
PROCESS INTENSIFICATION OF A 50 BPD MODULAR MINI-REFINERY: A SIMULATION-DRIVEN PINCH ANALYSIS APPROACH FOR ENHANCED HEAT RECOVERY AND SUSTAINABLE REFINING IN NIGERIA

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ABSTRACT

The global drive toward distributed small-scale petroleum refining has positioned modular mini-refineries as strategic assets for energy security in oil-producing developing economies. Yet, their widespread adoption in Nigeria remains constrained by simplistic process configurations, weak thermal integration, and heat exchanger networks designed without rigorous thermodynamic targeting, resulting in avoidable utility consumption, elevated operating costs, and diminished product value. While pinch-based energy integration is well established for large-scale refineries, its systematic coupling with commercial process simulation for sub-100 BPD modular systems has been sparsely addressed, constituting a distinct methodological gap that limits the energy-efficient scale-up of Nigeria's local refining capacity.

This work presents an original process integration and intensification framework for the Ahmadu Bello University Mini-refinery, transforming its existing 1 BPD topping unit into an optimized 50 BPD Atmospheric Distillation Unit processing a blend of Escravos and Forcados crude. Aspen HYSYS was applied for rigorous material and energy balancing, equipment sizing, and case-based yield optimization, with all simulation outputs cross-validated against independent manual calculations to within approximately 5% deviation, confirming model robustness.

Energy integration and optimization measurably improved naphtha, kerosene, and diesel recoveries while reducing residue generation, demonstrating tangible gains in crude value addition and heat recovery. By uniting simulation-driven design with structured heat integration at modular scale, this study delivers a novel, economically significant, and industrially replicable pathway toward sustainable, energy-efficient refining, directly advancing Nigeria's refining industry and supporting Sustainable Development Goals 7, 9, 12, and 13 through affordable clean energy, resilient infrastructure, responsible resource use, and climate-conscious industrial practice.

Keywords: Process Intensification; Energy Integration; Pinch Analysis; Heat Exchanger Network; Modular refinery; Optimization; Sustainable Refining

1.0 INTRODUCTION

Petroleum refining is among the most energy-intensive process industries; distillation, fired heating and steam generation together dominate a refinery's own fuel consumption, with efficiency strongly dependent on configuration, crude slate and installed heat recovery (IEA, 2024). Process Integration, and pinch analysis specifically, emerged in the late 1970s–early 1980s as a thermodynamically grounded response (Hohmann, 1971; Linnhoff & Flower, 1978; Umeda et al., 1978; Linnhoff & Hindmarsh, 1983): by locating the pinch temperature separating a process into interacting heat sources and sinks, it sets minimum hot- and cold-utility and heat-transfer-area targets before any exchanger is designed (Townsend & Linnhoff, 1984; Kemp, 2007), and decades of oil, gas and petrochemical application confirm material cuts in fired-heater and cooling-water demand (Smith, 2000; Klemeš et al., 2013). Process intensification pursues the same or better performance from smaller,

safer, more energy-efficient equipment through combined unit operations or enhanced transport phenomena (Stankiewicz & Moulijn, 2000; Van Gerven & Stankiewicz, 2009); where integration rearranges energy already in a flowsheet, intensification reduces the footprint, inventory and often the energy and capital demand of the equipment itself. Modern refinery design increasingly applies both together, since a smaller, better-integrated plant is cheaper to build and to run.

Nigeria holds substantial proven reserves but has historically relied on a few large, centralised state-owned refineries that, for much of the past two decades, ran well below installed capacity, forcing large-scale product imports even while crude was exported. Policy has consequently favoured modular and mini-refineries as a faster, lower-capital route to domestic capacity: the Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA) reported issuing 47 Licences to Establish and 30 Licences to Construct in a single year, combined capacity approaching three million BPD, with several modular refineries already operating in the Niger Delta at 1,000–11,000 BPD (as cited in Ahmed, 2025). Because modular units are small by definition, their thermal efficiency is easily compromised where energy integration is an afterthought — the economies of scale that make heat exchange attractive at large flowrates are largely absent at small ones. This is the setting for the ABU Mini-Refinery, an existing 1 BPD teaching/research facility in the Department of Chemical Engineering, ABU Zaria, now being redesigned and scaled to 50 BPD.

The existing 1 BPD facility is too small for meaningful scale-up study or a representative test of heat-integration strategy, and its heat exchanger network was never designed against a formal energy target. The engineering problem addressed here is therefore how to integrate, size and, in due course, intensify the heat-recovery system of a 50 BPD ADU/VDU processing blended Escravos and Forcados crude, using a rigorous simulation- and pinch-analysis-based methodology, so the redesigned unit can serve as a demonstrable, energy-conscious platform for Nigerian modular-refinery development. Prior work has applied pinch analysis and simulation to crude distillation and to Nigerian refinery retrofits, e.g. the Kaduna FCC unit (Abubakar, 2020), and a separate body of Nigerian work covers modular-refinery design and economics for indigenous crude assays (Olatona, 2022); less common is a single 50 BPD-scale study combining an Aspen HYSYS simulation of a named Nigerian crude, a full Problem Table Algorithm exercise across a range of $\Delta T_{\min}$, balanced-composite-curve area targeting, and a stated, in-progress programme to synthesise, fabricate and test the network on a physical unit. This study is positioned to close that gap, while candidly reporting network synthesis, fabrication, and commissioning as ongoing rather than completed.

