55
Monel / Monel	4.25				
CS / titanium	8.95			$F_C = F_M (F_D + F_P)$	

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Energy Recovery

Heat Integration

Taking a simple design case for all exchangers in example

Use formula on all exchangers (even the two small ones with $A < 20\ m^2$)

Carbon steel for both shell and tubes so $F_M = 1.0$

Fixed tubesheet design so $F_D = 0.80$

No pressures above 10 bar so $F_P = 0.00$

$F_C = F_M(F_D + F_P) = 1(0.8 + 0) = 0.8$

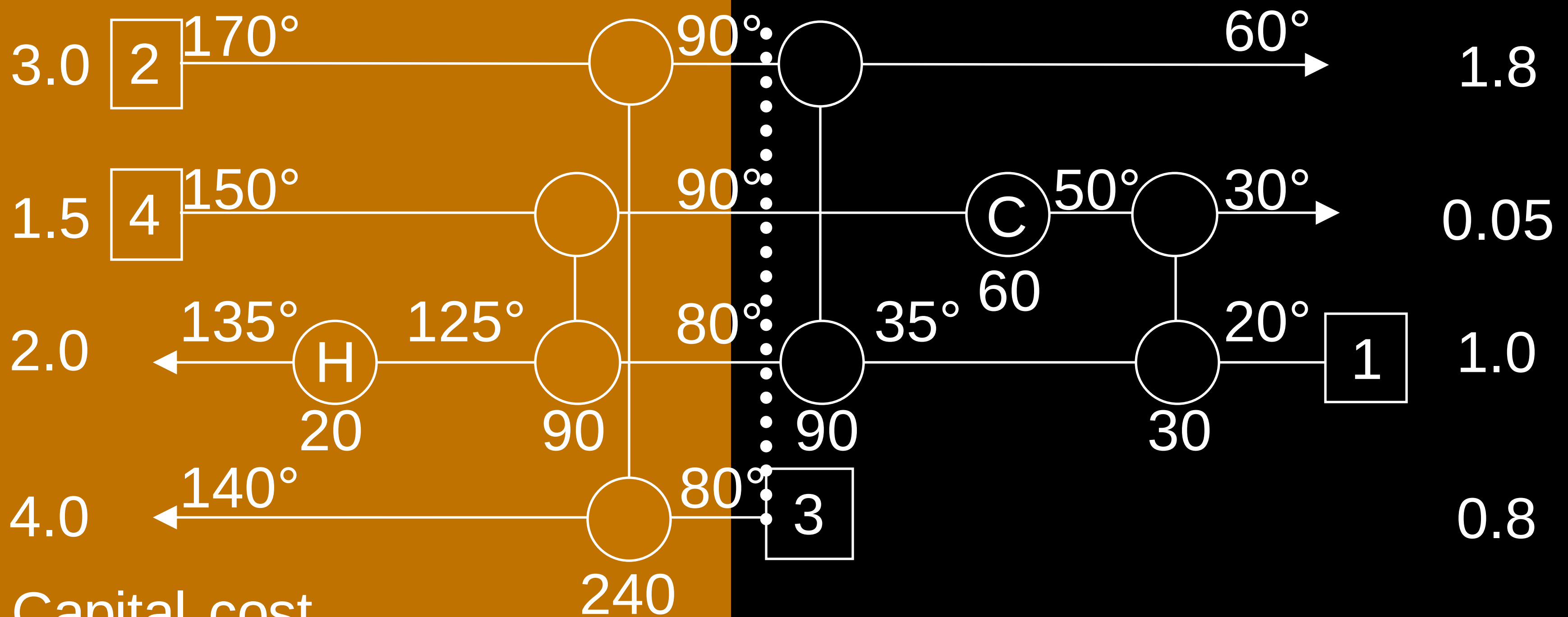
$$Installed\ cost\ (\$) = \left(\frac{2171.6}{280}\right) 474.7A^{0.65}(2.29 + 0.8)$$

Installed cost (\$, 2020) = $11376\ A^{0.65}$

Energy Recovery

Heat Integration

Original network was this:

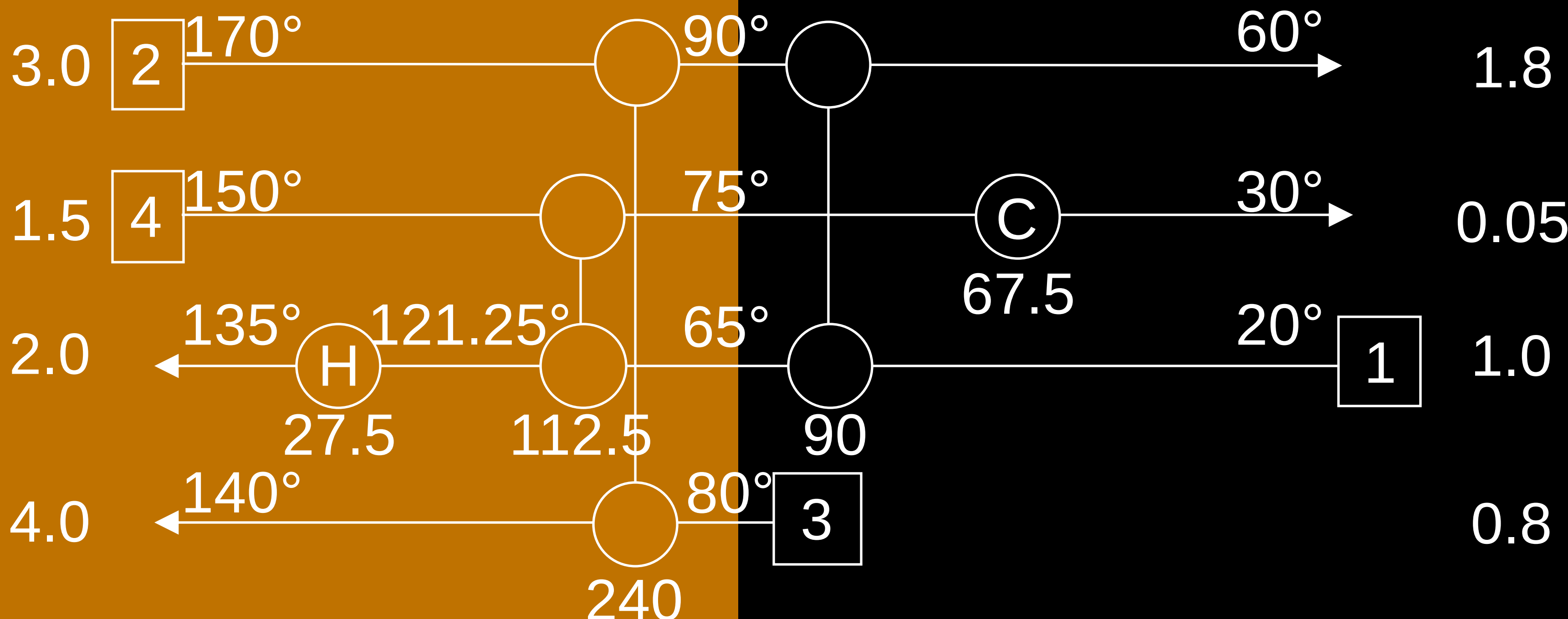


Capital cost
$= 11376[1.7^{0.65} + 114.5^{0.65} + 24.0^{0.65} + 8.6^{0.65} + 49.8^{0.65} + 50.7^{0.65}]$ = \$ 690 001 (December 2020)

Energy Recovery

Heat Integration

Now look at streamlined version of this network:



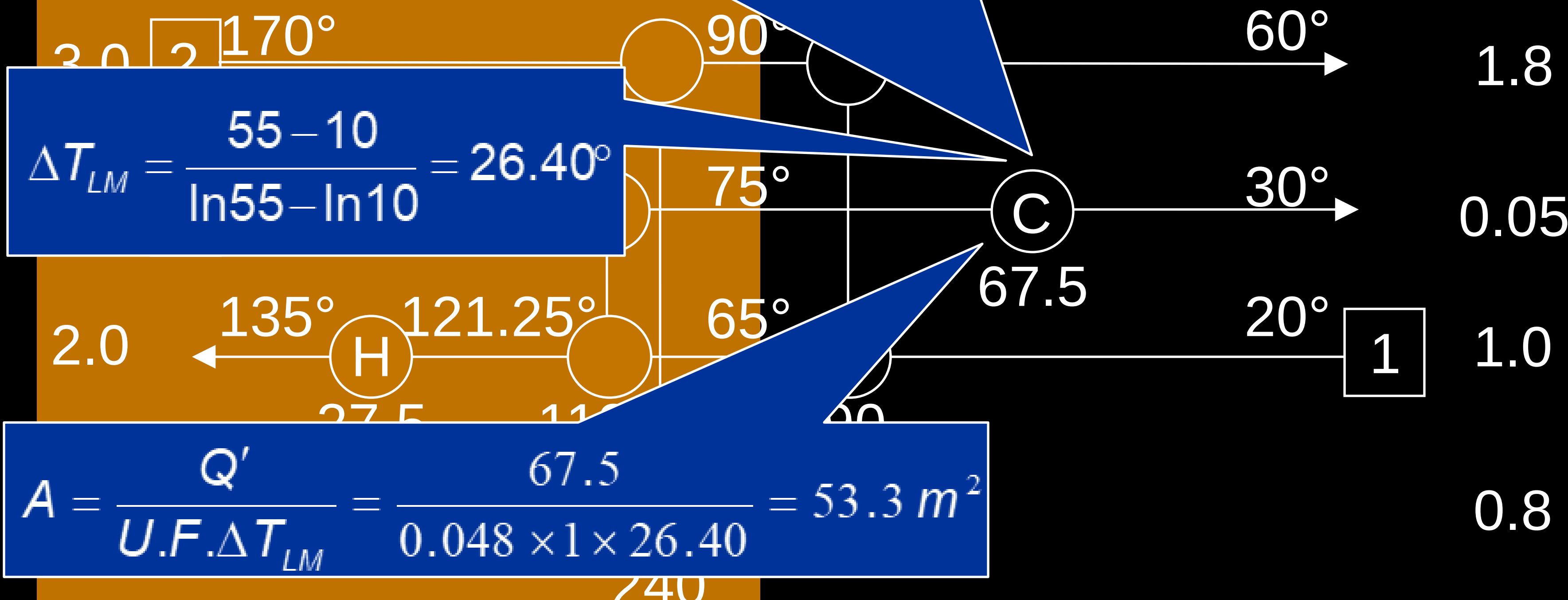
Take utilities as 145° at 4 kW $m^{-2}K^{-1}$, 20° at 1.6 kW $m^{-2}K^{-1}$

Energy Recovery

Heat Integration

Now look at strea

$$\frac{1}{U} = \frac{1}{0.05} + \frac{1}{1.6} = 20.625 \quad U = 0.048\ \text{kW m}^{-2}\text{K}^{-1}$$



$$\Delta T_{LM} = \frac{55 - 10}{\ln 55 - \ln 10} = 26.40^{\circ}$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{67.5}{0.048 \times 1 \times 26.40} = 53.3\ m^2$$

