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Review Article

Developing an Integrated Downstream Steel Value Chain in Saudi Arabia under Vision 2030: From Flat Steel Inputs to Tubes, Structural Components, and Cold-Formed Products

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Abstract: Saudi Arabia's industrial diversification requires more than expanding crude-steel capacity. The strategic issue is whether flat products can be converted reliably into certified tubes, structural assemblies and cold-formed components serving construction, energy, infrastructure and manufacturing. This critical review examines technical interdependencies, commercial constraints and institutional conditions across that downstream chain. Literature published between 2020 and 2025 is synthesised across material selection, forming processes, welded-tube manufacture, structural performance, production digitalisation and environmental performance. A product-oriented framework distinguishes upstream availability from downstream conversion capability, customer qualification and repeatable industrial value creation. The synthesis finds that dependable coil specifications, accurate slit-edge preparation, stable forming and welding parameters, traceable quality evidence and coordinated order planning are mutually reinforcing requirements. Localisation alone does not establish competitiveness when market fragmentation, grade mismatch or underutilised equipment undermine yield. The paper therefore proposes phased investment linked to qualified demand, shared testing infrastructure, digital genealogy and transparent resource accounting. It identifies the analytical gap between national steel-capacity narratives and factory-level evidence concerning conversion yields, product certification and delivery reliability. For Saudi Arabia, the proposed framework provides an assessable pathway from imported or domestic flat feedstock to higher-value finished products, while recognising that commercial validation and project-specific engineering are still required.

Keywords: Steel Value Chain, Flat Steel, Welded Tubes, Cold-Formed Sections, Manufacturing Localisation, Saudi Vision 2030, Industrial Competitiveness.

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1. INTRODUCTION

Steel is indispensable to the physical infrastructure of a diversified economy, but its industrial contribution depends on the products and capabilities created beyond the melt shop. Hot-rolled coil, cold-rolled sheet and coated strip are intermediate inputs; they become economically differentiated when converted into precision tubes, load-bearing hollow sections, structural members, equipment frames, cable-support systems and other engineered components. In Saudi Arabia, this downstream opportunity connects industrial localisation with supply-chain resilience,

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procurement quality and the development of technical occupations. Macroeconomic analysis identifies investment and complementary reforms as joint drivers of diversification, rather than treating investment volume as sufficient evidence of industrial transformation [1]. Comparable research on domestic capabilities in another Saudi manufacturing market likewise warns against equating formal localisation goals with proven supplier readiness [2].

Existing accounts frequently discuss steel production, building systems, joining technology and decarbonisation separately. Yet a producer's ability to supply a finished hollow section depends on a sequence that begins with coil metallurgy and dimensional consistency and ends with testing, certification and timely delivery. Plant-level evidence on the global steel sector demonstrates the importance of recognising process routes and asset characteristics when assessing industrial change [3]. Broader scholarship similarly argues that materials efficiency and recycling must accompany changes in primary steel production [4]. These observations motivate a value-chain perspective that connects metallurgical choices to commercially usable downstream output without assuming that every flat product suits every application.

The aim of this review is to develop a technically defensible framework for integrating flat-steel supply, conversion operations and product qualification in Saudi Arabia. Its objectives are to distinguish viable downstream product routes; identify quality and production dependencies between operations; evaluate the roles of digital coordination and material efficiency; and establish criteria for sequencing investment under demand uncertainty. The contribution is conceptual and evaluative, not a claim to have measured performance at Saudi factories. It addresses the question of how domestic industry might shift from selling intermediate tonnage towards delivering traceable, application-ready products at competitive total cost.

A downstream perspective also changes how industrial success is defined. Output tonnage and investment announcements are useful descriptors, but neither reveals whether a producer has accumulated difficult-to-replicate conversion expertise. More informative outcomes are the number of independently qualified product families, repeat-order retention, local engineering participation and the share of incoming steel converted into accepted components. These indicators distinguish a sustainable supplier relationship from a short-lived import-substitution project. They also illuminate interdependence with national projects: a construction programme may create temporary volume, whereas diversified industrial customers create more stable learning opportunities. The review accordingly treats domestic demand as a potential catalyst, not a guarantee of lasting manufacturing capability.

2. Review Design and Analytical Approach

A structured critical narrative review was adopted because the research question crosses materials engineering, structural design, operations management and industrial policy. The evidence window was limited to peer-reviewed work published from 2020 through 2025. Search concepts combined steel strip or coil with roll forming, high-frequency welding, hollow section, cold-formed structure, digital rolling, steel decarbonisation, circularity and industrial localisation. Relevant papers were identified through publisher records, scholarly indexing summaries and backward examination of technical themes. Inclusion required a verifiable publication identity, accessible DOI metadata and a substantive contribution to a defined link in the proposed chain. Studies unrelated to flat-product conversion or incapable of informing its enabling conditions were excluded from the analytical synthesis.