The aim is to design, simulate, validate, and optimise the 50 BPD ABU mini-refinery ADU for a blend of Escravos and Forcados crude and to carry out energy integration of its heat exchanger network. Specific objectives: (i) design, validate and optimise the 50 BPD unit; (ii) carry out material and energy balances by manual calculation and Aspen HYSYS simulation; (iii) size major equipment (preflash column, desalter, furnace, atmospheric column, side strippers, condenser, HEN); (iv) carry out energy-integration design via the Pinch Design Method; and (v) fabricate, install, and test-run the energy-integrated unit. By coupling rigorous simulation with pinch-based targeting on a physical modular refinery, the study generates concrete, quantified energy and area targets transferable to similarly scaled Nigerian mini-refineries, and its validation methodology — cross-checking HYSYS against independent manual calculation — offers a transferable quality-assurance approach for other indigenous modular-refinery projects, strengthening local technical capacity in simulation, pinch analysis and refinery equipment design.

2.0 LITERATURE REVIEW

Conventional refineries achieve economies of scale through highly heat-integrated preheat, furnace and fractionation trains that are difficult to replicate at a fraction of the throughput; modular refineries (roughly hundreds to a few thousand BPD) have therefore been promoted in Nigeria as a quicker, lower-capital route to local capacity (Olatona, 2022), reinforced by the scale of recent licensing activity (Ahmed, 2025). This literature, however, concentrates on crude-assay classification, mechanical sizing, and yield estimation, with comparatively little systematic energy targeting. Distillation and fired heating dominate refinery energy use, and refining remains one of the more energy- and emissions-intensive segments of the oil supply chain (IEA, 2024); at mini-refinery scale, where stream flowrates and heat-capacity flowrates are small, achieving comparable heat recovery to a

large plant requires more deliberate targeting, since the scope for stream-to-stream heat exchange narrows as flowrates fall.

Process Integration is a family of thermodynamically based methods for systematic design and analysis of process and utility systems (Smith, 2000; El-Halwagi, 2011). Its heat-exchanger-network branch, pinch analysis, grew from early work on optimal networks and systematic synthesis (Hohmann, 1971; Umeda et al., 1978; Linnhoff & Flower, 1978) before consolidation into the Pinch Design Method (Linnhoff & Hindmarsh, 1983), and has since extended to mass, water, hydrogen and total-site utility systems (Klemeš et al., 2013). Pinch analysis represents hot and cold streams as composite curves of temperature against enthalpy; the closest approach between the curves, offset by the chosen minimum approach temperature (ΔT_{min}), defines the pinch (Linnhoff & Hindmarsh, 1983; Kemp, 2007). Below the pinch the process is in heat deficit and needs external heating; above it, in surplus, it needs external cooling; no economically justified design transfers heat across the pinch, since doing so raises both utility targets above their true minimum — and because ΔT_{min} governs the utility/area/capital trade-off, scanning a range of values (here 10–40°C) is itself part of the design task.

The Problem Table Algorithm (PTA) is the numerical counterpart of the composite-curve construction: streams are shifted by half of ΔT_{min} , ranked into temperature intervals, and cascaded through interval-by-interval enthalpy balances to compute minimum utility targets without graphical plotting (Kemp, 2007); adding just enough hot utility at the top of the cascade to eliminate every negative running total yields the minimum hot- and cold-utility targets and locates the pinch. Once targets are known, network synthesis matches hot and cold streams above and below the pinch subject to feasibility rules — $C_{Phot} \leq C_{Pcold}$ immediately above the pinch and $C_{Phot} \geq C_{Pcold}$ immediately below it — so no exchanger crosses the pinch (Linnhoff & Hindmarsh, 1983); the corresponding area target can be estimated ahead of detailed design via the balanced composite curve method (Townsend & Linnhoff, 1984), valuable at the pre-design stage before the detailed network is finalised, with subsequent mathematical-programming and metaheuristic extensions catalogued by Furman and Sahinidis (2002).

Process Intensification seeks step-change gains in performance, smaller equipment and lower energy/material inventories by combining unit operations or exploiting more favourable driving forces (Stankiewicz & Moulijn, 2000), classified by the structure-energy-synergy-time framework according to whether they intensify the equipment or the process itself (Van Gerven & Stankiewicz, 2009); divided-wall columns and heat-pump-assisted distillation are commonly cited refining examples. Process integration and intensification are conceptually distinct — the former re-arranges existing flowsheet energy, the latter changes the equipment or process route — but complementary, and both are examined here. Commercial simulators such as Aspen HYSYS are widely used to generate the material/energy balances and preliminary sizing a pinch study requires, particularly for multi-component crude fractions where hand calculation of vapour-liquid equilibrium is impractical; sustainable refinery development links this energy efficiency directly to resource conservation and emissions reduction, since every unit of avoided fired-heater duty is a unit of crude-derived energy not burned to run the plant (El-Halwagi, 2011; Klemeš et al., 2013). Overall, what remains comparatively underexplored is the combination of these strands — HYSYS simulation, full PTA energy targeting, area targeting, and a stated network-synthesis/fabrication programme — on one physically realisable 50 BPD Nigerian platform; this study addresses that gap.

3.0 METHODOLOGY

3.1 Research Framework and Facility

The existing ABU Mini-Refinery, a 1 BPD ADU/VDU teaching and research facility in the Department of Chemical Engineering, ABU Zaria, served as the design basis for a scaled-up, energy-integrated replacement. The research framework proceeds sequentially from design-basis definition and process-option selection, through PFD development, manual-and-simulation material/energy balancing, base-versus-optimised case-study comparison, equipment sizing, energy-integration/HEN design, mechanical and P&ID drawing, and finally fabrication, installation, operating-procedure preparation and test-running. At the time of reporting, the sequence is complete as far as equipment sizing and pinch-based energy/area targeting; HEN synthesis, fabrication, installation, and test-running remain ongoing and are reported as such. The redesign retains the existing ADU-VDU configuration

with side strippers but re-establishes the crude preheat, distillation and heat-recovery scheme from first principles using simulation and pinch analysis.