Take utilities as 145° at 4 kW m^{-2}K^{-1}, 20° at 1.6 kW m^{-2}K^{-1}

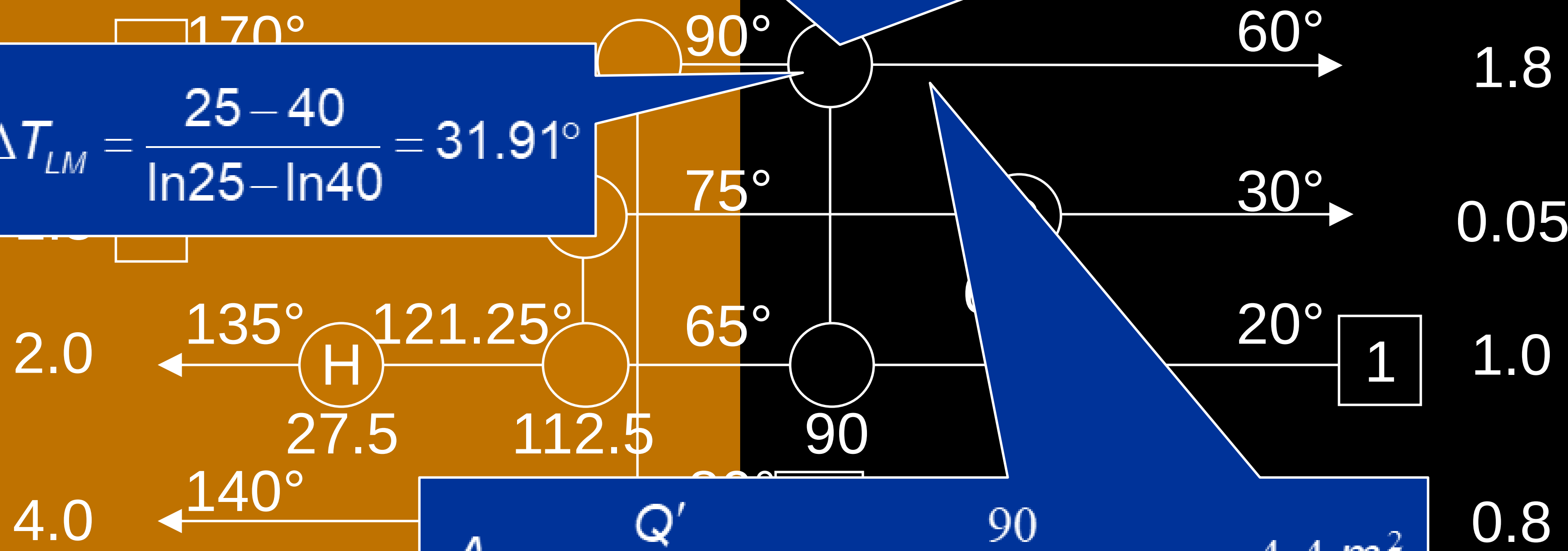
Total area = 53.3 + …

Energy Recovery

Heat Integration

Now look at streamline

$$\frac{1}{U}=\frac{1}{1.8}+\frac{1}{1}=1.556$$ U = 0.643 kW $m^{-2}K^{-1}$



$$\Delta T_{LM}=\frac{25-40}{\ln 25-\ln 40}=31.91^{\circ}$$

$$A=\frac{Q'}{U.F.\Delta T_{LM}}=\frac{90}{0.643\times 1\times 31.91}=4.4\,m^{2}$$

Take utilities as 145° at 4 kW $m^{-2}K^{-1}$, 20° at 1.6 kW $m^{-2}K^{-1}$

Total area = 53.3 + 4.4 + …

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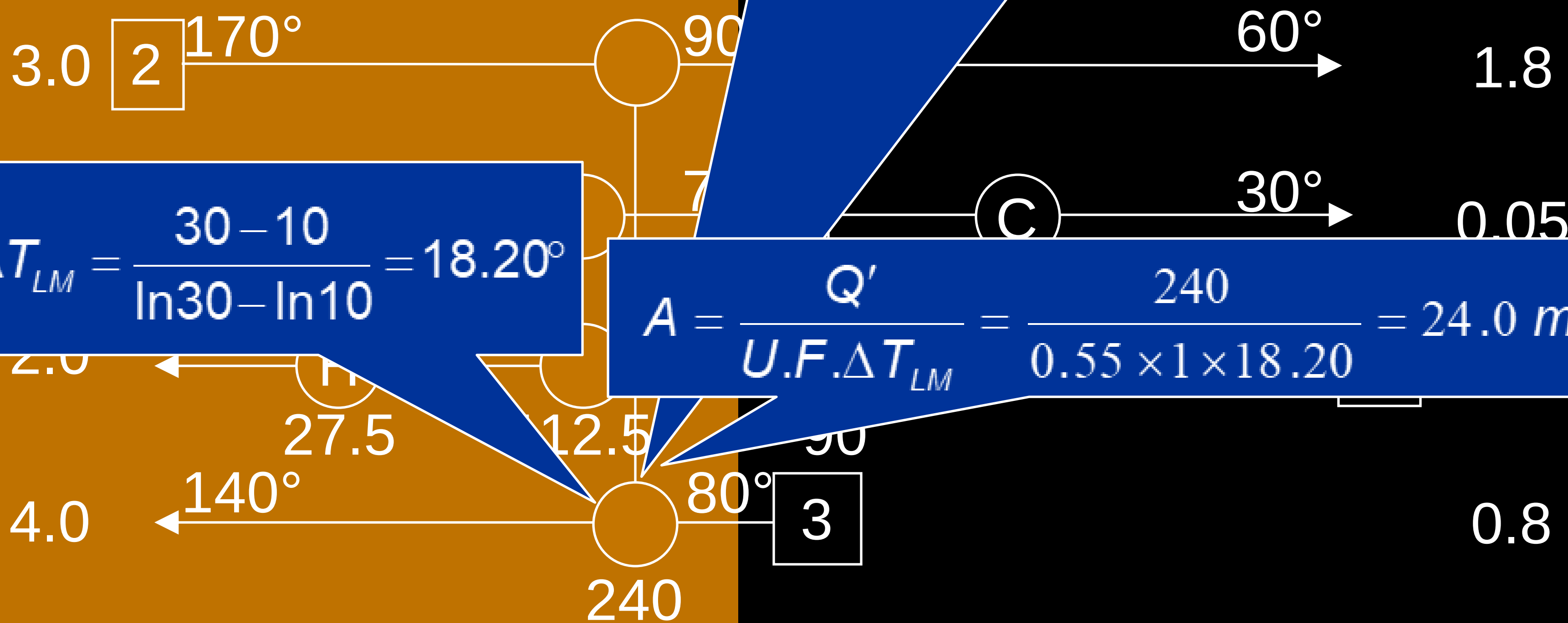
Energy Recovery