The literature was classified into five connected evidence domains: input and process capability; product mechanics; planning and digital interoperability; environmental accounting; and economic implementation. Each study was assessed for its methods, practical relevance, assumptions and transferability to Saudi conditions. Simulation and laboratory findings were interpreted as mechanistic evidence, not direct measurements of Saudi production. Structural tests were distinguished from design recommendations; policy studies were not treated as demonstrations of plant profitability. This approach allows comparisons without fabricating a pooled effect size or a study-selection count that cannot be audited. The review is therefore an interpretive synthesis with explicit limits rather than a quantitative meta-analysis.

The review evaluates evidence at the interface between disciplines rather than ranking a single process technology as universally superior. Technical papers typically optimise local variables, such as deformation or weld temperature, while market analyses aggregate sectors and investment flows. Neither scale independently explains whether an individual order moves profitably through procurement, conversion and dispatch. Findings were therefore translated into conditional propositions: a recommendation is applicable only when its material, equipment, specification and volume assumptions are satisfied. The framework

privileges evidence with measured process outcomes while using modelling studies to identify plausible sensitivities. This distinction guards against converting numerical demonstrations into unsupported claims about industrial readiness in the Kingdom.

3. From Flat Feedstock to Conversion-Ready Steel

Figure 1 frames integration around what mills and service centres can supply. Flat steel is not interchangeable inventory: chemistry, thickness tolerance, yield strength, surface condition, coating, width and mechanical-property uniformity determine downstream feasibility. A coil suitable for generic fabrication may not support tight-radius sections or demanding welded-tube specifications. Procurement should therefore translate product requirements backwards into a controlled input envelope covering steel grade, heat identity, edge condition and allowable variability. Cold-formed steel research demonstrates how properties and member geometry interact to produce useful lightweight structural systems, but also shows that performance is governed by constraints beyond nominal thickness [5, 6].

Coil preparation is the first operational interface. Levelling controls shape deviations that would otherwise impair feed accuracy; slitting creates widths needed for tube circumference or developed section geometry; edge preparation affects welding behaviour and visible product quality. Variations introduced here propagate into forming loads, closure gaps, dimensional deviations and scrap. A downstream platform should therefore track each slit mult from parent coil to finished order, including recorded width, position within the master coil, material certificate and surface findings. The economic advantage of purchasing a larger coil disappears if poor nesting, repeated changeovers or rejected edges erode usable yield. Product-family planning must optimise both material utilisation and equipment flexibility rather than pursuing maximum line speed alone.

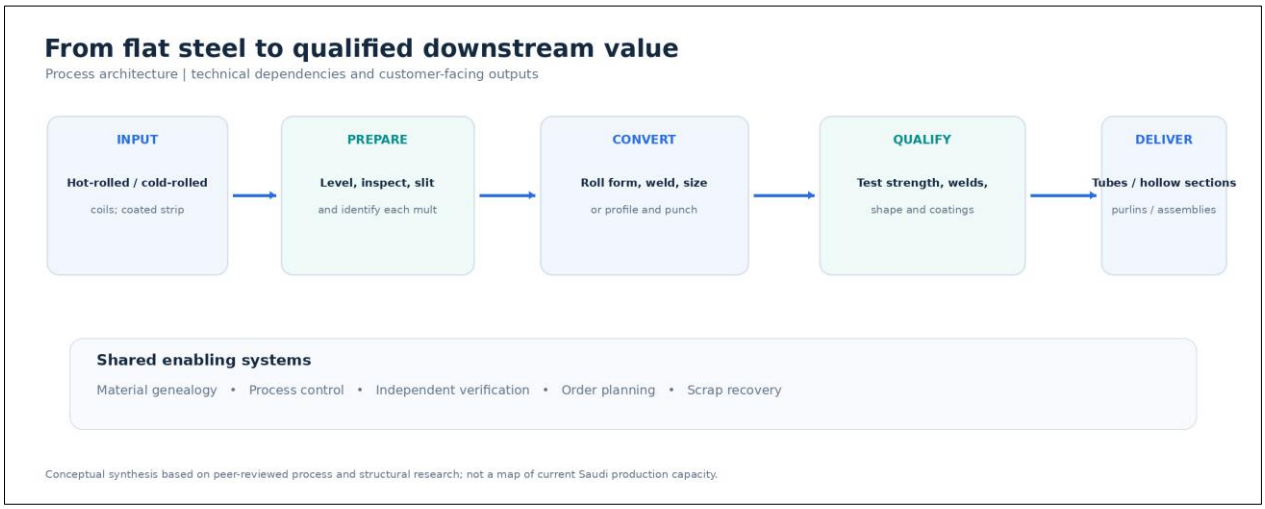


Figure 1: Integrated flat-steel conversion architecture and its shared enabling systems. Conceptual illustration developed for this review

Demand mapping must distinguish the starting product families before setting inventory policy. Hot-rolled uncoated coil often supports heavier structural applications; cold-reduced material supports tighter dimensional requirements; galvanised or otherwise coated strip offers corrosion protection but creates different joining and finishing challenges. Purchasers should avoid presuming that a nominal grade designation guarantees identical forming performance across suppliers. Yield-strength distribution, elongation, coating adherence and inclusion characteristics can materially alter forming routes. Therefore, receiving checks should be proportional to application criticality. A high-consequence structural order warrants more exact traceability and conformity controls than a non-load-bearing accessory, even when both originate from coils with similar dimensions.