3.2 Feedstock Characterisation

The design basis specifies a 50 BPD ADU capacity, an ambient temperature of 25°C, and an operating pressure of 760 mmHg. The blended crude comprises of Escravos characterised in Aspen HYSYS using the PIMS-based Escravos-2012 assay for West Africa/Nigeria, and Forcados crude characterised using the Forcados Blend-2014 assay. Evaluation of both assays indicates that Escravos is relatively lighter and sweeter, with an API gravity of 33.84° and sulphur content of 0.17 wt.%, whereas Forcados is slightly heavier, higher in sulphur content, and is more acidic, with an API gravity of 32.22°, sulphur content of 0.22 wt.%, and total acid number of 0.46 mg KOH/g, as shown in Table 1.

Table 1: Design Basis and Crude Oil Properties of the Blend (Escravos/Forcados Ratio 50:50)

Parameter	Escravos	Forcados	Units
Capacity of ADU	25	25	BPD
Ambient temperature	25	25	°C
Pressure	760	760	mmHg
API gravity	33.84	32.22	—
Standard liquid density	53.37	53.90	lb/ft ³
Molecular weight	203.52	204.66	—
Sulphur content	0.17	0.22	wt. %
Pour point	16.38	18.27	°C
Watson K factor	11.57	11.38	—
Total acid number	0.24	0.46	mg KOH/g
Viscosity @ 37.78°C	4.44	4.02	cSt

3.3 Process Configuration

Five candidate configurations were screened at the process-selection stage (Table 2): a conventional ADU with preheat train and side strippers; a preflash-column configuration with heat integration; a divided-wall-column (DWC) ADU; a heat-pump-assisted ADU; and a hybrid combining preflash, DWC and heat integration. The flowsheet developed and simulated for the 50 BPD unit (Figure 1) retains a preflash drum ahead of the fired heater and a full set of pump-around loops, consistent with the preflash-with-heat-integration option identified in screening. It comprises crude feed and metering; wash-water mixing and desalting; a preflash stage; a top/middle/bottom pump-around preheat train; a fired heater; an atmospheric column with kerosene, diesel and AGO side strippers (each steam-reboiled); an overhead condenser and reflux drum; and product routing to naphtha, kerosene, diesel, AGO and atmospheric-residue storage. The atmospheric residue is processed in a VDU, with its own preheater and pump-around coolers, to recover light and heavy vacuum gas oil (LVGO, HVGO) and vacuum residue.

Table 3: Pinch-Analysis Stream Data for the ADU/VDU Heat Integration Study

No.	Stream	Type	Ts (°C)	Tt (°C)	CP (kJ/°C·s)
1	Top pump-around	H1 (hot)	169	110	0.069
2	Naphtha	H2 (hot)	73	40	0.035
3	Kerosene	H3 (hot)	230	40	0.025
4	Mid pump-around	H4 (hot)	236	152	0.050
5	Diesel	H5 (hot)	250	50	0.048
6	Bottom pump-around	H6 (hot)	305	232	0.034
7	Atmospheric gas oil	H7 (hot)	294	50	0.014
8	Atmospheric residue	H8 (hot)	304	118	0.057
9	Pre-desalted crude	C1 (cold)	25	95	0.161
10	Preflash crude	C2 (cold)	95	118	0.169
11	Pre-heated crude (furnace feed)	C3 (cold)	118	180	0.182
12	Heated crude (furnace outlet)	C4 (cold)	180	360	0.212
13	Steam	Hot utility	305	304	26.468
14	Cooling water	Cold utility	20	60	0.052

Pinch analysis was carried out by shifting each stream by half of the chosen ΔT_{min} and applying the PTA to the shifted temperatures for seven values spanning 10–40°C in 5°C increments; for each ΔT_{min} the shifted temperatures were recomputed, streams ranked into intervals, and an unconstrained-then-constrained enthalpy cascade constructed to obtain Q_{Hmin} , Q_{Cmin} and the pinch temperature. The full PTA computation is reported for the design case $\Delta T_{min} = 35^\circ\text{C}$, with targets for all seven ΔT_{min} values reported alongside it (Section 4). Area targeting for $\Delta T_{min} = 35^\circ\text{C}$ used the balanced composite curve method: utility duties were added to the streams so the composite curves coincide at every interval, and area contributions computed from each interval's log-mean temperature difference and aggregate CP. Detailed stream-by-stream network matching by the Pinch Design Method is identified as pending, ongoing work. Intensification considerations were incorporated principally at process selection (Table 2), where DWC and heat-pump-assisted options were evaluated, and in the adopted flowsheet through the preflash stage (reducing downstream vapour load and equipment size) and pump-around loops (combining reflux control with preheat duty in-column rather than in additional external exchangers). Validation compared HYSYS material/energy balances against independent MathCAD manual calculations using the same assay, design basis and specifications, on a percentage-deviation basis (Section 4.10).

4.0 RESULTS

The Aspen HYSYS flowsheet (Figure 1) converged for both the base case and the optimised case, generating full material and energy balances across every mixing point, the desalter, fired heater, condenser, each side stripper and the overall atmospheric column. Representative and summarised results are reported below.

