Case 24 - Benchmark Solutions for a Crude Fractionation Unit.

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This crude fractionation unit case was presented by Kim et al. in 2016 and 2017 [1], [2]. It was also studied by Pavão et al. [3] and by Nair et al. [4] in 2018.

Stream data and financial parameters are presented in Table 24.1.

Table 24.1 - Data

Tsupply	Ttarget	Heat	DT-shift	U*f	Descript.	mcp
°C	°C	kW	K	kW/K,m²	-	kW/K
360.0	290.0	2786.7	1.0	0.47	VR1	39.81
290.0	115.0	6966.8	1.0	0.47	VR2	39.81
303.6	270.2	7848.3	3.0	0.41	LCR	234.98
359.6	280.0	1952.6	1.0	0.47	SR-Quench	24.53
250.6	90.0	21231.3	4.0	0.26	HVGO	132.2
248.8	110.0	4415.2	-1.0	0.72	LGO	31.81
277.0	121.9	3812.4	0.0	0.57	HGO	24.58
210.0	163.0	5440.7	3.0	0.33	MCR	115.76
170.1	60.0	3735.7	0.0	0.45	Kerosene	33.93
140.2	39.5	10724.6	5.0	0.26	TCR	106.5
178.6	108.9	3335.1	-1.0	0.60	LVGO	47.85
30.0	130.0	20248.0	0.0	0.26	Crude 1	202.48
130.0	350.0	63782.4	0.0	0.72	Crude 2	289.92
500.0	499.0	20375.0		0.53	Heating	
20.0	40.0	8593.98		0.53	Cooling	

Financial parameters		
Heating :	100.0	$/kW,year
Cooling :	10.0	$/kW,year
HEX-unit cost : 25 000 + 55.0*Area		$/year

It is not clear what kind of hot utility has been used: steam does not condense at the given temperature level and flue gas would have a different temperature profile. The temperatures were maintained, however, to allow comparison with results from other studies and, furthermore, they have no real impact on the results.

The heating load has been chosen on the basis of the trade-off curve in Figure 24.1. Shift values were optimized by crisscross optimization for minimum cost. Composite curves are shown in Figure 24.2. The pinch is caused by hot stream MRC; the minimum number of units is 18 for a system segregated at the pinch.

From practical point of view, it might be interesting to split the network not at the pinch, but at 130°C, the supply temperature of the high-temperature crude section after the desalter. With the split at that level, however, both the kerosene and the LVGO would have a small exchanger above and one below the desalter, which would increase the number of units from 18 to 19. This has been avoided in the trade-off analysis by pushing these streams down to below the desalter level by applying an increased shift on those streams, resulting into the green curve in Figure 24.1. The number of units in the analysis drops from 18 to 17, whilst the area goes up with 478 m² from 12944 m² to 13422 m². The additional area cost of 26290 $/y is quasi compensated by avoiding one unit, saving 25000 $/y and, expectedly, the network will be simpler.

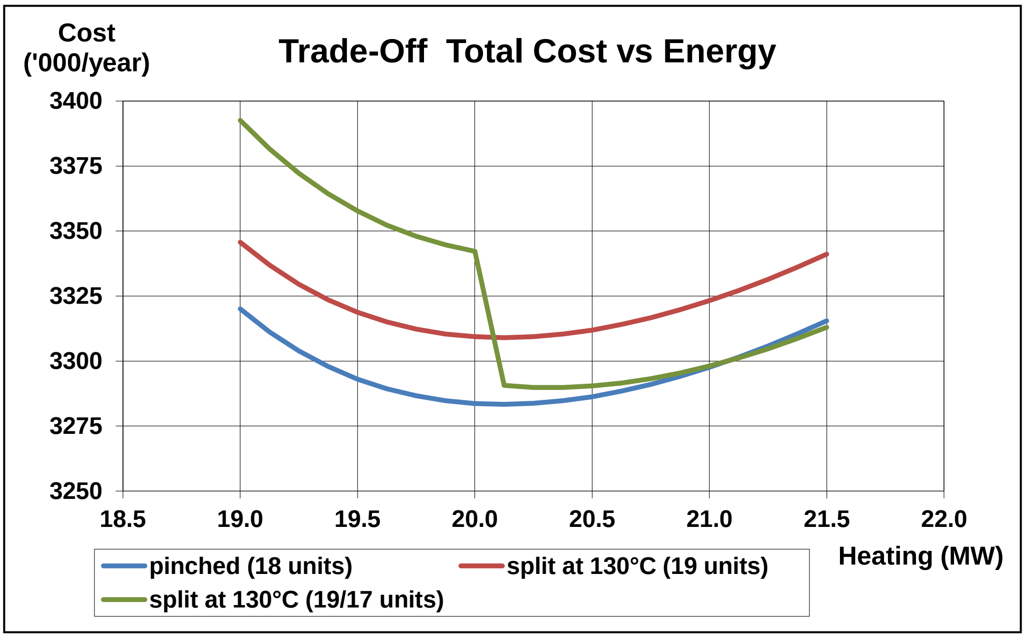

Figure 24.1 – Trade off

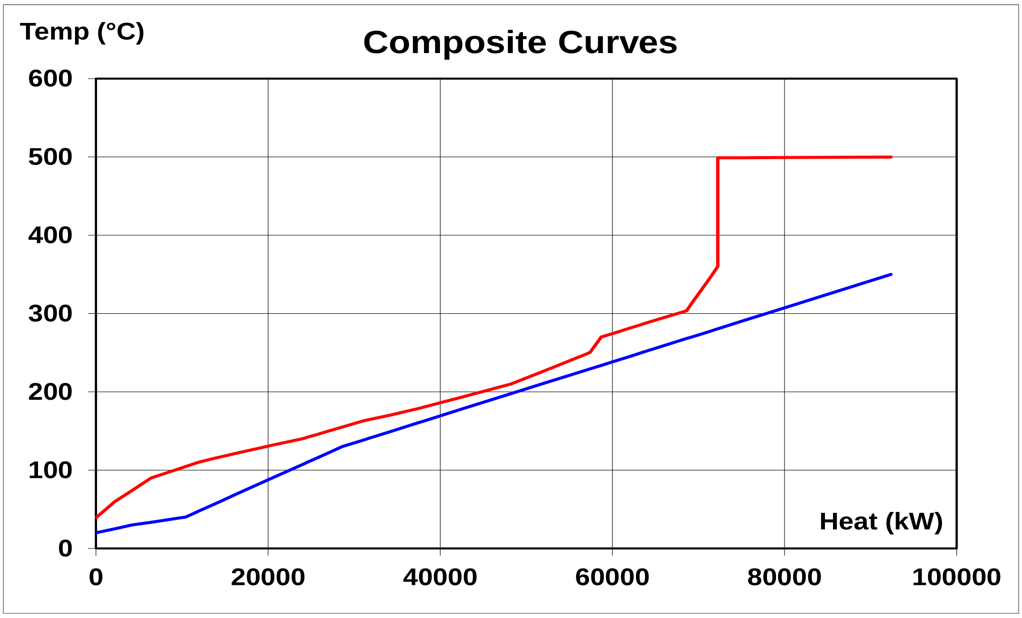

Figure 24.2 – Composite Curves

The results of the pinch analysis are presented in Table 24.2. The difference between vertical and criss-cross area is only 1.0%, due to the small shift values.

Table 24.2 - Results of pinch analysis

Results Pinch analysis			
InputUtil.Hot/Cold	kW	20375.00	8593.98
HEX area (vertical):	m²	13059.61	
HEX area (criss-cross):	m²	12943.94	
Annual cost utilities	'000 $/y	2123.44	
Pinched at 210°C (MCR)			
HEX area (criss-cross):	m²	12943.94	
Feasible # units above/below Pinch :		8	10
Annual cost Investment	'000 $/y	1161.92	
Total annual cost	'000 $/y	3285.36	
Split at 130°C and KERO and LVGO pushed down			
HEX area (criss-cross):	m²	13421.97	
Feasible # units above/below split:		9	8
Annual cost Investment	'000 $/y	1163.21	
Total annual cost	'000 $/y	3286.65	

The grid diagram contains 23 integration bands. Applying LP on the diagram generates a network with 80 heat exchanger units; simplification of the grid seems appropriate.

Further analysis indicates that the cooling can be concentrated in one unit on the TCR and suggests putting all hot stream below the desalter on parallel branches of the crude. Herewith, the initial network below the desalter can be synthesised with the target number of units of 8. The grid above the desalter can be reduced to 7 bands as shown in Table 24.4. The number of units is reduced to 29, with 21 units above and 8 units below the desalter.

The grid was fed into an LP-program, the results of which were transferred into an initial network for further optimisation. Application of smart optimisation procedures [5] with non-isothermal splits reduced the network to 17 units with an area of 13398 m², 11 splits and an annual cost of 3328.57 k$/year (Figure 24.5). As indicated in that figure, this network was fine-tuned by alternating the pipe connections between the exchangers A1 trough A5 and further optimized, leading to the network in Figure 24.6a with 10 splits and a cost of 3324.61 k$/year.

It was further studied whether the network could be further improved and simplified by reducing the number of splits. Above the desalter, the 5 streams VR2, HVGO, LGO, HGO and MCR must be cooled down with branches of the crude above the desalter to stay close to the energy target. Consequently, the crude above the desalter remains split in 5 branches. Below the desalter, however, the number of branches can be reduced by merging branches or by replacing an exchanger on a branch by a cooler. There are many alternative solutions and, so far, there is no clear indication whether the optimum network has been found. In the search for systematics, the following additional heuristics were tested:

- Move the heat exchanger with the smallest heat transfer coefficient to the cold side with larger driving force.
- Increase the load on that branch by adding other loads and increasing the split ratio on that branch to increase the driving force.