Heat Integration

Now look at streamline

$$\frac{1}{U} = \frac{1}{1.8} + \frac{1}{0.8} = 1.805 \qquad U = 0.55\ \text{kW m}^{-2}\text{K}^{-1}$$



$$\Delta T_{LM} = \frac{30-10}{\ln 30 - \ln 10} = 18.20°$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{240}{0.55 \times 1 \times 18.20} = 24.0\ m^2$$

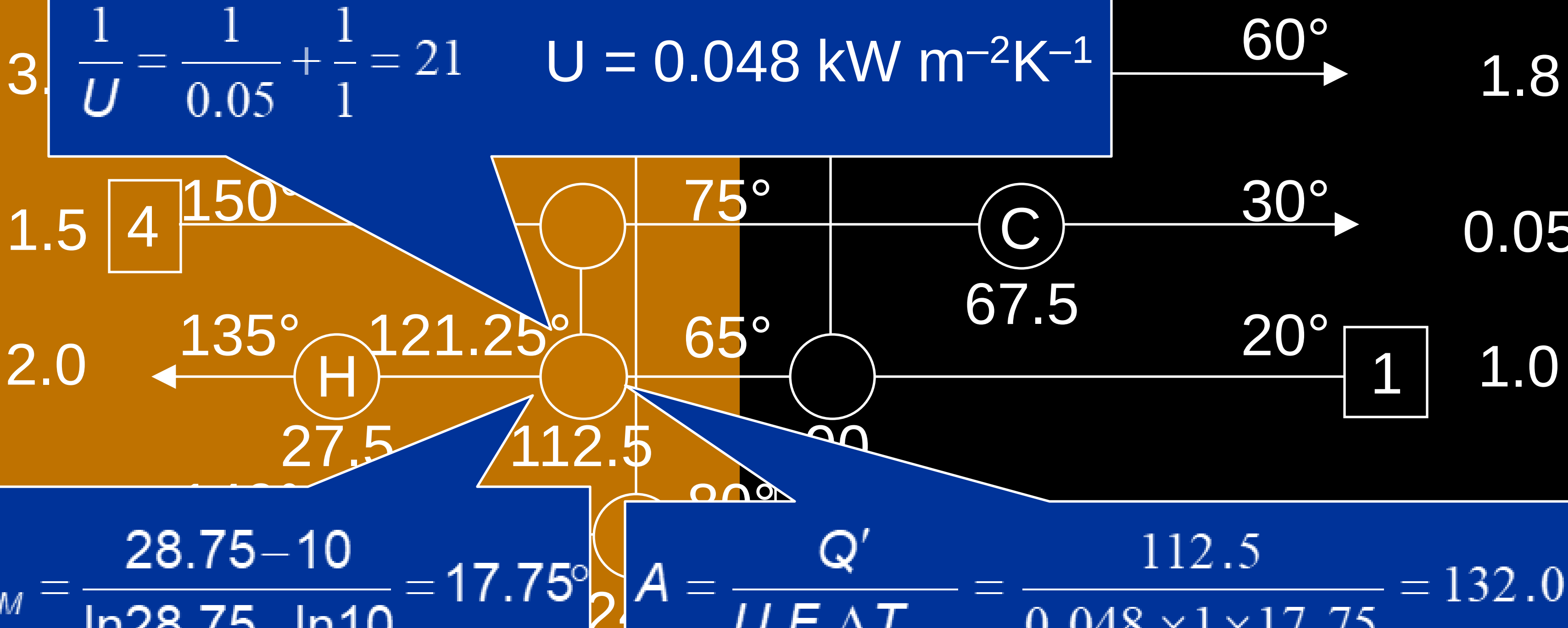
Take utilities as 145° at 4 kW m^{-2}K^{-1}, 20° at 1.6 kW m^{-2}K^{-1}