4.1 Material Balance

Table 4 summarises the overall material balance for the 50 BPD atmospheric column. Steam introduced to the column and side strippers totals 10.406 kg/h against a crude feed of 284.747 kg/h; the column produces wastewater (10.247 kg/h), off-gas (3.153 kg/h), naphtha (59.256 kg/h), kerosene (40.595 kg/h), diesel (77.397 kg/h), AGO (21.510 kg/h) and residue (82.994 kg/h), this indicates a differential of + 0.001 kg/h (0.00034%) which is attributed to rounding error closing at 295.153 kg/h inlet and 295.152 kg/h outlet, however, balances closed across the crude/wash-water mixing points, desalter, fired heater and each side stripper as shown in (Table 5), which confirmed an internal consistency.

Table 4: Overall Material Balance for the Designed 50 BPD Atmospheric Distillation Column

Component	Inlet (kg/h)	Outlet (kg/h)
Main steam	8.592	0.000
Diesel side-stripper steam	0.907	0.000
AGO side-stripper steam	0.907	0.000
Crude feed	284.747	0.000
Waste water	0.000	10.247
Off-gas	0.000	3.153
Naphtha	0.000	59.256
Kerosene	0.000	40.595
Diesel	0.000	77.397
AGO	0.000	21.510
Residue	0.000	82.994
Total	295.153	295.152

Table 5: Selected Unit Material Balances Across the ADU Flowsheet

Unit / component	Inlet (kg/h)	Outlet (kg/h)
MIX-100 – Water / Crude / Desalter feed	23.1 / 284.6 / –	– / – / 307.7
Desalter – Feed / Crude (desalted) / Waste water	307.7 / – / –	– / 284.7 / 23.0
Furnace – Crude in / Air / Fuel	284.7 / 108.0 / 5.3	–
Furnace – Crude out / Flue gas	–	284.7 / 113.3
Condenser – Feed	234.9	–
Condenser – Off-gas / Naphtha / Reflux / Waste water	–	3.2 / 59.3 / 162.2 / 10.3
Kerosene stripper – Draw / Boil-up	58.4 / 28.9	–
Kerosene stripper – Reboiler out / Return	–	69.5 / 17.8
Diesel stripper – Draw / Steam	88.7 / 0.9	–
Diesel stripper – Reboiler out / Return	–	77.4 / 12.2
AGO stripper – Draw / Steam	27.2 / 0.9	–
AGO stripper – Reboiler out / Return	–	21.5 / 6.6

4.2 Energy Balance

Table 6 reports the energy balance. The fired-heater/preheat-train duty on the crude side (CDU preheater) shows a net enthalpy gain of +157,981.85 kJ/h; the atmospheric condenser removes 120,912.86 kJ/h; and the three pump-around coolers remove 14,553.01, 15,166.55 and 8,942.28 kJ/h (top, middle, bottom). On the vacuum side, the VDU preheater gains 53,196.00 kJ/h, while its top and bottom pump-around coolers remove 16,784.74 and 19,472.53 kJ/h respectively.

Table 6: Energy Balance for the Designed ABU Mini-Refinery's ADU and VDU

Component	Input streams (kJ/h)	Output streams (kJ/h)	Duty (kJ/h)
CDU preheater	-521,249.43	-363,267.58	+157,981.85
ADU condenser	-509,500.73	-630,413.59	-120,912.86
Top-stage PA cooler	-197,367.83	-211,920.84	-14,553.01
Middle-stage PA cooler	-125,366.81	-140,533.36	-15,166.55
Bottom-stage PA cooler	-69,536.10	-78,478.38	-8,942.28
VDU preheater	-169,799.90	-116,603.90	+53,196.00
VDU top-stage PA cooler	-67,569.39	-84,354.14	-16,784.74
VDU bottom-stage PA cooler	-135,638.52	-155,111.05	-19,472.53

4.3 Product Yields

Table 7 compares base-case and optimised-case yields. Relative to base case, the optimised case increased naphtha yield 9.0% (11.000→11.994 BPD), kerosene 21.5% (6.000→7.291 BPD), diesel 2.2% (13.000→13.288 BPD), AGO fell 0.001% (3.559→3.558 BPD) which is an insignificant change, atmospheric residue fell 11.3% and vacuum residue fell 63.8% — a shift of material from low-value bottoms toward higher-value light/middle distillates. Off-gas and HVGO increased sharply in percentage terms (+86.5%, +285.5%) though both remain small absolute streams relative to the 50 BPD total.

Table 7: Product Yields — Base Case versus Optimised Case 50 BPD (Escravos/Forcados Blend Ratio 50:50)

Product	Base case (BPD)	Optimised case (BPD)	Variation (%)
Off-gas	1.691	3.153	+86.482
Naphtha	11.000	11.994	+9.040
Kerosene	6.000	7.291	+21.509
Diesel	13.000	13.288	+2.215
Atmospheric gas oil (AGO)	3.559	3.558	-0.001
Atmospheric residue	14.877	13.195	-11.306
Light vacuum gas oil (LVGO)	2.761	2.524	-8.584
Heavy vacuum gas oil (HVGO)	1.798	6.932	+285.540
Vacuum residue	10.300	3.731	-63.776

4.4 Equipment Sizing

Table 8 summarises sizing for the principal units, sized directly from converged HYSYS hydraulic and rating calculations. The column sections operate at 69–70% approach-to-flood in the sieve-tray sections and about 9% in the valve-tray section, with tray pressure drops of 1.1–4.0 kPa and vapour residence times of 22–35 s, indicating hydraulically stable operation with margin before flooding.