4. Welded Tubes: Coupling Shape and Metallurgy

Electric-resistance or high-frequency induction welded tubes are a central bridge between flat strip and engineered products. Strip passes through successive stands until its edges approach in a controlled seam geometry, after which concentrated heating and pressure establish the weld. The process cannot be partitioned into independent forming and welding calculations. A coupled numerical study showed that band-edge geometry, residual stresses, electromagnetic heating and phase transformation influence finished tube characteristics together [7]. Subsequent experimental and modelling research analysed the

residual-stress consequences of roll forming, welding, straightening and final calibration [8]. Such evidence supports integrated process qualification instead of treating the weld as a final inspection problem.

Tube-making performance should be assessed through first-pass acceptance, dimensional capability, weld integrity, surface preservation, product straightness and delivery consistency. For each grade and thickness range, a documented process window should control strip entry condition, roll alignment, weld energy, squeeze force, seam position, cooling and sizing. Non-destructive examinations and destructive validation are complementary: examination detects relevant indications, whereas destructive tests confirm seam and parent-metal properties for a specified product standard. A certificate should link results to production lots and test methods, rather than providing generic reassurance. Where demanding uses require additional toughness or service-specific validation, qualification must precede customer commitments.

Commercial distinctions matter equally. Round tubing for general fabrication, structural rectangular hollow sections and precision service tubing differ in tolerance, testing, end preparation and buyer expectations. Attempting to serve all markets with one undifferentiated line risks costly changeovers and underqualified products. A better sequence establishes a limited, repeatable grade-and-size portfolio, validates its economics and only then moves towards specialised geometries. This protects manufacturing learning, inventory discipline and reputation. The downstream value chain becomes genuine when standard products can be reproduced with measurable conformity, not when a line merely demonstrates that a tube can be formed.

One frequent source of hidden cost is a mismatch between line capability and commercial tolerance commitments. Additional sizing passes may improve circularity or squareness but reduce speed, complicate setup and increase handling. Excessive weld trimming can compromise wall thickness, whereas inadequate trimming affects fit-up and surface acceptance. Production trials should record performance across the expected dimensional range rather than rely on a single nominal sample. For tubes intended for further bending or fabrication, downstream trials are also needed because the customer's forming operation can expose weaknesses not evident in initial dimensional inspection. Qualification is thus a chain of linked evidence, extending beyond the factory gate.

5. Cold-Formed Structural Products and System Performance

Cold forming provides a different conversion route: sheet and strip are shaped into channels, studs, purlins, rails, trays and other open or closed profiles without reheating the entire stock. The flexibility permits high strength-to-mass ratios and rapid fabrication, but slender elements exhibit local, distortional and global instability. Studies on optimised cold-formed members stress that manufacturing feasibility and serviceability must be treated as design constraints alongside ultimate strength [9]. Experimental and numerical research on cold-formed high-strength hollow sections extends this principle to combined axial and bending actions [10]. A commercially attractive geometry is therefore not automatically a code-compliant structural member.

System qualification extends beyond the section. Fastener arrangements, local bearing, hole placement, bracing and fire exposure affect assembled performance. A recent review of connection technology documents why fastener selection and design assumptions require special attention in slender sections [11]. Numerical work on compound members further demonstrates the relevance of connection details and established design methods to buckling resistance [12]. Analysis of hollow-section joints shows that nonlinear behaviour near welded intersections must be recognised rather than extrapolated from straight-member capacity [13]. These issues argue for standardised connection libraries, documented loading assumptions and type testing where warranted.

Further conversion options include punching, roll profiling, cutting, welding and surface finishing. Their optimal sequence depends on the product's structural and corrosion requirements. Pre-punched holes can increase throughput but may constrain roll deformation; welding after coating raises surface-restoration questions; aggressive cold bending can change residual stresses and local mechanical response. Research on perforated channels highlights how openings alter section resistance [14], while numerical investigation of high-strength roll forming illustrates fracture risks where ductility is limited [15]. Thus, a downstream strategy should combine an equipment catalogue with design-for-manufacture rules specifying bend radii, permissible piercings, coating repair and inspection points.

As Table 1 illustrates, the case for cold-formed components rests on engineered systems rather than isolated kilograms. A purlin delivered with verified dimensions, compatible fasteners,

marked parts and installation drawings may create greater customer value than an unprocessed strip. Nevertheless, overcomplicated profiles can increase roll-tooling costs, restrict raw-material substitution and make reliable procurement difficult. Structural size-optimisation work demonstrates the potential of geometry refinement [16], but factory adoption still requires validation against available tooling, tolerances and demand volumes. Digital product libraries should accordingly use a controlled family of manufacturable shapes, retaining bespoke profiles for sufficiently large or strategic programmes.