Results can be monitored by analyzing the trend. A preliminary overview is shown in Figure 24.3.

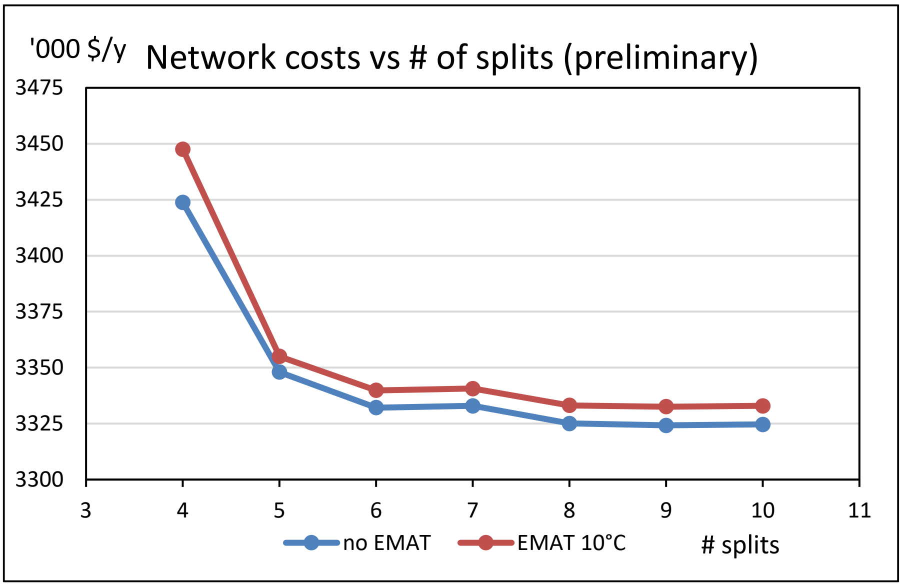

Figure 24.3 – Preliminary overview of results.

The graph in Figure 24.3 would suggest that further improvements are likely for the networks with 7 splits and those with 4 splits. After application of the heuristics, results as shown in Figure 24.4 were achieved. Almost all networks could be improved.

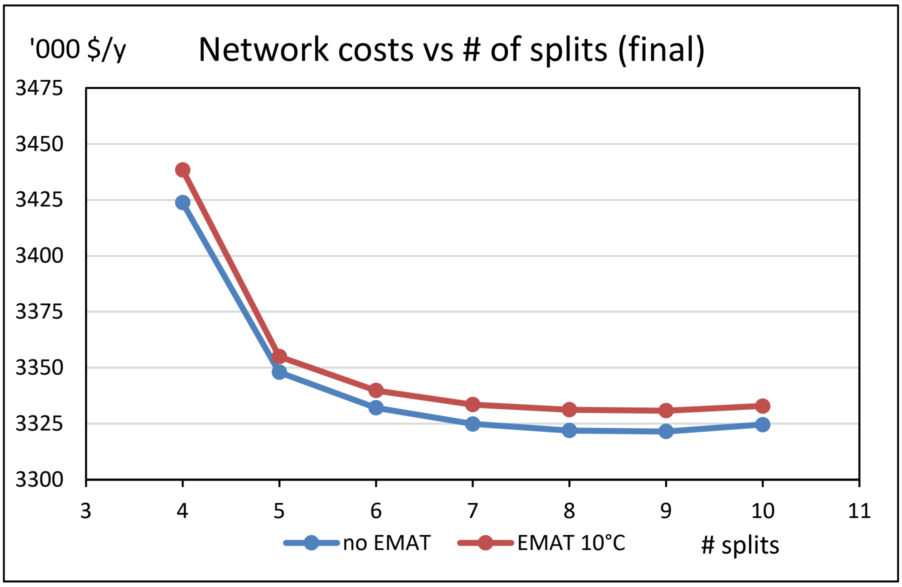

Figure 24.4 – Final overview of results.

Networks with less splits are presented in Figures 24.7a through 24.12a.

The above networks have no minimum approach temperature (EMAT). To enable full comparison with the network by Kim in [2], an EMAT of 10 °C was imposed on the previous networks. These networks are presented in Figures 24.6b through 24.12b. The results are summarised and compared with published results in Table 24.3. All networks have 17 units, except the networks without splits below the desalter that have 18 and 19 units.

The networks with lowest cost have 9 splits with a cost of 3321.53 k$/year, respectively 3330.85 k$/year with an EMAT of 10 K. The cost difference with the other networks is very small. There exist more than 50 networks with a cost range within 0.5% of the optimum.

Conclusion: targeting with insight in the process combined with simple methods enables synthesis of competitive heat exchanger network structures.

Table 24.3 - Results

	Heating	Cooling	Area	Utility cost	Area cost	Total cost	Units	Splits	Delta
	kW	kW	m²	'000 $/y	'000 $/y	'000 $/y	-	-	%
no EMAT									
Pavão et al.	20 891	9108	13 835	2180.18	1 210.89	3 391.07	18	7	2.09%
Nair et al. (best of)	20 894	9114	13 432	2180.54	1 163.78	3 344.32	17	10	0.69%
this research	20 747	8 966	13 368	2 164.36	1 160.25	3 324.61	17	10	0.09%
	20 705	8 924	13 396	2 159.74	1 161.79	3 321.53	17	9	0.00%
	20 710	8 929	13 393	2 160.29	1 161.64	3 321.93	17	8	0.01%
	20 717	8 936	13 433	2 161.06	1 163.80	3 324.86	17	7	0.10%
	20 795	9 014	13 409	2 169.64	1 162.47	3 332.11	17	6	0.32%
	20 908	9 127	13 472	2 182.07	1 165.95	3 348.02	17	5	0.80%
	21 224	9 443	13 763	2 216.83	1 206.95	3 423.78	18	4	3.08%
EMAT 10°C									
Kim et al. (best of) °)	23 566	11 783	9 794	2 474.43	982.22	3 456.65	17	6	3.78%
Kim et al. °°)	23 566	11 785	10 044	2 474.45	977.40	3 451.85	17	6	3.63%
this research	21 034	9 253	12 945	2 195.93	1 136.98	3 332.91	17	10	0.06%
	21 017	9 236	12 942	2 194.06	1 136.79	3 330.85	17	9	0.00%
	21 017	9 236	12 949	2 194.06	1 137.17	3 331.23	17	8	0.01%
	21 021	9 240	12 982	2 194.50	1 139.00	3 333.50	17	7	0.08%
	21 066	9 285	13 007	2 199.45	1 140.39	3 339.84	17	6	0.27%
	21 177	9 396	13 060	2 211.66	1 143.30	3 354.96	17	5	0.72%
	21 468	9 687	13 088	2 243.67	1 194.82	3 438.49	19	4	3.23%
°) reported	°°) recalculated and optimised								

Literature.

[1] Kim, S. Y.; Bagajewicz, M. Global optimization of heat exchanger networks using a new generalized superstructure. Chem. Eng. Sci. 2016, 147, 30−46.

[2] Kim, S. Y.; Jongsuwat, P; Suriyapraphadilok, U; Bagajewicz, M. Global Optimization of Heat Exchanger Networks. Part 1: Stages/Substages Superstructure. Ind. Eng. Chem. Res. 2017, 56, 5944-5957; DOI: 10.1021/acs.iecr.6b04686.

[3] L.V. Pavão, Caliane B.B. Costa, Mauro A.S.S. Ravagnani, A new stage-wise superstructure for heat exchanger network synthesis considering substages, sub-splits and cross flows, Applied Thermal Engineering 143 (2018) 719–735; DOI: 10.1016/j.applthermaleng.2018.07.075.

[4] Sajitha K. Nair and Iftekhar A. Karimi, Unified Heat Exchanger Network Synthesis via a Stageless Superstructure, Ind. Eng. Chem. Res. pubs.acs.org/IECR; DOI: 10.1021/acs.iecr.8b04490.

[5] Case 21 – Synthesis of Heat Exchanger Networks – Smart optimisation procedures.
DOI: 10.13140/RG.2.2.26429.51683

Table 24.4 - Reduced grid diagram

	area	**#HEX**	**AreaCost**
Heatit	13444.45	17	1164.44
Designit	13607.31	29	1473.40

N°	Tsupply	Ttarget	Heat	Description	mcp										
	°C	°C	kW	-	kW/K	Bands	1	2	3	4	5	6	7	8	9
14	500.0	499.0	20375.00	Heating	20375	500.0	499.0								
1	360.0	290.0	2786.70	VR1	40		360.0	301.6	290.0						
2	290.0	115.0	6966.75	VR2	40				290.0	280.0	250.8	208.0	147.6	115.0	
3	303.6	270.2	7848.33	LCR	235			303.6	292.0	282.0	270.2				
4	359.6	280.0	1952.59	SRQ	25		359.6	301.6	290.0	280.0					
5	250.6	90.0	21231.32	HVGO	132						250.6	211.0	150.6	90.0	
6	248.8	110.0	4415.23	LGO	32						248.8	206.0	145.6	110.0	
7	277.0	121.9	3812.36	HGO	25					277.0	249.8	207.0	146.6	121.9	
8	210.0	163.0	5440.72	MCR	116							210.0	163.0		
9	170.1	60.0	3735.69	KERO	34								170.1	60.0	
10	140.2	39.5	10724.55	TCR	107								140.2	120.2	39.5
11	178.6	108.9	3335.15	LVGO	48								178.6	108.9	
12	30.0	130.0	20248.00	Crude 1	202								130.0	30.0	
13	130.0	350.0	63782.40	Crude 2	290	350.0	279.7	266.8	254.8	244.5	228.6	196.4	130.0		
15	20.0	40.0	8593.98	Cooling	430									40.0	20.0