Table 8: Equipment Sizing Summary for the 50 BPD ABU Mini-Refinery ADU

Equipment	Key dimensions	Other parameters
Desalter	Diameter 1.252 m*; length 0.9146 m; head height 0.1636 m	Boot dia. 0.25 m; boot height 0.50 m; volume 0.3545m ³
Preflash column	Diameter 0.6473 m; length 0.9710 m; elevation 0.50 m	Boot dia. 0.2158 m; boot height 0.3237 m; volume 0.3313m ³
Furnace – tube bank	ID 0.089 m; OD 0.102 m; 20 tubes/pass	Inner area 21.23 m ² ; outer area 24.26 m ² ; net vol. 0.4718m ³
Furnace – shell	ID 1.700 m; OD 2.000 m; zone height 4.280 m	Inner area 22.86 m ² ; outer area 26.89 m ² ; net vol. 9.0982m ³
ADC section 1 (sieve)	Diameter 0.23 m; height 3.75 m	ΔP 4.045 kPa; 70.13% flood; 26.82 s residence; 26 holes
ADC section 2 (sieve)	Diameter 0.23 m; height 2.76 m	ΔP 1.595 kPa; 69.91% flood; 35.3 s residence; 50 holes
ADC section 3 (ballast valve)	Diameter 0.23 m; height 0.69 m	ΔP 1.075 kPa; 9.21% flood; 21.67 s residence

4.5 Pinch Analysis Results

Table 9 reports the detailed PTA cascade for the design case $\Delta T_{min} = 35^\circ\text{C}$. Working down the shifted-temperature intervals, the unconstrained cascade (Cascade I) reaches its most negative value of -26.468 kJ/s at the interval bounded by 212.5°C ; adding this quantity of hot utility at the top produces the constrained cascade (Cascade II), which first reaches zero at that same interval — identifying 212.5°C as the pinch on the shifted scale, corresponding to an actual hot-stream pinch of 230°C and cold-stream pinch of 195°C .

Table 9: Problem Table Algorithm Cascade for $\Delta T_{\min} = 35^{\circ}\text{C}$

Int.	Temp. Profile ($^{\circ}\text{C}$)	Streams Population	ΔT $^{\circ}\text{C}$	ΣCPH	ΣCPC	Q (kJ/s)	Cascade I $u = 0.000$	Cascade II $u = 26.468$
1	377.5	12	90	0.000	0.212	19.080	-19.080	7.388
2	287.5	6,12	1	0.034	0.212	0.178	-19.258	7.210
3	286.6	6,8,12	10	0.090	0.212	1.220	-20.478	5.990
4	276.5	6,7,8,12	44	0.104	0.212	4.752	-25.230	1.238
5	232.5	5,6,7,8,12	14	0.152	0.212	0.840	-26.070	0.398
6	218.5	4,5,6,7,8,12	4	0.202	0.212	0.040	-26.110	0.358
7	214.5	4,5,7,8,12	2	0.168	0.212	0.088	-26.198	0.270
8	212.5	3,4,5,7,8,12	15	0.194	0.212	0.270	-26.468	*0.000
9	197.5	3,4,5,7,8,11	46	0.194	0.182	-0.552	-25.916	0.552
10	151.5	1,3,4,5,7,8,11	16	0.263	0.182	-1.296	-24.620	1.848
11	135.5	1,3,4,5,7,8,10	1	0.263	0.169	-0.094	-24.526	1.942
12	134.5	1,3,5,7,8,10	22	0.213	0.169	-0.968	-23.558	2.910
13	112.5	1,3,5,7,8,9	12	0.213	0.161	-0.624	-22.934	3.534
14	100.5	1,3,5,7,9	8	0.156	0.161	0.040	-22.974	3.494
15	92.5	3,5,7,9	37	0.087	0.161	2.738	-25.712	0.756
16	55.5	2,3,5,7,9	13	0.122	0.161	0.507	-26.219	0.249
17	42.5	2,3,5,7	10	0.122	0.000	-1.220	-24.999	1.469
18	32.5	2,3	10	0.060	0.000	-0.600	-24.399	2.069
19	22.5							

*PINCH POINT

4.6 Energy Targets Across $\Delta T_{\min}$

Table 10 summarises pinch-analysis energy targets for seven $\Delta T_{\min}$ values. As $\Delta T_{\min}$ rises from 10°C to 40°C , $QH_{\min}$ rises from 24.44 to 27.44 kJ/s and $QC_{\min}$ from effectively zero to 3.04 kJ/s, while the pinch condition moves from a threshold-problem at $\Delta T_{\min} = 15^{\circ}\text{C}$ (overall heat surplus; in principle only one utility required) to a working pinch of 212.5°C (shifted) at $\Delta T_{\min} = 35^{\circ}\text{C}$. This is in conformity with the literature that utilities requirement increases as the approach temperature widens further. For the design case ($\Delta T_{\min} = 35^{\circ}\text{C}$), confirmed targets are $QH_{\min} = 26.47$ kJ/s and $QC_{\min} = 2.07$ kJ/s.

Table 10: Summary of Energy Targets and Pinch Points for $\Delta T_{\min} = 10\text{--}40^{\circ}\text{C}$

$\Delta T_{\min}$ ($^{\circ}\text{C}$)	$QH_{\min}$ (kJ/s)	$QC_{\min}$ (kJ/s)	Pinch (shifted, $^{\circ}\text{C}$)	Hot pinch ($^{\circ}\text{C}$)	Cold pinch ($^{\circ}\text{C}$)
10.0	24.44	0.00	TP	TP	TP
15.0	23.45	0.00	TP	TP	TP
20.0	24.70	0.30	40.0	50.0	30.0
25.0	25.00	0.60	60.5	73.0	48.0
30.0	25.61	1.21	58.0	73.0	43.0
35.0	26.47	2.07	212.5	230.0	195.0
40.0	27.44	3.04	210.0	230.0	190.0

*TP - Threshold Problem

4.7 Heat Exchanger Area Requirements

Detailed stream-by-stream HEN matching by the Pinch Design Method has not yet been completed; this remains pending, alongside fabrication, installation, operating-procedure preparation and test-running of the energy-integrated unit. Table 11 reports the interval-by-interval log-mean-temperature-difference and area computation for the balanced composite curves at $\Delta T_{\min} = 35^\circ\text{C}$. Summing the eighteen interval area contributions gives a minimum HEN area target of 8.86 m^2 for the redesigned 50 BPD ADU heat-recovery system — an early, network-independent estimate usable for preliminary capital-cost screening ahead of detailed exchanger design.