Table 1: Representative downstream product routes and their technical qualification priorities

Product family	Feedstock controls	Conversion sensitivities	Acceptance evidence
Welded round tubes	Grade, strip width, edges	Forming seam alignment; HFI weld stability	Dimensions, weld tests, heat traceability
Structural hollow sections	Specified strength and ductility	Sizing, residual stress and corner geometry	Structural grade, properties, section tolerances
Cold-formed open profiles	Coil thickness, coating, bendability	Punching sequence, bend radii, buckling	Geometry, coatings, member resistance
Fabricated structural assemblies	Qualified section and connection details	Cutting, fastening, welding, installation	Connection tests, documented design assumptions

Product certification is strongest when it connects the engineering model to the actual production route. A calculated load capacity assumes a defined steel grade, thickness, geometry, boundary condition and imperfection level; an installed structural assembly may depart from those assumptions through connection eccentricity or inadequate bracing. Manufacturers should provide designers with controlled drawings and declared properties rather than promote nominal catalogue capacity as a universal guarantee. The resulting technical files become assets: they reduce repeated design effort, support substitution decisions and allow revisions when a supplier changes feedstock. Shared design protocols could also reduce duplication among converters while preserving each manufacturer's duty to demonstrate conformity.

6. Shared Quality Infrastructure and Traceability

A fragmented downstream ecosystem can multiply testing costs while producing inconsistent evidence. Shared laboratory capability for chemistry, tensile properties, dimensions, coating quality and weld verification could lower entry barriers for smaller converters without weakening independent acceptance criteria. Quality plans should identify responsibility at every interface: supplier declaration, receiving inspection, slit-coil release, machine setup, in-process measurement, finished-product assessment and dispatch. Nonconforming material must remain traceable to its source and disposition. Certificates should record actual evidence for an identified lot, with alterations controlled and audit trails preserved.

Traceability is important when products move between firms. A coil may be slit by one company, welded by another and fabricated into a structural assembly by a third. Each transfer should retain the original heat identity alongside new processing and inspection records. Without this linkage, a customer cannot reliably investigate a dimensional failure, defective weld or coating problem. Digital records are useful only when they correspond to physical identifiers and validated measurements. The objective is not to collect every possible data point but to preserve enough trustworthy information to support conformity, investigation, warranty and repeat orders.

A robust quality system separates prevention from sorting. Incoming-material approval, calibrated tooling and documented setup reduce the creation of defects; in-process measurements identify drift; final inspection verifies acceptance but cannot restore lost yield. Useful measures include first-pass yield by product family, defects per length, calibration variance and customer returns referenced to original production batches. Aggregate defect percentages are misleading if low-risk accessories dilute serious structural nonconformances. A risk-based escalation process should isolate affected batches, examine preceding machine conditions and specify corrective actions with effectiveness checks. This approach turns product genealogy into a learning mechanism rather than a passive archive of certificates.

7. Production Coordination and Digital Integration

Downstream integration needs planning mechanisms that reconcile grade, width, production sequence, order mix and dispatch constraints. The scheduling problem differs from crude-steel planning because small orders may require frequent roll changes, cutting patterns and specialised acceptance inspections. Research on digital shape control in hot-strip rolling demonstrates how models can link process conditions to final strip quality [17]. A study of connected hot- and cold-rolling data argues that information silos impede cross-stage optimisation [18]. These findings suggest a practical digital

architecture in which enterprise orders, coil genealogy, manufacturing execution and laboratory results share stable product and lot identifiers.

The primary design question is which decisions benefit from better data. Production sequencing can reduce changeovers and optimise slit patterns; condition monitoring can identify drift in welded-tube quality; order visibility can reduce surplus finished stock. However, predictions must be compared against inspection results and machine interventions. Organisational research associates traceability and visibility with supply-chain resilience in manufacturing [19]. A broader analysis of digital capabilities and circular manufacturing similarly emphasises coordination and managerial capacity rather than technology adoption alone [20]. For a Saudi cluster, the implication is that interoperability agreements, shared definitions and operator skills can be as consequential as expensive predictive software.

A phased implementation should start with accurate master data and digital travellers before pursuing simulation-led control. Stage one links purchase orders and heat numbers to manufacturing lots; stage two records defects and process capability; stage three uses verified data for yield forecasting, maintenance and order sequencing. Machine-learning models should not be permitted to override qualified process limits without engineering review. Digital performance claims must specify baselines, time horizons and rejected material, avoiding improvements measured solely against an unrepresentative pilot. Integration is successful when production planners, quality engineers and sales teams resolve trade-offs using common evidence, rather than maintaining incompatible spreadsheets across departments.