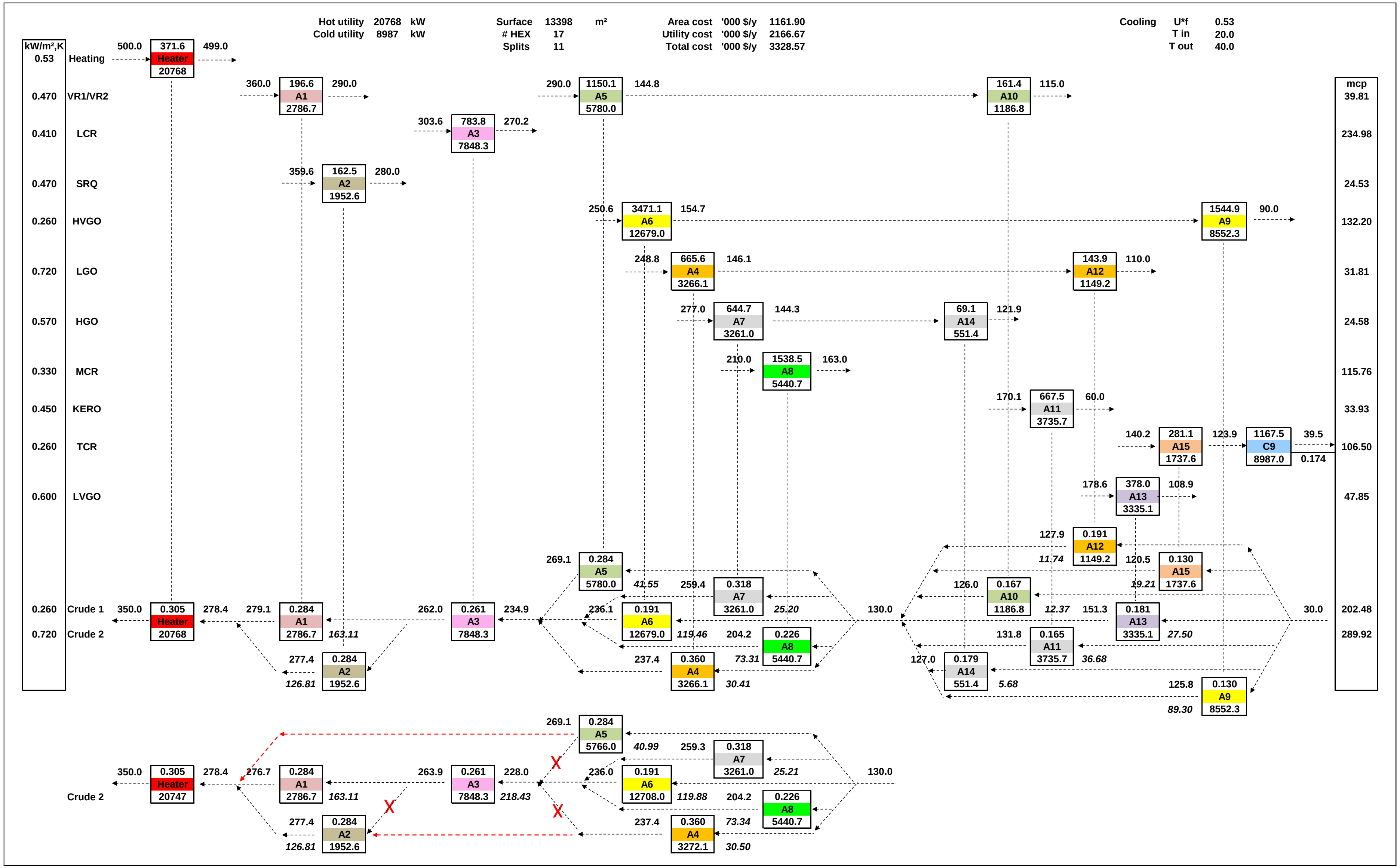

Figure 24.5 - Network after systematic development, repiping above desalter and fine-tuning.