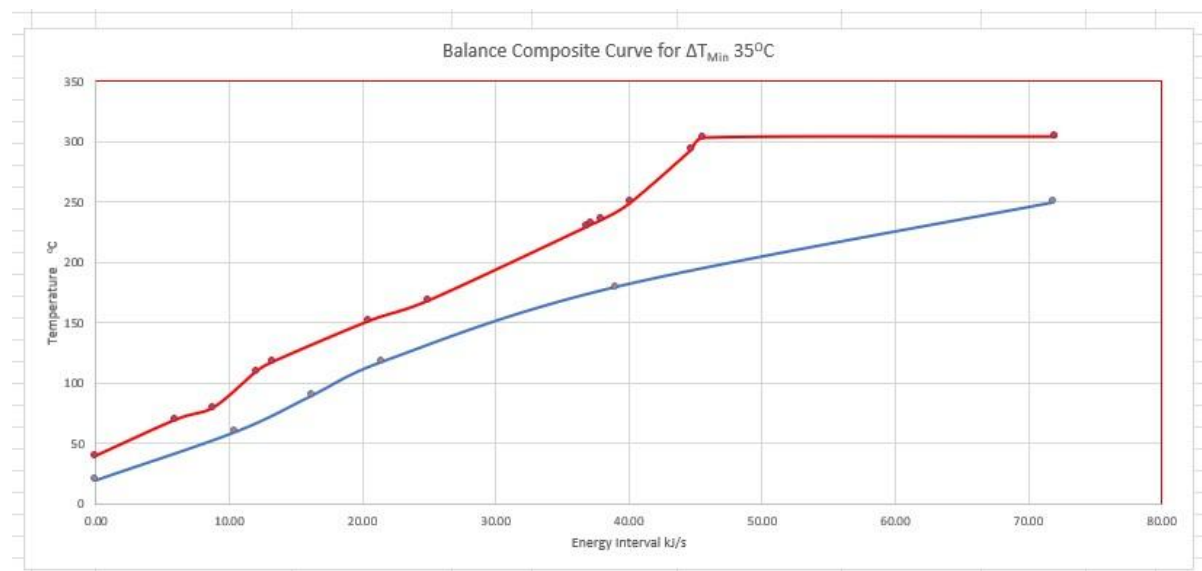


Figure 2: Balanced Composite Curve Graph for the ADU/VDU Heat Integration Study ($\Delta T_{\min} = 35^\circ\text{C}$)

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Table 11: Balanced Composite Curve Area-Targeting for ($\Delta T_{\min} = 35^{\circ}\text{C}$). Total heat-exchanger area target = 8.86 m^2

Int.	Thi($^{\circ}\text{C}$)	Tci($^{\circ}\text{C}$)	$\Sigma\text{CPH/h}$	$\Sigma\text{CPC/h}$	$\Sigma\text{Q/h,i(kJ/s)}$	LMTD($^{\circ}\text{C}$)	Area(m^2)
1	70	32	0.61	0.81	27.96	28.04	1.00
2	80	50	0.61	0.81	20.59	33.84	0.61
3	91	60	0.44	0.81	12.84	30.50	0.42
4	110	64	0.44	0.81	11.49	38.01	0.30
5	118	72	0.78	0.81	12.68	46.00	0.28
6	132	90	1.07	0.81	29.40	43.97	0.67
7	152	112	1.07	0.85	39.89	40.99	0.97
8	156	118	1.32	0.85	10.33	38.99	0.26
9	169	123	0.97	0.91	17.16	41.87	0.41
10	230	168	0.97	0.91	100.12	53.60	1.87
11	232	170	0.84	0.91	3.50	62.00	0.06
12	236	174	1.01	0.91	7.68	62.00	0.12
13	243	180	0.76	0.91	10.78	62.50	0.17
14	250	182	0.76	0.61	6.53	65.47	0.10
15	294	186	0.52	0.61	25.30	86.46	0.29
16	304	187	0.45	0.61	5.11	112.44	0.05
17	304	194	132.35	0.61	4.24	113.46	0.04
18	305	198	132.35	0.61	134.77	108.49	1.24

4.8 Validation of HYSYS and Manual Calculations

Table 12 compares HYSYS-simulated and manually calculated (MathCAD) product yields, and Table 13 the corresponding heat-exchanger duties. Yield deviations range from -3.12% (LVGO) to +1.17% (diesel), and duty deviations from -3.27% (condenser) to +5.32% (ADU preheater); all deviations lie within approximately $\pm 5.3\%$. This level of agreement supports the internal consistency of the HYSYS flowsheet and its manual cross-check, giving confidence in the stream data subsequently used for pinch analysis.