Integrated production should not require every participant to adopt identical software. Instead, participants need agreement on minimal common data fields: product identifier, coil heat, revision-controlled specification, unit of measure, process route, inspection outcome and dispatch status. Structured exchanges can coexist with different enterprise platforms, reducing barriers for smaller firms. Data governance must identify who may amend records and when laboratory measurements become final. Cybersecurity and contingency procedures are also necessary because disrupted digital systems should not result in the release of unverified material. The purpose of common information is decision continuity across organisational boundaries, especially where a product is fabricated and inspected by several independent suppliers.

8. Environmental Performance and Resource Efficiency

A downstream value chain must be judged against resource use and greenhouse-gas consequences as well as economic output. Contemporary reviews show that credible steel decarbonisation requires verified emission inventories, attention to production routes and transparent boundaries [21]. Emerging chemical and electrochemical steelmaking options may change the upstream carbon intensity of flat products [22], while reviews of hydrogen-based production identify cost, energy and raw-material constraints that remain material to investment decisions [23, 24]. These upstream developments are relevant to downstream competitiveness, but their prospective benefits must not be automatically attributed to existing Saudi coils or finished products.

For converters, immediate environmental levers include higher material yield, less rework, efficient motors, controlled weld energy, recovery of usable offcuts and appropriate coating practices. The proper denominator is saleable, compliant product, not gross tonnes entering the factory. Research on direct reduction and alternative steelmaking illustrates why emissions assumptions must remain route-specific [25], and multilevel decarbonisation modelling warns against mixing factory-level improvements with national scenario results [26]. A low-emission label is inadequate unless upstream input data, conversion energy, transport and scrap treatment are documented consistently. Product declarations should therefore state their scope and uncertainty instead of presenting simplified comparisons.

Steel recycling offers a route to conserving material value but does not remove all material-quality constraints. Global flow analysis indicates that the proportion of recycled iron in steelmaking remains constrained by stock accumulation and differences between national systems [27]. A Saudi downstream cluster should segregate scrap by known grade and coating type, maintain return channels to appropriate processors and minimise mixed-material contamination. Such practices can improve recoverability without claiming that all offcuts can be reused directly as qualified strip. Wider decarbonisation strategies confirm the need to combine technology change with operational efficiency and materials management [28]. The most defensible approach is to measure scrap generation and recovery separately, ensuring that improved recycling does not conceal avoidable processing losses.

Environmental comparisons require attention to functional equivalence. A lighter cold-

formed profile may reduce steel mass but could require additional connections, coatings or fire protection. A locally manufactured tube may save transport emissions, yet a high rejection rate could offset that benefit. Conversely, longer-lasting galvanised components can reduce replacement frequency despite the impacts of their protective treatment. A meaningful assessment should compare products delivering the same structural or service function over an appropriate life, disclosing the assumptions used for maintenance, recovery and end-of-life treatment. This avoids rewarding a factory for reducing apparent emissions simply by moving an energy-intensive step to an upstream supplier. Evaluation must also distinguish announced projects from operational suppliers. Credible progress requires repeat orders, demonstrated product conformity and transparent capacity utilisation. These practical indicators ensure that industrial policy rewards conversion capability while allowing firms to adapt their product portfolios as demand evolves.

9. Economics of Localisation and Downstream Demand

The investment decision is governed by qualified demand, total delivered cost and capability accumulation. Imported finished components may appear expensive, but local production introduces tooling, certification, maintenance, working capital and capacity-utilisation obligations. Conversely, importing every specialised section can expose projects to long lead times and specification changes. A rigorous comparison should include procurement risk, transport, fabrication labour, testing, finishing, packaging, warranty and delay costs. Neither local-content percentages nor installed machine capacity demonstrate competitiveness in isolation. The relevant question is whether a domestic converter can repeatedly meet an agreed technical specification at an acceptable lifecycle price.

Product selection should reflect demand aggregation. Standard structural hollow sections, frequently ordered purlins and general fabrication tubing can provide learning volumes, while highly specialised products may require anchor customers or contractual commitments. A cluster model allows common coil supply and shared laboratory services while leaving product engineering and commercial accountability with individual manufacturers. Where demand is uncertain, flexible service centres may be more viable than tightly specialised mills. The optimum arrangement depends on minimum efficient batch size, import parity, logistics and the availability of qualified maintenance personnel; no universal localisation sequence can be inferred from international plant studies.

Evidence from cold-formed structural optimisation reinforces the need to incorporate manufacturability into product development [29]. Industrial policy must also distinguish the feasibility of supplying a product from the desirability of subsidising its production. Targeted standards support, supplier-development programmes and technical training can address coordination failures more directly than indiscriminate capacity additions. Vision 2030 provides a rationale for capturing greater value in manufacturing, but individual steel investments still require transparent feasibility studies, customer acceptance and periodic reassessment as domestic and regional demand evolves. The proposed value-chain framework is consequently an investment-screening instrument rather than a prediction that every product family will be profitable.