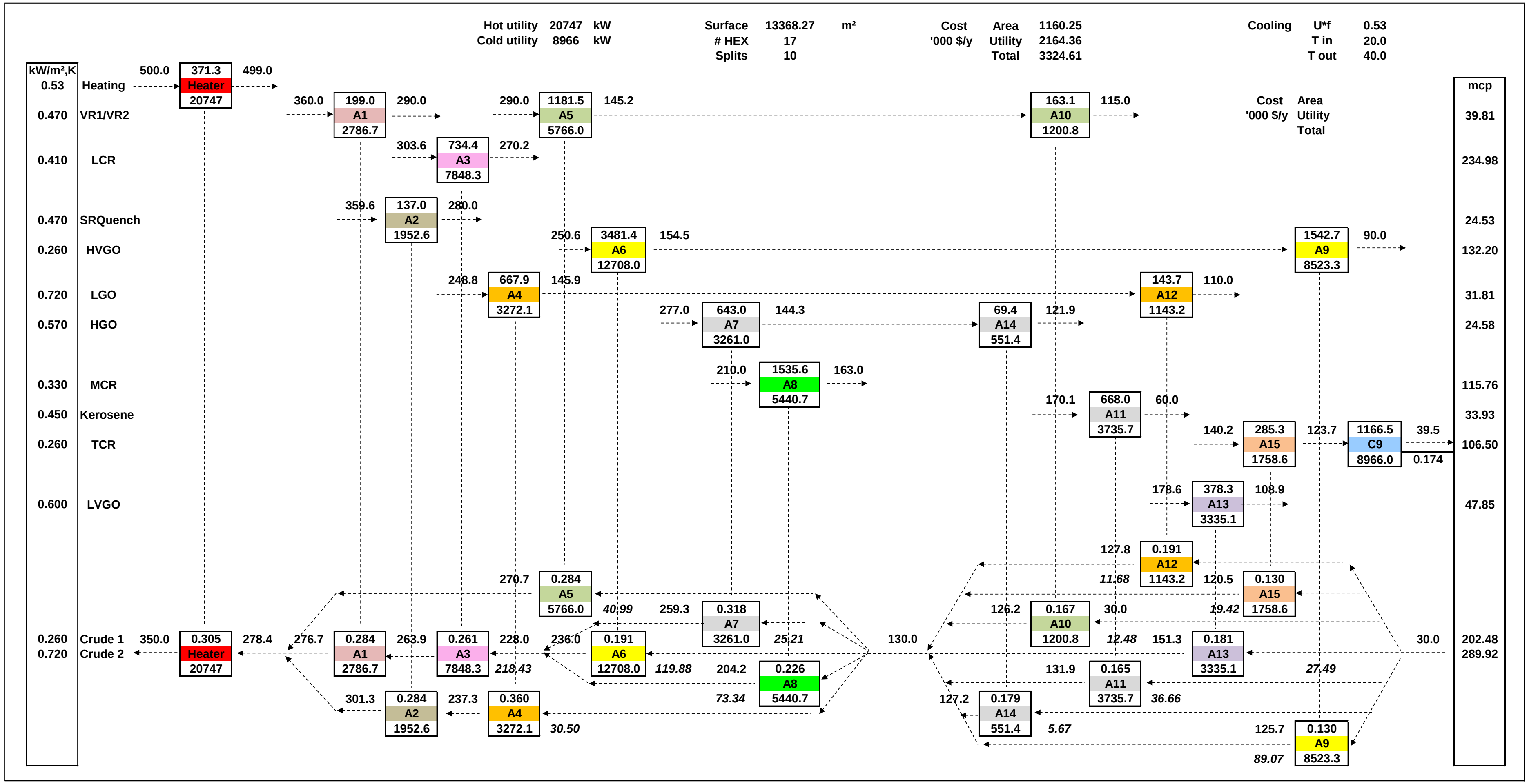

Figure 24.6a – Optimum network with 10 splits

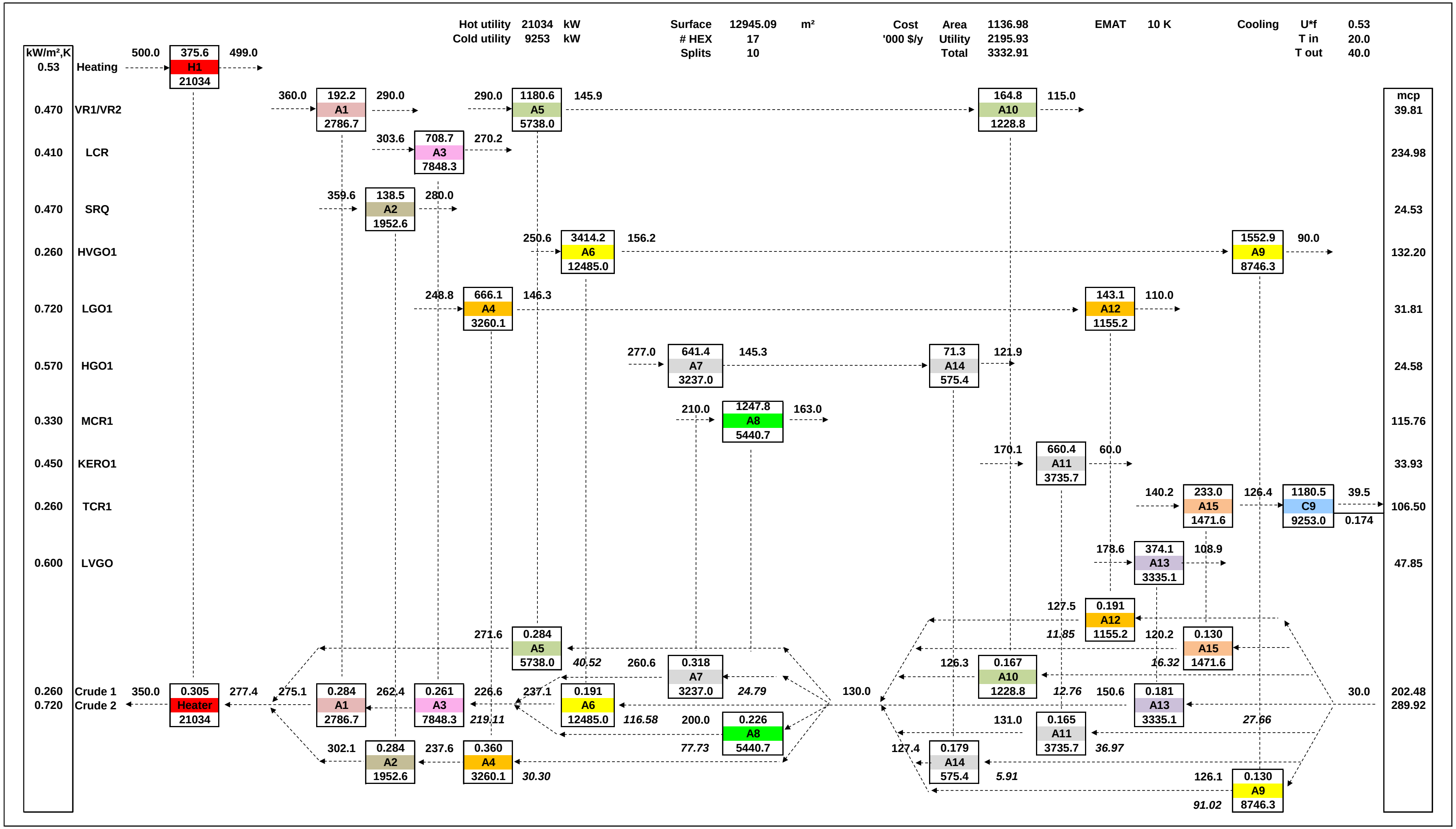

Figure 24.6b - Optimum network with 10 splits – EMAT 10K

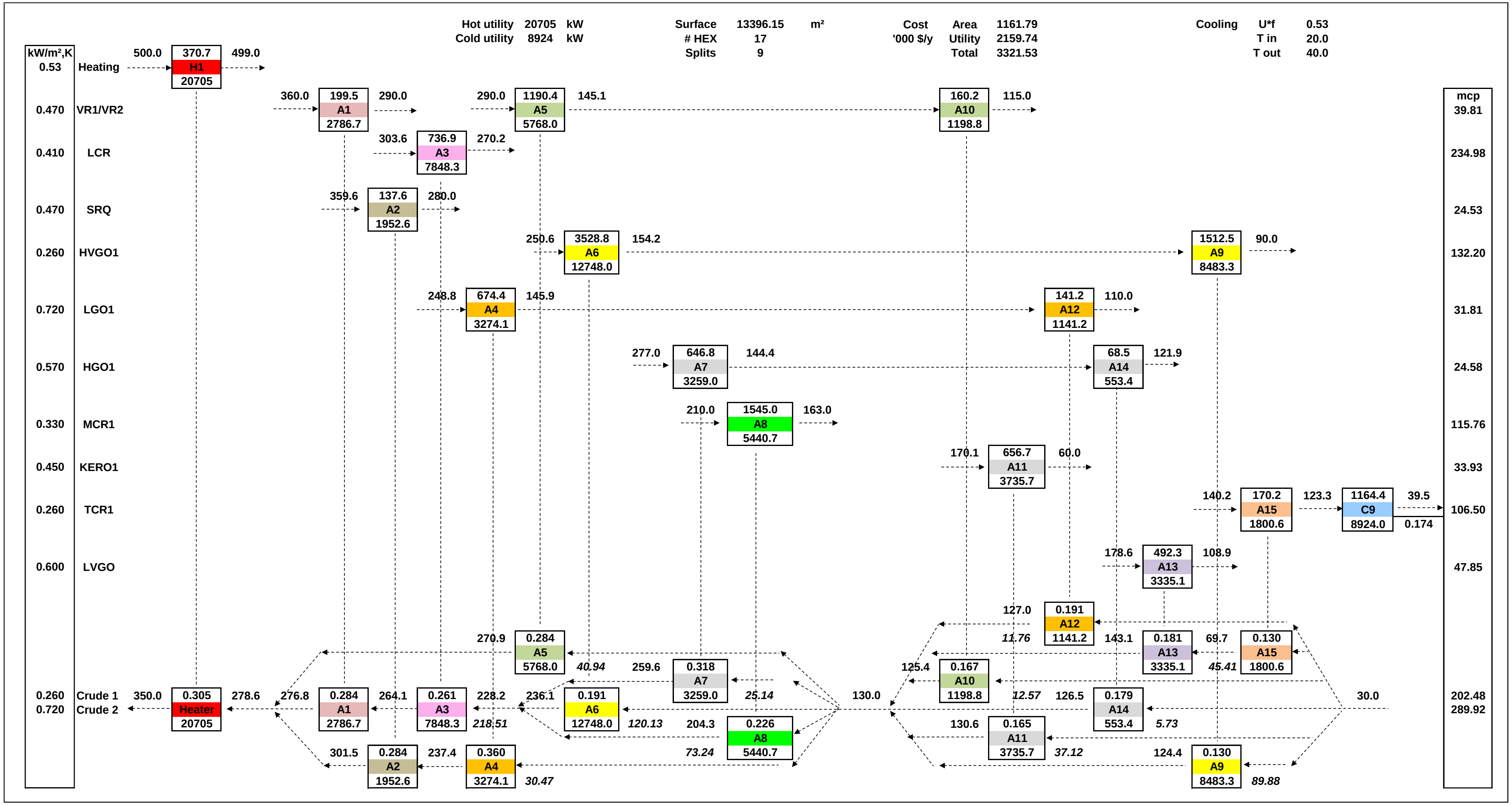

Figure 24.7a – Optimum network with 9 splits