Total area = 53.3 + 4.4 + 24.0 + …

Energy Recovery

Heat Integration

Now look at streamlined version of this network:



$$\frac{1}{U} = \frac{1}{0.05} + \frac{1}{1} = 21 \qquad U = 0.048\ \text{kW m}^{-2}\text{K}^{-1}$$

$$\Delta T_{LM} = \frac{28.75 - 10}{\ln 28.75 - \ln 10} = 17.75°$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{112.5}{0.048 \times 1 \times 17.75} = 132.0\ m^2$$

Take utilities as 145° at 4 kW m^{-2}K^{-1}, 20° at 1.6 kW m^{-2}K^{-1}

Total area = 53.3 + 4.4 + 24.0 + 132.0 + …

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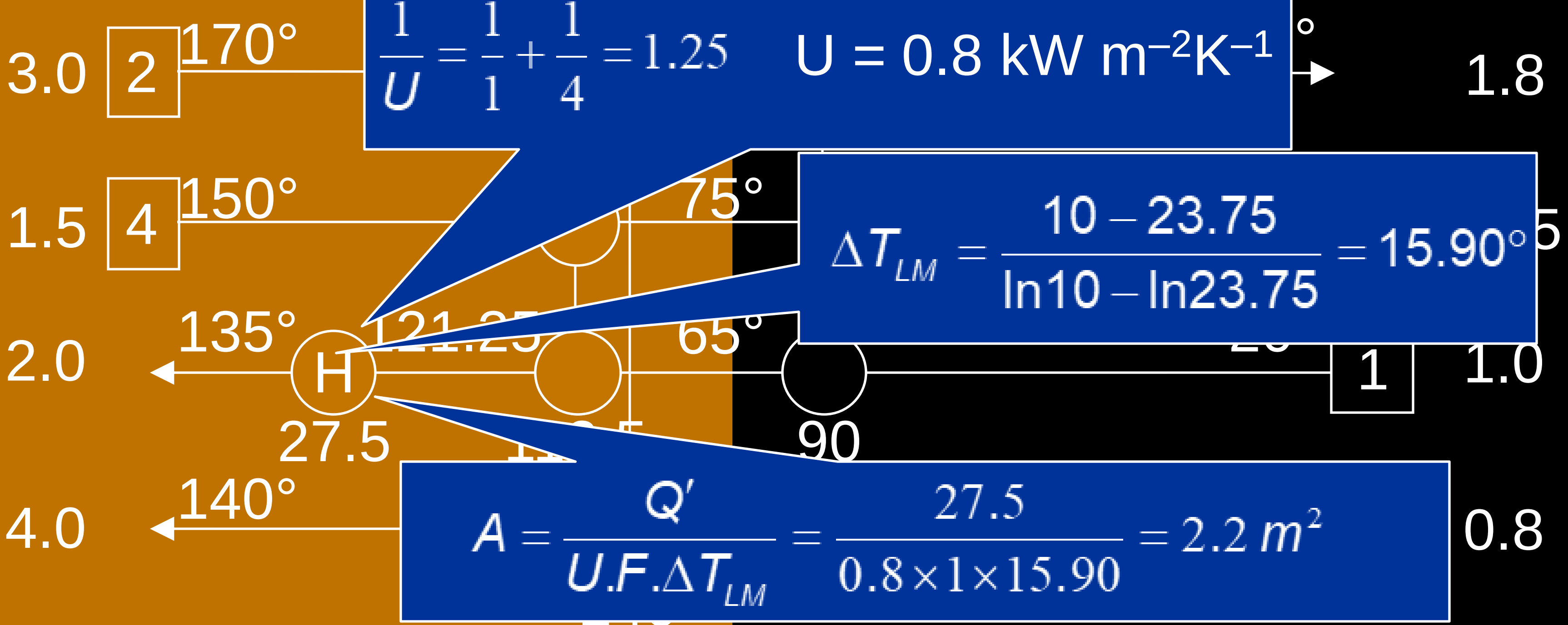
Energy Recovery