Table 2 sets out an evidence-based scorecard for assessing each product family without reliance on one weighted localisation target. Technical feasibility requires qualified feedstock and stable process settings; market feasibility requires recurring orders and clear acceptance standards; financial feasibility requires cash coverage under conservative utilisation; strategic contribution requires measurable skill transfer and supplier depth. The criteria should be assessed separately because averaging can conceal a decisive failure. A product that lacks customer approval should not advance merely because its forecast domestic demand is attractive. Equally, technically elegant profiles without sufficient volume may be retained as pilot capabilities rather than expanded into uneconomic production lines.

Table 2: Proposed decision gates for Saudi downstream investment and supplier qualification

Gate	Minimum evidence	Review emphasis
G1 · Market	Repeatable orders and buyer specifications	Customer qualification pathway and volume risk
G2 · Input	Conforming grades, widths and alternate supply	Receiving evidence and usable strip yield
G3 · Conversion	Stable process windows and documented acceptance	First-pass yield and critical defect rates
G4 · Customer	Approved tests, traceable certificates, delivery reliability	Independent acceptance and returns

Gate	Minimum evidence	Review emphasis
G5 · Scale	Utilisation, cash flow, competence and recovery systems	Audited performance across multiple batches

A product-route matrix can operationalise these choices. For each target component, the manufacturer would specify allowable feedstock grades and widths, transformation steps, required tests, typical lead times and responsible parties. The matrix should record whether each process is available domestically, requires subcontracting or depends on imported material. It should also distinguish full local manufacture from merely cutting or repackaging an imported finished product. Such transparency improves the credibility of localisation assessments and highlights capability gaps worth financing. Crucially, technical dependencies should guide sequencing: reliable tube welding cannot compensate for variable coil edges, while efficient roll forming is commercially wasted when qualified inspection is unavailable. Investment should address the narrowest binding constraint in the actual order-to-delivery chain.

10. Implementation Framework and Research Priorities

Figure 2 outlines a rollout that maps demand by finished-product specification rather than projecting one national steel deficit. The first decision gate verifies stable demand, accessible feedstock grades and identified buyers; the second tests whether selected conversion routes achieve target dimensions and mechanical properties. A third gate establishes repeatable quality capability, traceable certificates and operator competence. Only after these gates should larger capital expenditure be justified through throughput, changeover and cash-flow analysis. The final gate assesses resilience, including alternative coil sources, maintenance support and performance under order fluctuations.

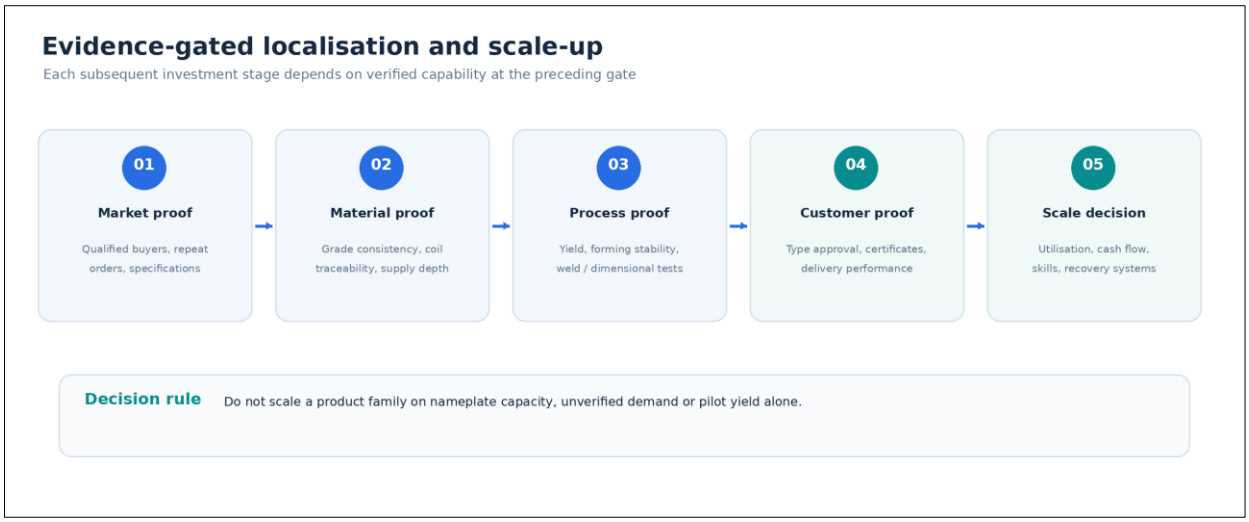


Figure 2: Evidence-gated sequence for qualifying downstream product families and scaling manufacturing capability. Conceptual proposal

The framework also creates a research agenda. Representative Saudi pilot data are needed on coil-to-product yield, weld rejection, tooling life, energy per accepted tonne, inventory dwell time and customer qualification cycles. Research should distinguish tubes from load-bearing hollow sections, coated products from bare steel and standard sections from bespoke systems. Comparisons across regions should control for electricity tariffs, transport distances, procurement rules and product mix. Validation requires repeated industrial production and independent conformity assessment rather than isolated laboratory specimens. If lower-carbon upstream routes expand, their actual material specifications and traceable emissions data should be incorporated into product decisions; technology reviews alone cannot establish local availability [30].