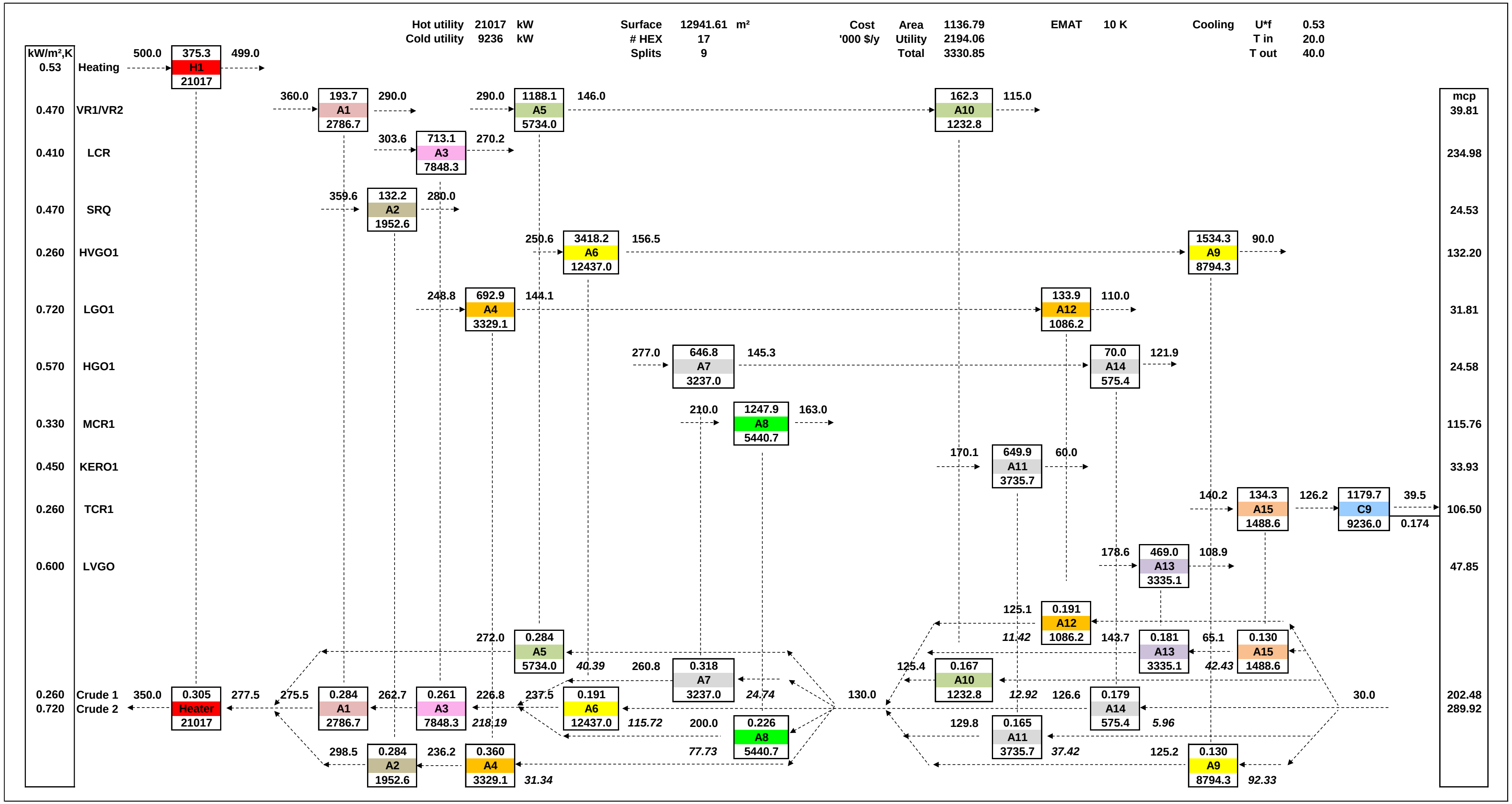

Figure 24.7b - Optimum network with 9 splits – EMAT 10K

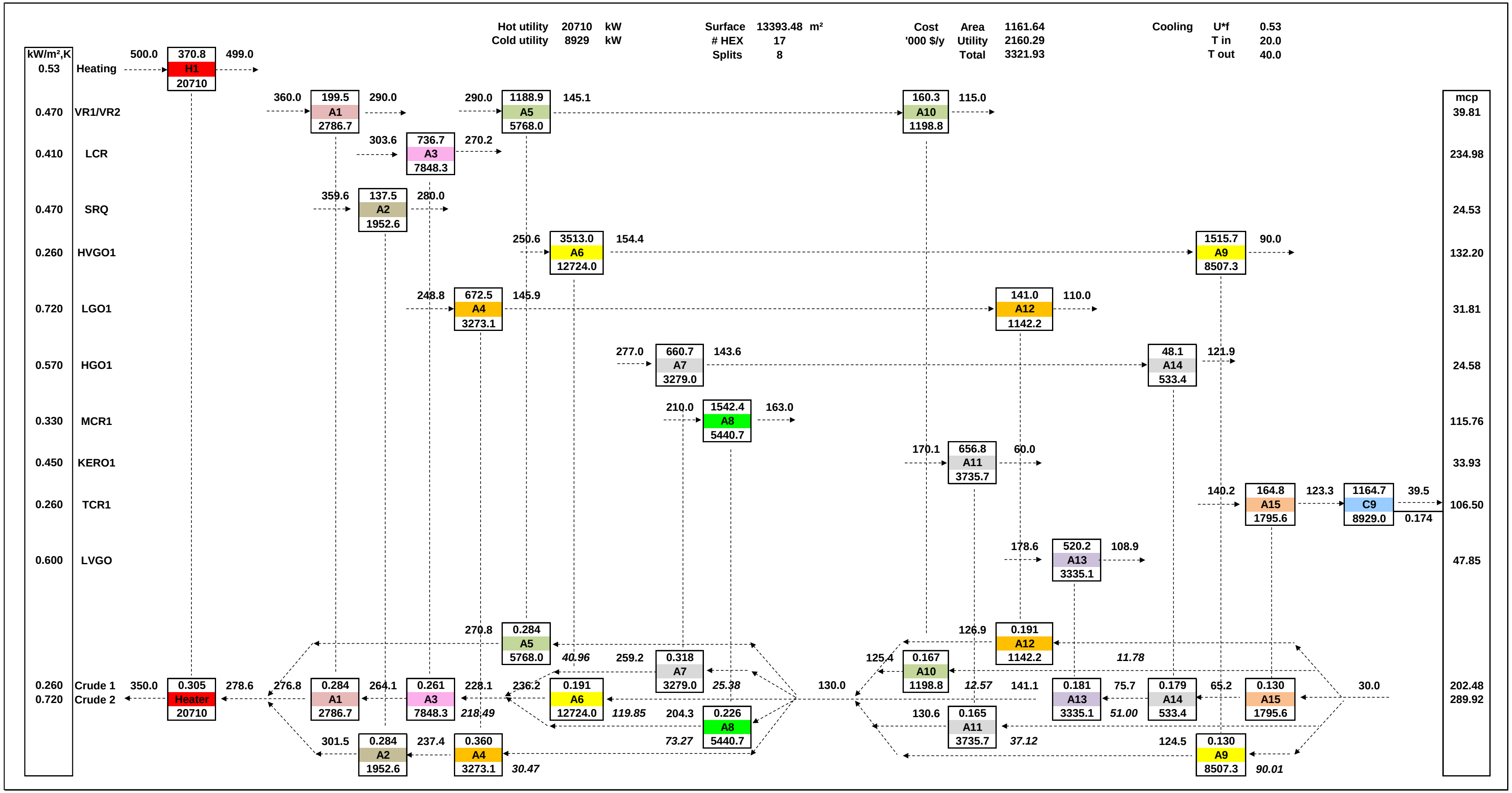

Figure 24.8a - Optimum network with 8 splits

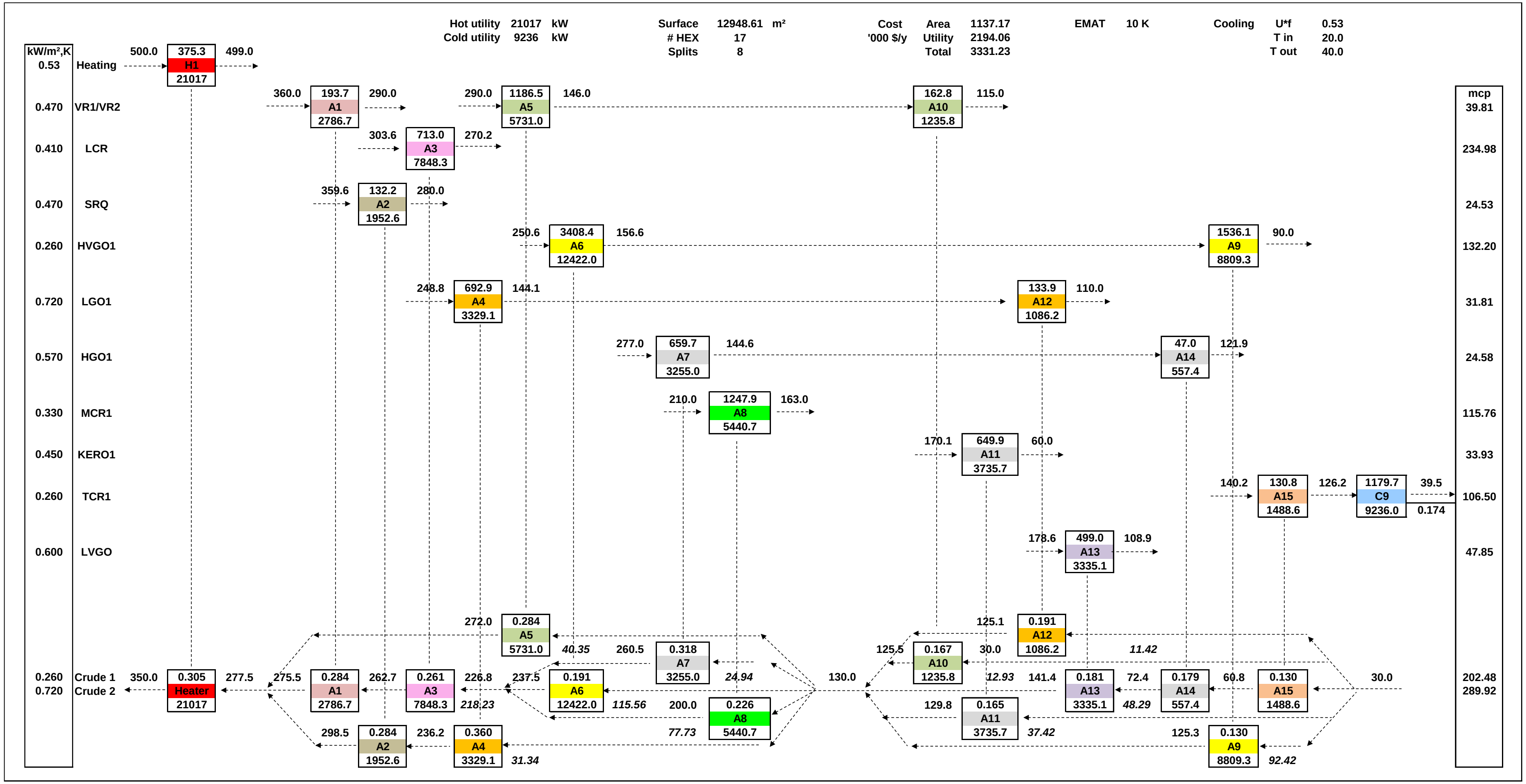