Heat Integration

Now look at streamlined version of this network:



$$\frac{1}{U} = \frac{1}{1} + \frac{1}{4} = 1.25 \qquad U = 0.8 \text{ kW m}^{-2}\text{K}^{-1}$$

$$\Delta T_{LM} = \frac{10 - 23.75}{\ln 10 - \ln 23.75} = 15.90°$$

$$A = \frac{Q'}{U.F.\Delta T_{LM}} = \frac{27.5}{0.8 \times 1 \times 15.90} = 2.2\, m^2$$

Take utilities as 145° at 4 kW m^{-2}K^{-1}, 20° at 1.6 kW m^{-2}K^{-1}

Total area = 53.3 + 4.4 + 24.0 + 132.0 + 2.2 = 215.9 m^2

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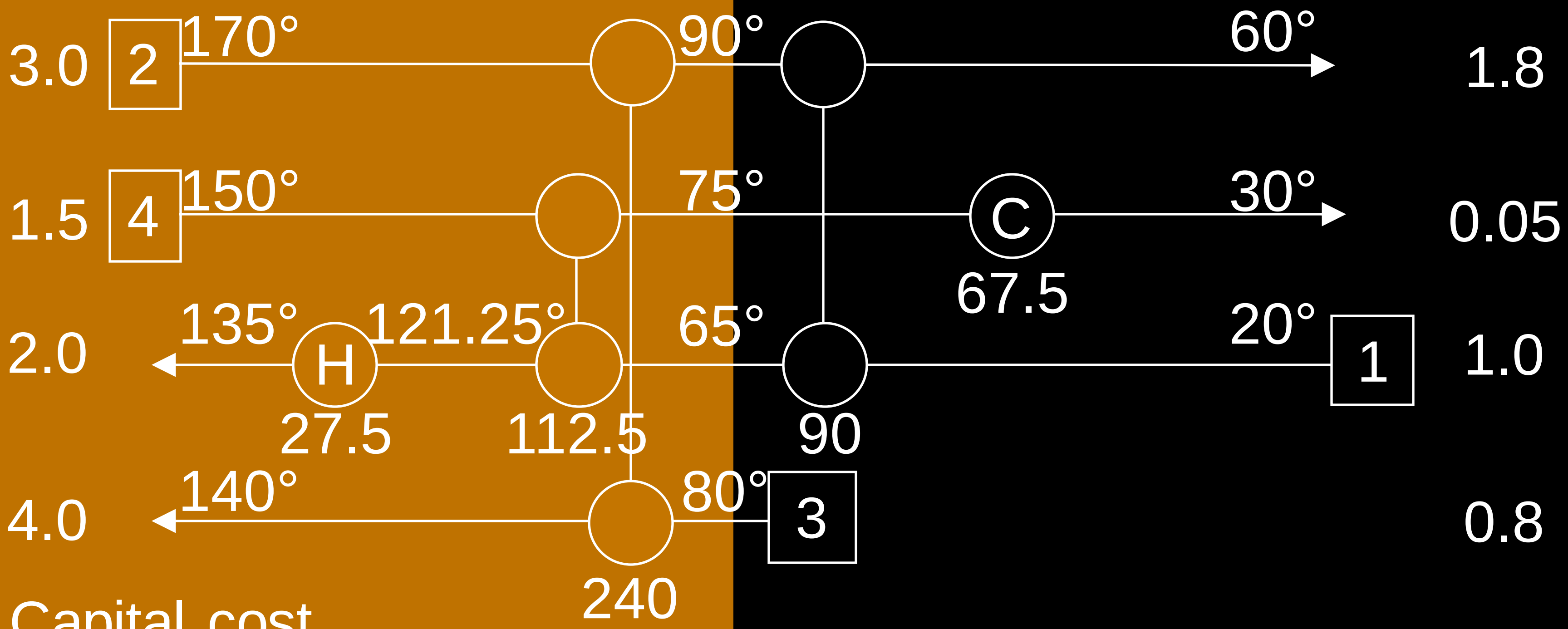
Energy Recovery

Heat Integration

Now look at streamlined version of this network:



Capital cost

$= 11376\ [53.3^{0.65} + 4.4^{0.65} + 24.0^{0.65} + 132.0^{0.65} + 2.2^{0.65}]$

= \$561 219 (December 2020)

Energy Recovery

Heat Integration

MER consumes
20 kW 145° steam
60 kW 40° water
6 units: total area 249.3 m^2
Capital cost = $690 001

U_{min} consumes
27.5 kW 145° steam
67.5 kW 20° water
5 units: total area 215.9 m^2
Capital cost = $561 219

December 2020 prices but allows comparison