A durable implementation programme also needs workforce and governance provisions. Operators require training in roll alignment, welding-process control and dimensional measurement; quality engineers need competence in material certificates and nonconformity investigation; planners need to understand the cost consequences of small batches. Independent customer trials should occur before scale-up. Universities and technical institutes can help with metallurgy, finite-element validation and laboratory methods, but training outputs should be linked to measurable workplace competence. Public support can prioritise shared

facilities and standardisation, while firms remain accountable for market exposure. These arrangements would test whether collaboration genuinely reduces barriers to competitive manufacturing rather than merely distributing costs across participating organisations.

Institutional coordination should remain proportionate. Common purchasing specifications and shared test methods can benefit participating firms, but excessive uniformity may suppress valuable product differentiation. Procurement authorities can encourage fair technical qualification without prescribing particular equipment brands or business models. Customers should publish performance-based requirements sufficiently early for domestic suppliers to complete trials, rather than making retrospective local-content demands after design decisions are frozen. Pilot evaluation ought to include missed deliveries, quality escapes and cash tied up in inventory, not only factory demonstration outputs. By disclosing failures and corrective action as well as successes, industrial programmes would generate transferable knowledge about what downstream steel localisation actually requires.

11. CONCLUSION

Saudi Arabia's downstream steel opportunity lies in connecting flat feedstock to products whose geometry, structural performance, quality records and delivery can be trusted. This review finds that technical capabilities form a dependency chain: material selection constrains forming; forming affects weld integrity and dimensional accuracy; qualification determines customer acceptance; and production coordination determines whether acceptable products generate sustainable margins. Consequently, investment in one machine or one upstream capacity figure cannot establish a mature value chain. A phased, product-led approach would prioritise repeatable tubes and selected cold-formed components, develop shared testing and digital traceability, then expand into more demanding structural assemblies as demand and competence mature. Environmental improvements should be judged per accepted product using transparent data. The framework offers a basis for industrial prioritisation, but its commercial assumptions need verification through Saudi plant trials and customer contracts. Its central recommendation is to measure integration by qualified, saleable output and retained manufacturing capability rather than by nominal steel throughput alone.

REFERENCES

1. Moreau, F.; Aligishiev, Z. (2024). Diversification in sight? A macroeconomic assessment of Saudi Arabia's Vision 2030. International Economics, 180, 100538. https://doi.org/10.1016/j.inteco.2024.100538
2. Alghamdi, N.; James, P.; Bahaj, A. (2025). Vision and reality: An assessment of Saudi Arabia's in-country capacity to deliver on its solar ambitions. Sustainability, 17, 5721. https://doi.org/10.3390/su17135721
3. Lei, T.; Wang, D.; Yu, X.; et al. (2023). Global iron and steel plant CO2 emissions and carbon-neutrality pathways. Nature, 622, 514–520. https://doi.org/10.1038/s41586-023-06486-7
4. Algers, J.; Åhman, M.; Nilsson, L.J. (2025). Steel decarbonization—from optimization to transformation. Annual Review of Environment and Resources, 50, 433–454. https://doi.org/10.1146/annurev-environ-111523-101851
5. Liang, H.; Roy, K.; Fang, Z.; Lim, J.B.P. (2022). A critical review on optimization of cold-formed steel members for better structural and thermal performances. Buildings, 12, 34. https://doi.org/10.3390/buildings12010034
6. Roxas, C.L.C.; Bautista, C.R.; Dela Cruz, O.G.; et al. (2023). Systematic literature review of cold-formed steel at elevated temperature scenario. Heliyon, 9, e19142. https://doi.org/10.1016/j.heliyon.2023.e19142
7. Egger, C.; Lüchinger, M.; Schreiner, M.; Tillmann, W. (2022). Numerical simulation of tube manufacturing consisting of roll forming and high-frequency induction welding. Materials, 15, 1270. https://doi.org/10.3390/ma15031270
8. Egger, C.; Simon, N.; Lüchinger, M.; et al. (2024). Experimental and numerical analysis of residual stresses induced by the manufacturing process of longitudinal welded tubes. Journal of Strain Analysis for Engineering Design. https://doi.org/10.1177/03093247241234988
9. Mojtabaei, S.M.; Hajirasouliha, I.; Becque, J. (2021). Optimized design of cold-formed steel elements for serviceability and ultimate limit states. ce/papers, 4, 481–486. https://doi.org/10.1002/cepa.1319
10. Ma, J.L.; Pandey, M.; Chan, T.M.; Young, B. (2022). Structural performance of cold-formed high-strength steel circular hollow sections under combined compression and bending. Journal of Structural Engineering, 148, 04022148. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003438
11. Hussein, A.B.; Papp, F. (2023). State-of-the-art: Integrating fastener technology and design guidelines for enhanced performance of cold-formed steel sections. Buildings, 13, 2338. https://doi.org/10.3390/buildings13092338
12. Wu, J.R.; Di Sarno, L.; Hesketh, S.; Phan, N. (2022). Buckling resistance of axially loaded cold-formed steel compound sections: Numerical simulation and assessment of codified design approach.