Figure 24.8b - Optimum network with 8 splits – EMAT 10K

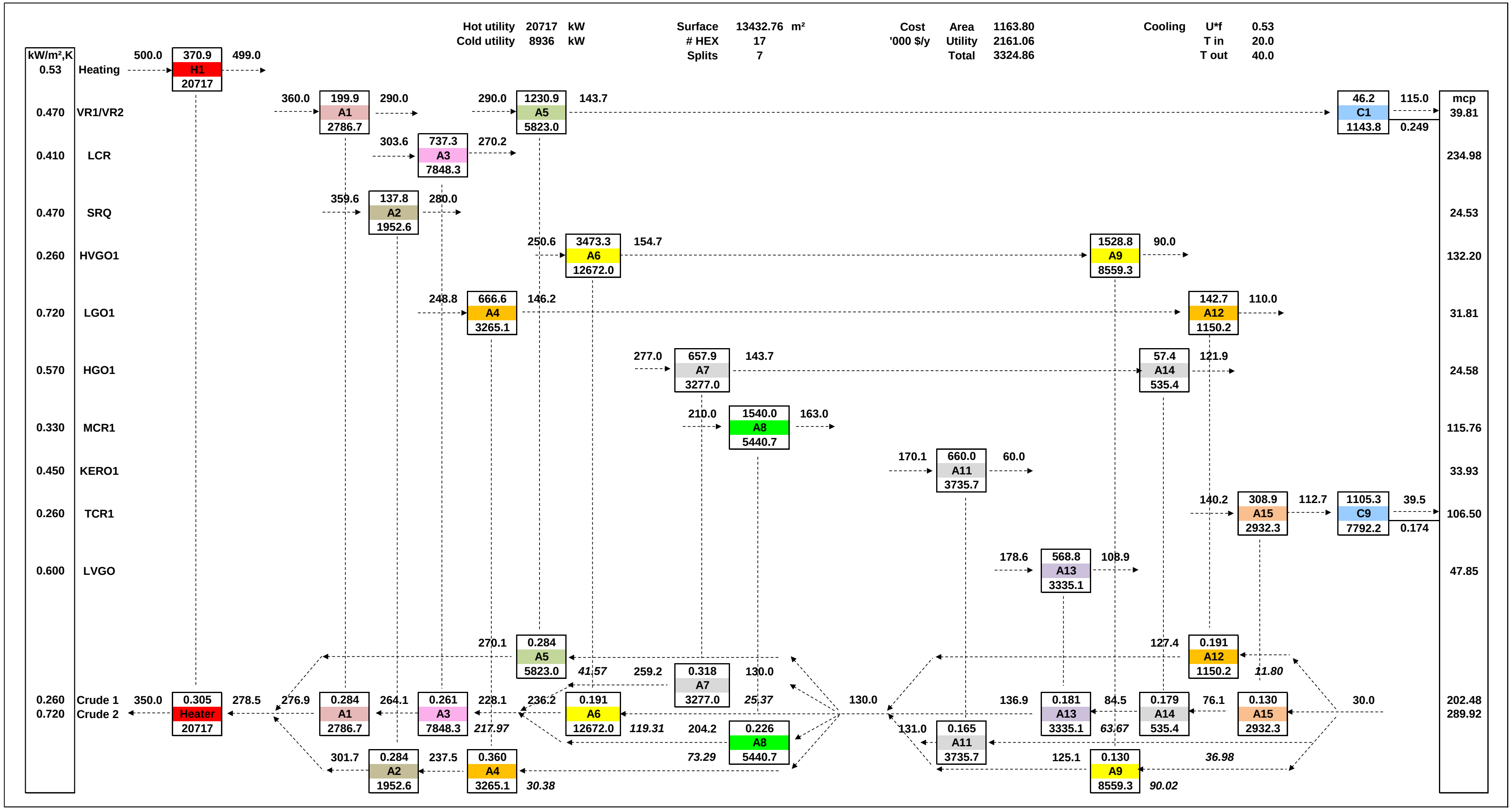

Figure 24.9a - Optimum network with 7 splits

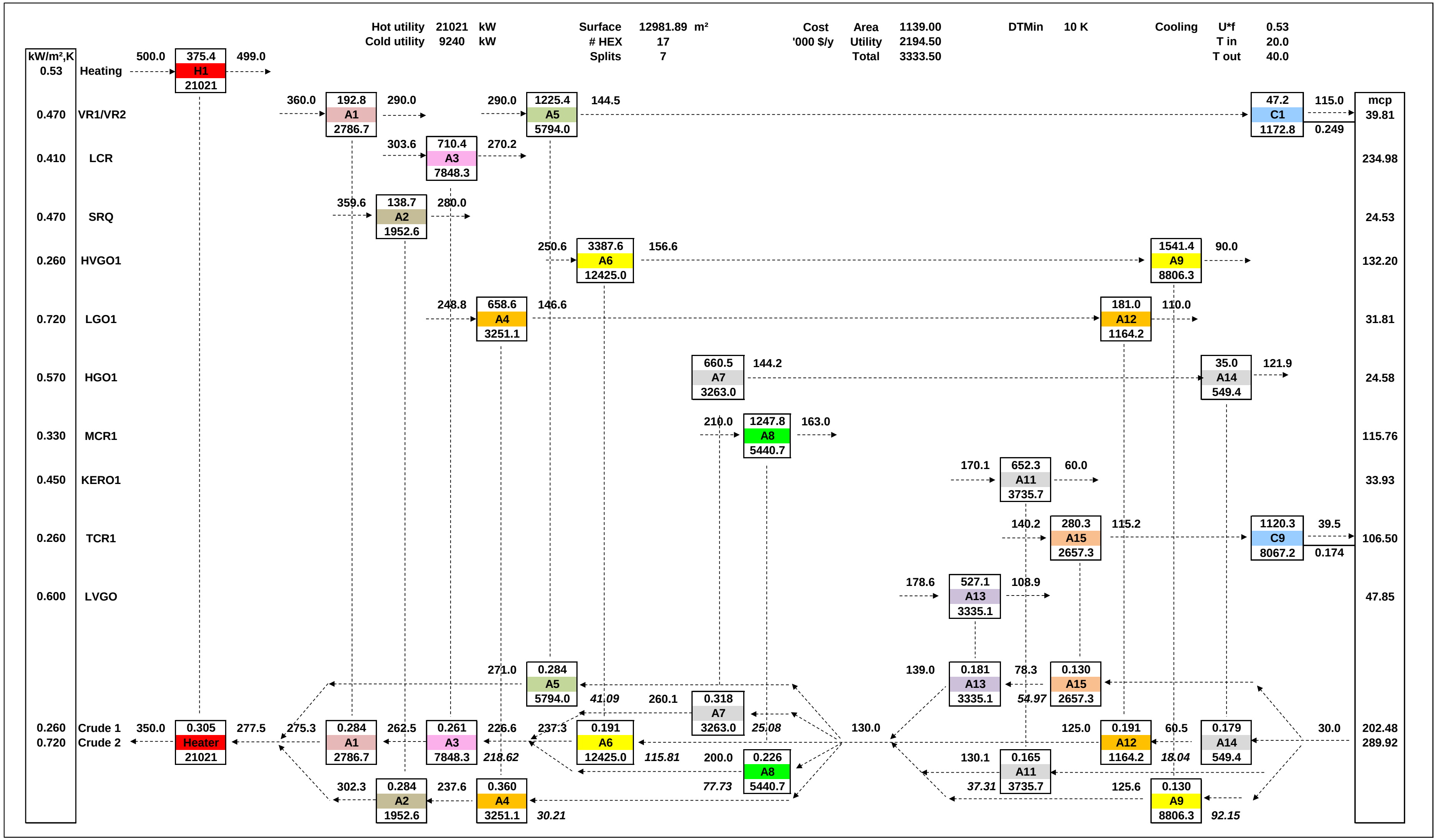

Figure 24.9b - Optimum network with 7 splits – EMAT 10K

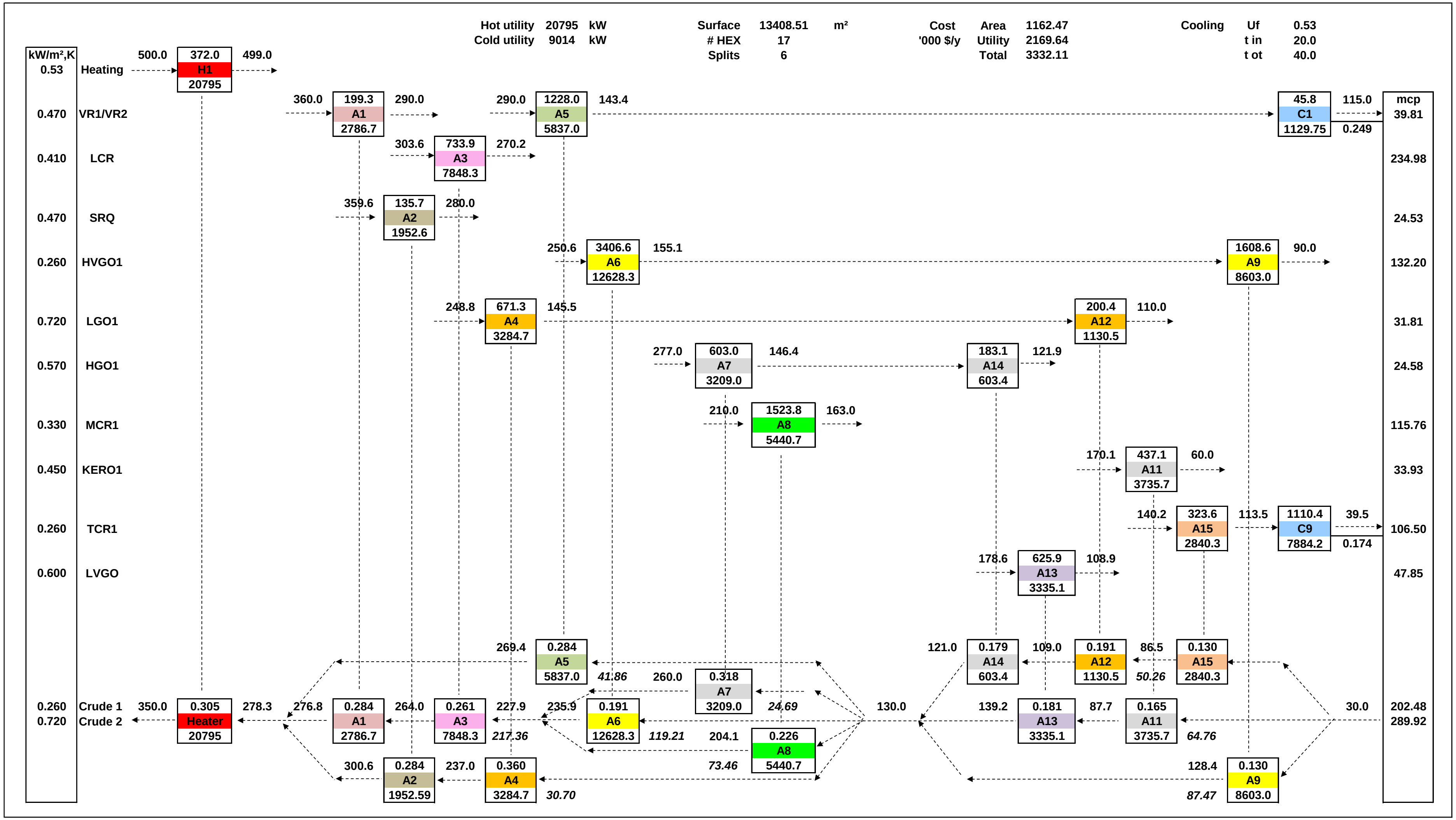