Table 12: Validation of Product Yields — Aspen HYSYS versus Manual (MathCAD) Calculation

Product	HYSYS (BPD)	yield	Manual yield (BPD)	Deviation (%)
Off-gas	1.691		1.723	-1.86
Naphtha	11.000		11.200	-1.79
Kerosene	6.000		6.150	-2.44
Diesel	13.000		12.850	+1.17
Atmospheric gas oil (AGO)	3.559		3.600	-1.14
Atmospheric residue	14.877		15.000	-0.82
Light vacuum gas oil (LVGO)	2.761		2.850	-3.12
Heavy vacuum gas oil (HVGO)	1.798		1.780	+1.01
Vacuum residue	10.300		10.500	-1.90

Table 13: Validation of Heat Exchanger Duties — Aspen HYSYS versus Manual (MathCAD) Calculation

Component	HYSYS duty (kJ/h)	Manual duty (kJ/h)	Deviation (%)
CDU preheater	+157,981.85	+150,000	+5.32
ADU condenser	-120,912.86	-125,000	-3.27
Top-stage PA cooler	-14,553.01	-14,000	+3.95
Middle-stage PA cooler	-15,166.55	-14,500	+4.59
Bottom-stage PA cooler	-8,942.28	-9,000	-0.64
VDU preheater	+53,196.00	+52,000	+2.30
VDU top-stage PA cooler	-16,784.74	-17,000	-1.27
VDU bottom-stage PA cooler	-19,472.53	-20,000	-2.64

5.0 DISCUSSION

The Problem Table results show the redesigned 50 BPD unit has a genuine, quantifiable minimum energy requirement: at the design $\Delta T_{\min}$ of 35°C, only 26.47 kJ/s of hot utility and 2.07 kJ/s of cold utility are thermodynamically necessary to satisfy all process heating and cooling simultaneously. Because these figures come directly from validated HYSYS stream data, they are a reasonably reliable lower bound against which any HEN eventually installed — including the existing, non-pinch-designed 1 BPD network — can be benchmarked once scaled and re-commissioned. The pinch-point behaviour across $\Delta T_{\min} = 10\text{--}40^\circ\text{C}$ is informative in its own right: at the tightest approach temperatures (10°C and 15°C) the process behaves as a threshold problem, in overall heat surplus with, in principle, only one utility required; as $\Delta T_{\min}$ widens, a genuine pinch emerges and both targets increase, since a larger $\Delta T_{\min}$ always trades reduced exchanger area for increased utility consumption. The working pinch at a shifted 212.5°C (actual hot/cold pinch 230°C/195°C) at $\Delta T_{\min} = 35^\circ\text{C}$ sits high in the column's temperature range, near the bottom pump-around and atmospheric-residue streams, indicating the highest-temperature hot streams and the furnace-outlet cold stream sit thermally close together, leaving little scope for further preheat recovery above this point without intensifying that match or accepting additional furnace duty.

Although the detailed exchanger network has not yet been synthesised, the area target of 8.86 m² gives an early indication that the heat-recovery surface required to approach the energy targets is modest, consistent with the small absolute duties at 50 BPD — useful for planning the forthcoming network-design and fabrication stage, since it suggests the redesigned network need not be large or capital-intensive, provided matches are selected per the pinch-design feasibility rules (Section 2).

Process intensification is reflected primarily at the process-selection stage, where DWC and heat-pump-assisted configurations were evaluated as more compact or less utility-intensive alternatives, and in the retention of a preflash stage and multiple pump-around loops in the developed flowsheet, reducing the duty (and hence size) that would otherwise fall on the fired heater and on separate external exchangers; the compact equipment sizing obtained (column diameters ~0.23 m, section heights under 4 m) is itself evidence of successful scale intensification relative to a conventional refinery train, even though a full DWC or heat-pump-assisted column was not carried into the final flowsheet.

The case-study comparison shows the optimised case recovers materially more kerosene and naphtha, and less low-value residue, from the same blended crude feed — significant for a 50 BPD unit supplying a local market, since it improves the revenue mix per barrel processed without altering crude feed rate, directly supporting the value-addition objective motivating modular refining in Nigeria. The study's validated deviations ($\sim\pm 5.3\%$) are consistent with the general expectation that independently cross-checked balances for well-characterised hydrocarbon systems agree closely and compare favourably with the agreement reported in the Kaduna FCC pinch study (Abubakar, 2020). Whereas earlier Nigerian modular-refinery studies have tended to report design parameters and yields without a full PTA exercise (Olatona, 2022), the present study extends that literature by carrying a validated HYSYS model through explicit pinch-analysis targeting across a range of $\Delta T_{\min}$ values — comparatively underrepresented for mini-refineries at this scale.

For Nigerian modular refinery development, the practical implication is that pinch-based energy targeting is achievable and worthwhile even at 50 BPD, not reserved for large conventional refineries: an operator able to specify a HEN designed against an explicit QH_{min}/QC_{min} target, rather than an ad hoc exchanger arrangement, stands to reduce fired-heater and cooling-utility demand, reducing dependence on imported fuel or diesel firing on site, strengthening the local-content case for indigenous engineering design, and supporting value addition to Nigerian crude closer to the point of production. Every kilojoule of hot-utility duty avoided is, in effect, a kilojoule of crude-derived fuel the mini-refinery need not burn to heat itself, with corresponding reductions in flue-gas emissions and in the fraction of processed crude consumed as fuel rather than converted to marketable product; at 50 BPD this reduction is small in absolute terms, but the methodology is directly transferable to the larger population of modular refineries (hundreds to low thousands of BPD) now being licensed across Nigeria, where the cumulative effect of routine pinch-based targeting could be considerably more significant.