International Journal of Steel Structures, 22, 1695–1709. https://doi.org/10.1007/s13296-022-00641-y
13. Živković, S.; Stojković, N.; Turnić, D.; et al. (2023). Analysis of hollow section "Y" connections with the application of non-linear material modeling. Metals, 13, 855. https://doi.org/10.3390/met13050855
14. Pham, N.H. (2023). Investigation of sectional capacities of cold-formed perforated steel channel sections. Steel Construction, 16, 105–113. https://doi.org/10.1002/stco.202200007
15. Mehari, Z.A.; Han, J. (2022). Numerical prediction of ductile fracture during the partial heating roll forming process of DP980. International Journal of Fracture, 234, 97–112. https://doi.org/10.1007/s10704-021-00572-5
16. Mojtabaei, S.M.; Becque, J.; Hajirasouliha, I. (2021). Structural size optimization of single and built-up cold-formed steel beam-column members. Journal of Structural Engineering, 147. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002987
17. Sun, Y.; Li, J.; Sun, Y.; Song, L.; Yang, Q.; Wang, X. (2024). Modeling and simulation of shape control based on digital twin technology in hot strip rolling. Sensors, 24, 614. https://doi.org/10.3390/s24020614
18. Li, J.; Wang, X.; Yang, Q.; et al. (2024). IoT-based framework for digital twins in steel production: A case study of key parameter prediction and optimization for CSR. Expert Systems with Applications, 250, 123909. https://doi.org/10.1016/j.eswa.2024.123909
19. Riaz, A.; Rehman, H.M.; Sohail, A.; Rehman, M. (2025). Industry 4.0 supply chain nexus: Sequential mediating effects of traceability, visibility and resilience on performance. Asia Pacific Journal of Marketing and Logistics, 37, 842–860. https://doi.org/10.1108/APJML-02-2024-0202
20. Neri, A.; Cagno, E.; Susur, E.; et al. (2025). The relationship between digital technologies and the circular economy: A systematic literature review and a research agenda. R&D Management, 55. https://doi.org/10.1111/radm.12715
21. Qian, Y.; Li, Y.; Hao, Y.; Yu, T.; Hu, H. (2024). Greenhouse gas control in steel manufacturing: Inventory, assurance, and strategic reduction review. Carbon Research, 3, 27. https://doi.org/10.1007/s44246-024-00118-z
22. Rippy, K.; Bell, R.T.; Leick, N. (2024). Chemical and electrochemical pathways to low-carbon iron and steel. npj Materials Sustainability, 2, 33. https://doi.org/10.1038/s44296-024-00036-6
23. Shahabuddin, M.; Brooks, G.; Rhamdhani, M.A. (2023). Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis. Journal of Cleaner Production, 395, 136391. https://doi.org/10.1016/j.jclepro.2023.136391
24. Shen, J.; Zhang, Q.; Tian, S.; Li, X.; Liu, J.; Tian, J. (2024). The role of hydrogen in iron and steel production: Development trends, decarbonization potentials, and economic impacts. International Journal of Hydrogen Energy, 92, 1409–1422. https://doi.org/10.1016/j.ijhydene.2024.10.368
25. Ling, J.; Yang, H.; Tian, G.; et al. (2024). Direct reduction of iron to facilitate net zero emissions in the steel industry: A review of research progress at different scales. Journal of Cleaner Production, 441, 140933. https://doi.org/10.1016/j.jclepro.2024.140933
26. Sun, J.; Na, H.; Yuan, Y.; et al. (2024). A systematic review of decarbonization pathway and modeling conception in iron and steel industry at micro-, meso-, and macro-levels. Environmental Science and Pollution Research, 31, 60749–60777. https://doi.org/10.1007/s11356-024-35136-2
27. Watari, T.; Fishman, T.; Wieland, H.; Wiedenhofer, D. (2025). Global stagnation and regional variations in steel recycling. Resources, Conservation and Recycling, 220, 108363. https://doi.org/10.1016/j.resconrec.2025.108363
28. Rodríguez Diez, J.; Tomé-Torquemada, S.; Vicente, A.; Reyes, J.; Orcajo, G.A. (2023). Decarbonization pathways, strategies, and use cases to achieve net-zero CO2 emissions in the steelmaking industry. Energies, 16, 7360. https://doi.org/10.3390/en16217360
29. Parastesh, H.; Mojtabaei, S.M.; Taji, H.; Hajirasouliha, I.; Bagheri Sabbagh, A. (2021). Constrained optimization of anti-symmetric cold-formed steel beam-column sections. Engineering Structures, 228, 111452. https://doi.org/10.1016/j.engstruct.2020.111452
30. Ji, Y.; et al. (2024). Development and application of hydrogen-based direct reduction iron process. Processes, 12, 1829. https://doi.org/10.3390/pr12091829.