Figure 24.10a - Optimum network with 6 splits

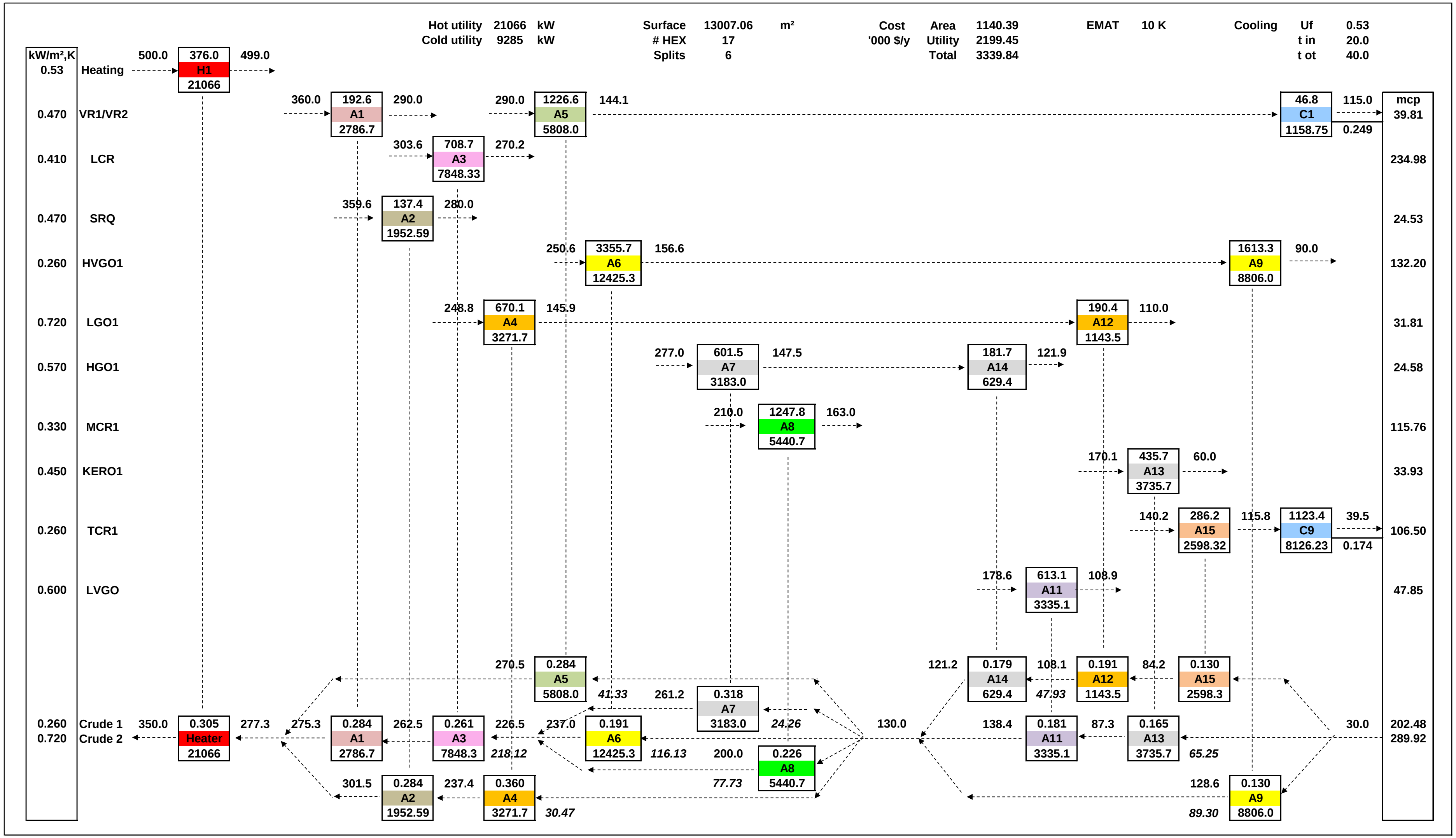

Figure 24.10b - Optimum network with 6 splits – EMAT 10K

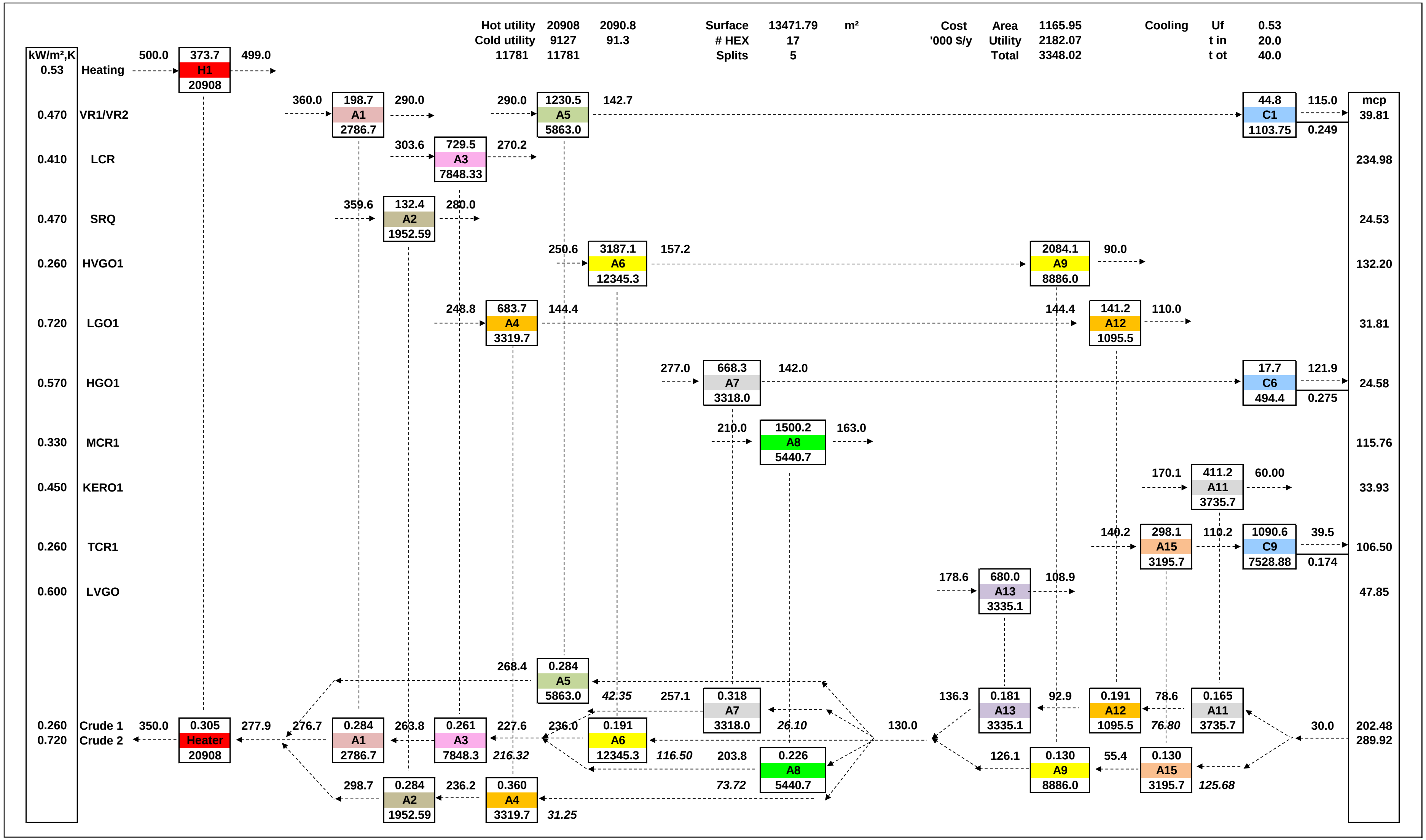

Figure 24.11a - Optimum network with 5 splits

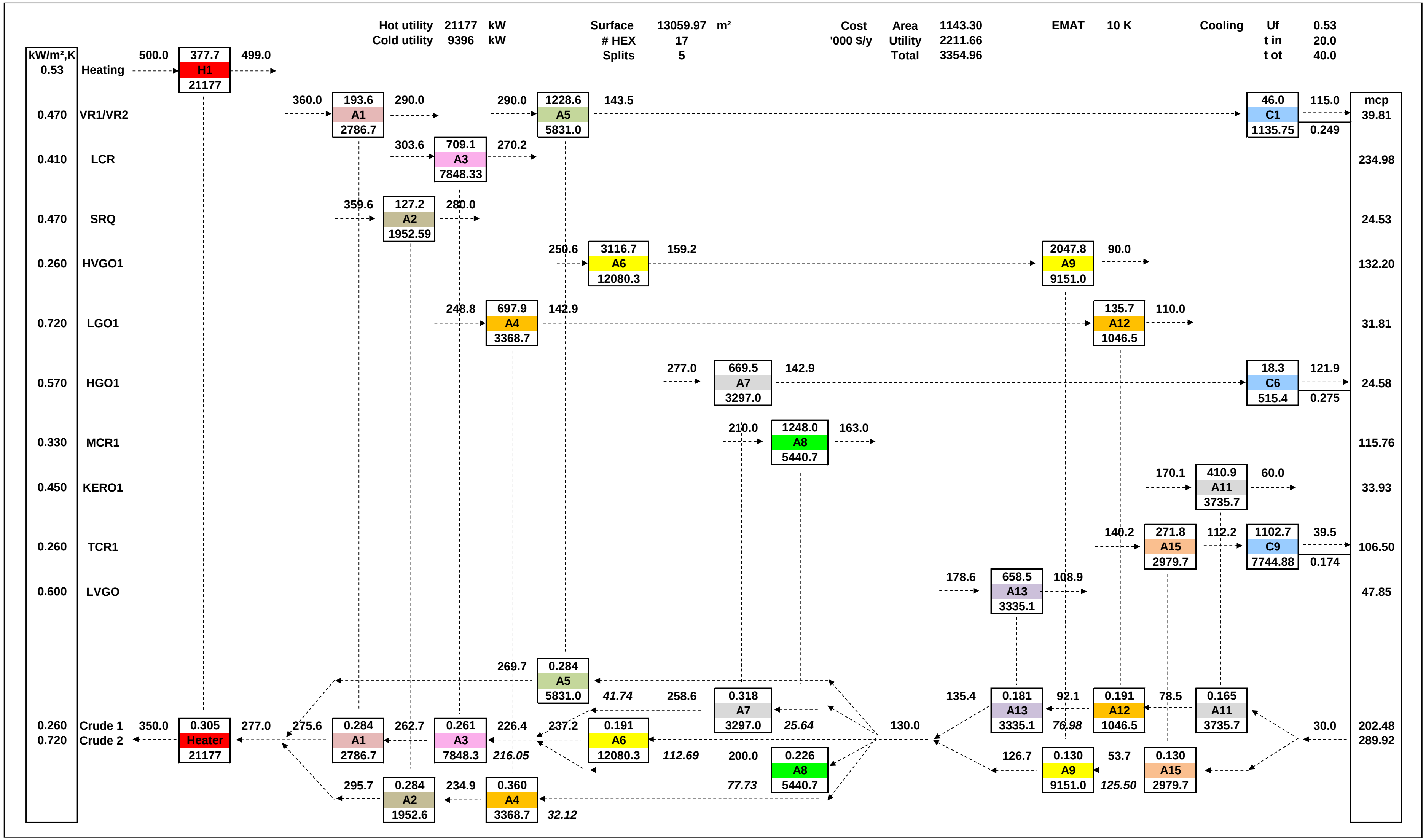