Several limitations should be acknowledged. First, the energy and area targets rest on a steady-state HYSYS simulation and manual cross-check that have not been confirmed against physical plant data, since the energy-integrated unit has not yet been fabricated, installed or test-run. Second, pinch analysis and area targeting were carried out in full detail for a single ΔT_{min} (35°C), with the remaining values reported only at the target-summary level; a fuller utility-cost/exchanger-area economic trade-off across all seven ΔT_{min} values remains to be completed. Third, crude oils characterisation relies on a PIMS-based Escravos and Forcados assays rather than a laboratory assay of a specific delivered batch, so batch-to-batch variability is not captured. Finally, the heat-exchanger network itself, together with its fabrication and commissioning, remains pending, so the as-built performance of the redesigned ABU Mini-Refinery cannot yet be reported.

6.0 ENGINEERING INNOVATION AND CONTRIBUTION

The engineering innovation lies less in any single novel unit operation than in the systematic combination, on a physically realisable 50 BPD Nigerian modular refinery, of validated Aspen HYSYS simulation, a full Problem Table Algorithm exercise across a realistic range of ΔT_{min} , and balanced-composite-curve area targeting, carried out for an identified indigenous blended crude oils (Escravos and Forcados) rather than a generic feedstock. The process-integration innovation is the explicit establishment of quantified hot- and cold-utility targets (26.47 and 2.07 kJ/s at $\Delta T_{min} = 35^\circ\text{C}$) and a heat-exchanger area target (8.86 m²) at a scale where such targeting is comparatively rare in the accessible literature, providing a concrete benchmark for the forthcoming HEN design. The intensification dimension — evaluating DWC and heat-pump-assisted alternatives at process selection and retaining a preflash stage and pump-around-integrated preheat in the adopted flowsheet — keeps equipment count and size close to what a modular, skid-mountable refinery can accommodate. Applied to blend of Escravos and Forcados crude on a unit intended for local fabrication and operation, the work shows, with real numbers rather than generic claims, how a small, locally built refining unit can be designed against the same thermodynamic rigour used in large, conventional plants, so growth in local refining capacity need not come at the cost of avoidable energy waste.

7.0 CONCLUSION

This study sets out to design, simulate, and energy-integrate a 50 BPD ABU mini-refinery ADU processing blended Escravos and Forcados crude in the ratio 50:50, and to establish how process integration and intensification could be embedded in that design. A validated Aspen HYSYS flowsheet cross-checked against independent manual calculation to within approximately $\pm 5.3\%$, provided the material and energy balance basis. Pinch analysis via the Problem Table Algorithm across $\Delta T_{min} = 10\text{--}40^\circ\text{C}$ established minimum hot- and cold-utility targets of 26.47 and 2.07 kJ/s at the design condition ($\Delta T_{min} = 35^\circ\text{C}$), a pinch temperature of 212.5°C on the shifted scale, and a minimum heat-exchanger area target of 8.86 m² by the balanced composite curve method. A base-versus-optimised case-study comparison showed the redesigned unit can recover more kerosene and naphtha, and less low-value residue, from the same blended crude feed. These results confirm that systematic energy targeting, not previously applied to the ABU Mini-Refinery's existing 1 BPD network, is feasible and worthwhile at modular scale, and provides the quantified basis on which the unit's heat-exchanger

network can now be synthesised. Network design, fabrication, installation, and test-running remain ongoing, and their completion is the natural next step. The study demonstrates that energy efficiency and modular-scale refining are not competing objectives, and that process integration and intensification can, and should, be designed into modular refineries from the outset.

8.0 RECOMMENDATIONS

Arising directly from this study: the heat-exchanger network for the 50 BPD ABU mini-refinery ADU should be synthesised using the Pinch Design Method, matching hot and cold streams above and below the established pinch per the feasibility rules in Section 2; the resulting network should be checked against the 8.86 m² area target established here; and the ΔT_{min} values not yet analysed in full detail (10, 15, 20, 25, 30 and 40°C) should be carried through the same area-targeting procedure used for 35°C, so an economically optimum ΔT_{min} can be selected before final network design. For future research beyond the present scope: the synthesised network should be fabricated, installed and test-run, with measured performance compared against the targets reported here; a techno-economic evaluation covering capital cost, utility savings and payback should be conducted once network design is complete; an environmental assessment should quantify the emission reduction associated with the lower fired-heater duty implied by the pinch targets; intensification options such as a divided-wall column or heat-pump-assisted distillation, evaluated only at screening stage here, should be investigated in more design detail; and crude oils characterisation should be extended to laboratory assay data for specific delivered Escravos and Forcados crude batches.

9.0 CONFERENCE THEME ALIGNMENT

This study responds directly to the conference theme, "Innovating Tomorrow: Harnessing Engineering to Drive Nigerian Growth for Sustainable Development," by applying rigorous, internationally established process-integration and process-intensification methods to an indigenous Nigerian crude on a Nigerian university-based modular refining platform. In relation to SDG 7 (Affordable and Clean Energy), the pinch-based utility targets point toward a redesigned refinery drawing less fired-heater and cooling-utility duty per barrel than an unintegrated equivalent. In relation to SDG 9 (Industry, Innovation, and Infrastructure), the work builds indigenous simulation, pinch-analysis, and equipment-design capability around the ABU Mini-Refinery, deliberately scaled up as a demonstration and training platform. In relation to SDG 12 (Responsible Consumption and Production), improved recovery of higher-value light and middle distillates from the same blended Escravos and Forcados crude feed represents fuller use of the resource extracted. In relation to SDG 13 (Climate Action), a validated reduction in fired-heater duty would be expected to reduce associated combustion emissions per barrel processed, although this study establishes the energy targets that would enable such a reduction rather than measured emissions data, and the claim is framed as a plausible, targets-based implication rather than a demonstrated outcome.

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