Figure 24.11b - Optimum network with 5 splits – EMAT 10K

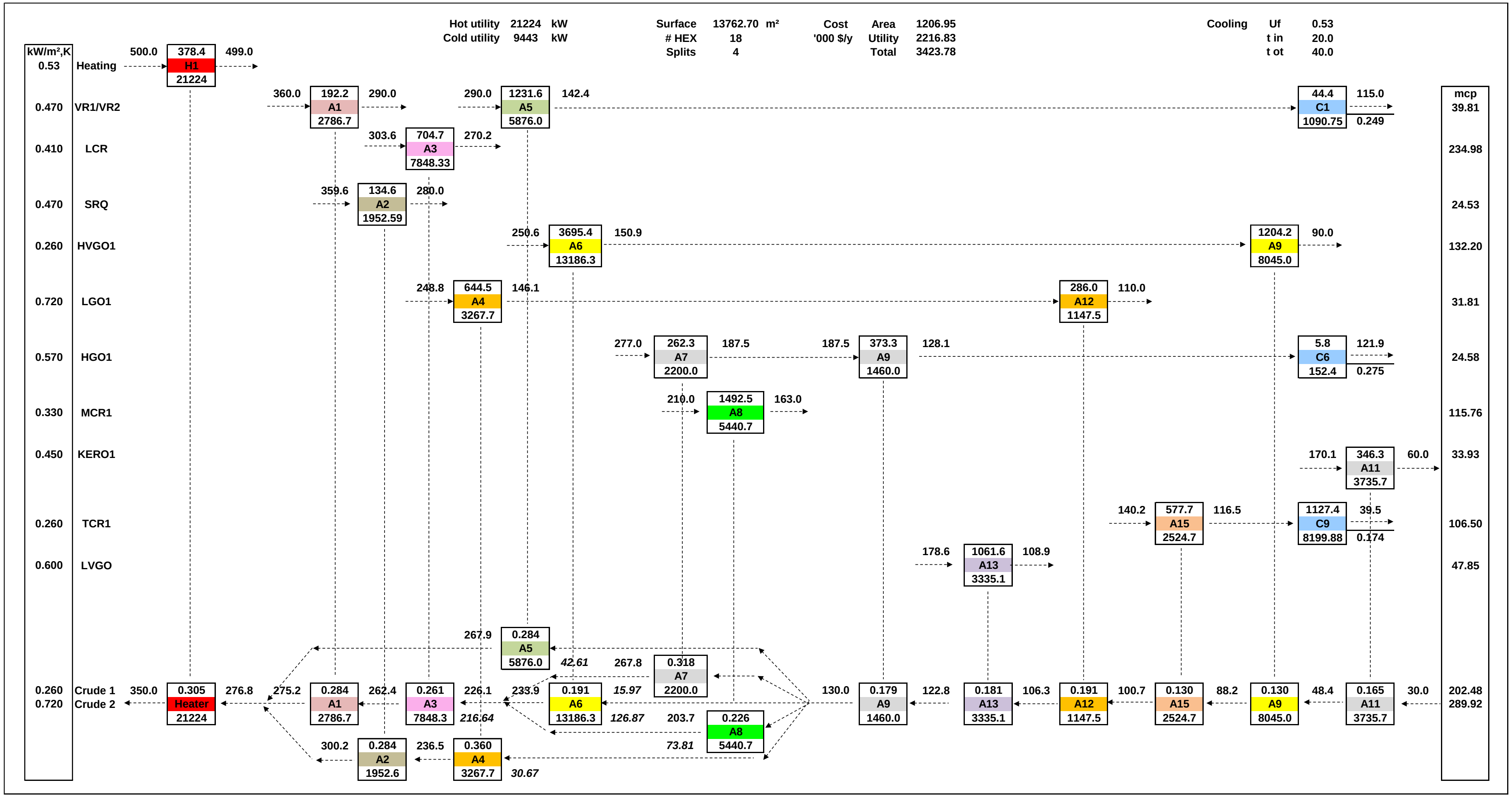

Figure 24.12a - Optimum network with 4 splits

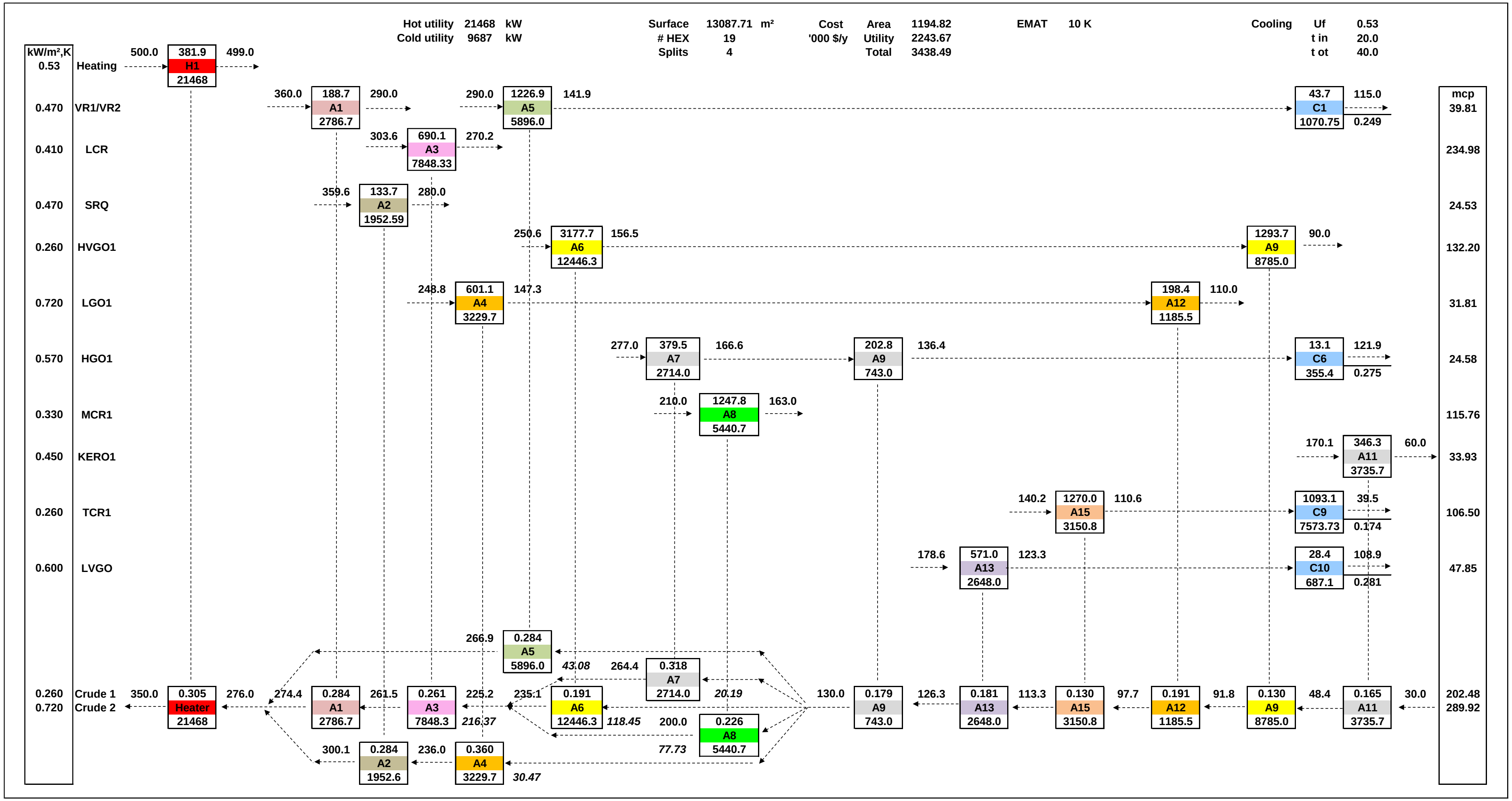

Figure 24.12b - Optimum network with 4 splits – EMAT 10K