Digital–Green Capability Co-evolution in India's Steel Industry: A Multi-Case Study

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Abstract
The steel industry of the world is facing digital as well as decarbonization pressures that are "analytically analyzed separately but operationally inseparable." The process of steel production is still among the most carbon-intensive industrial processes and the digital technologies like artificial intelligence, predictive maintenance, digital twins, and integrated operations centers are restructuring the process control of the capital-intensive manufacturing. This paper evaluates the question on whether digital maturity is merely a functional efficiency enhancer of whether or not it is an enabling infrastructure to environmental governance and low-carbon technological transition. The research examines the role of the digital technological affordances in the production of the operational stabilization and energy visibility along with how organizational governance converts the visibility to sustainability performance and how structural and institutional constraints moderate the rate at which digital-green capability is integrated with the goal of achieving sustainability through a qualitative multi-case study of four large Indian steel manufacturers and 45 semi-structured interviews triangulated with documentary evidence. The results show that there is a sequence of dynamics. The digital affordances reduce the production volatility and build granular energy transparency; the governance transforms the transparency to performance discipline; and structural constraints determine the time and scope of experiment. The stacking of capabilities comes up with the increase of digital maturity, which enhances the absorptive capacity of sustainability transition, thus able to model hydrogen-readiness and experiment on carbon.Digital and decarbonization trajectories do not evolve independently but form mutually reinforcing capability architecture shaping competitiveness in climate-constrained markets.

Keywords: Digital maturity, Decarbonization, Steel industry, Dynamic capabilities, Industry 4.0,Sustainability transition

1. Introduction

Digitalization and decarbonization are the two significant changes that the global steel industry is facing at the same time. Making of steel is still one of the processes that are the most carbon intensive (Z. Zhang et al., 2024), whereas digital technologies, like artificial intelligence, predictive maintenance, digital twins, and integrated operations centres are completely transforming the process control of the capital-intensive manufacturing (Cormos et al., 2020). These changes are frequently discussed independently but, practically, they cannot be separated operationally (Pang et al., 2023). Companies no longer have to make a choice between digital efficiency and environmental sustainability; instead, they strive to combine both in the circumstances of infrastructural lock-in, capital intensity and regulatory uncertainty.

The current literature, however, considers these changes as an analytically different one. The research in Industry 4.0 is mostly concerned with automation, productivity, and efficiency improvement (Singh et al., 2025), whereas the studies of transition to sustainability point out the direction of technological substitution as hydrogen-based steelmaking, electrification, and carbon capture (C. Zhang et al., 2022). In turn, institutional research looks at the implication of governance in the process of innovation adoption. Although these streams have valuable information, they lack sufficient explanation of the influence of digital capability development on the feasibility, sequencing, and depth of decarbonization in the capital-intensive industries. Specifically, the mechanism by which digital maturity is not only a functional resource but also an infrastructure of transforming the environment is theorized inadequately.

This is particularly rift in the emerging economies like India. India is the second-largest steel manufacturer in the world (Pang et al., 2023), which has a two-fold challenge in maintaining industrial development and fulfilling decarbonization promises (Gu et al., 2023). The constraints of the fast technological replacement are the legacy blast furnace infrastructure, their capital intensity, and uncertainty in the policy (Hou et al., 2024). Simultaneously, companies are placing more investments in the digital technology reflected in the predictive maintenance, digital twins, and energy analytics (Anaba et al., 2024). In this respect, digital maturity can serve not just as an efficiency-enhancing principle, but also as a precondition that allows managing the environment, and internalizing the low-carbon technologies.

In order to solve this problem, the proposed study uses a qualitative multi-case study research design that involves four large Indian steel manufacturers and 45 semi-structured interviews, which are triangulated with documentary data. The discussion centers on three processes, which are interrelated: (1) how the digital technological affordances facilitate operational stabilization and energy visibility, (2) how the organization governance mechanisms would transform the capabilities into the sustainability performance, (3) how the structural and institutional constraints would determine the rate and level of integration of digital and green capabilities. The results indicate that there is a staged process with digital affordances making production volatile less, and forming granular energy transparency; governance mechanisms transforming this visibility into performance discipline, and structural constraints conditioning the scope and time of strategic experiment. These processes over time allow the capability stacking, whereby the digital maturity increases the absorptive capacity that is needed to innovate low carbon, such as hydrogen-readiness modelling and carbon experimentation.

The present study has three major theoretical contributions. First, it redefines digital maturity as a dynamic capability that facilitates performance at the environmental level, but not just the performance at an operational level. Second, it builds upon sustainability transition theory by defining digital absorptive infrastructure as a condition to successful decarbonization of carbon-intensive industries. Third, it uses institutional and structural restrictions to the development of capabilities, which proves the role of the infrastructural heritage, ownership system, and policy uncertainty in determining the nature and order of transformation in emerging economies.

Comprehensively, the research contributes to the dynamic of the mechanism of co-evolution of digital and green capabilities by indicating that digitalization and decarbonization do not go hand in hand but are complementary processes in the context of competitiveness in climate-limited industrial settings.

2. Theoretical Background and Conceptual Framing

Digital Technological Affordances as Microfoundations of Dynamic Capability

The industry 4.0 technologies are traditionally viewed as efficiency-enhancing tools, which enhance automation and throughput (Jamwal et al., 2021). Nevertheless, this school of thought undermines their structural contribution in the capital-intensive industries like steel. Such technologies as digital twins, predictive maintenance, and energy dashboards do not only optimize the processes; they completely redefine the sense-making and control systems of the firm (Sajadieh and Noh, 2025).

Based on the dynamic capabilities theory, the digital technological affordances increase the sensing and seizing capabilities of the firm. They also allow monitoring the variability of the processes and energy use, which increases the ability of the firm to identify deviations in real-time (Dressler and Paunovic, 2021). Meanwhile, they advocate anticipatory intervention, enabling companies to move away with corrective actions and move to optimizing actions that are proactive (Vanderhasselt et al., 2014). These cycles of sensing-seizing with time change the operational routines so that the operational performance dependence on ad hoc problem-solving is minimized and leads to systematic performance regulation.

In line with this, the conceptualization of digital maturity can be a dynamic capability that reorganizes the manner in which firms perceive and react to operational and environmental cues (Al Jabri et al., 2024). Nonetheless, digital affordances do not produce sustainability per se effects. They generate intermediate capabilities, namely, the operational stabilization and energy visibility, instead, which become the core layer on top of which the sustainability-oriented transformations shall take place.

Operational Stabilization and Energy Visibility as Absorptive Infrastructure

Also, operational instability limits the experimental capacity of firms on long-term strategic levels (Xu et al., 2025). When organizations have been engaged in losing time, process variability, and short-term disruptions, the managers are so preoccupied that they cannot focus on long-term sustainability programs. Predictive maintenance and integrated monitoring systems are examples of digital technologies that make variability in operations less frequent and release cognitive and financial resources to develop strategic choices (Bello et al., 2024).

An unimportant product of digital stabilization is energy visibility. Granularity and real-time energy consumption order carbon intensity has become not a far off abstract measure of compliance but a variable of operations that can be dealt with (Sarkar et al., 2024). This change is fundamental to the theory of absorptive capacity because it allows firms to develop plausible foundations, test alternative technologies, and incorporate low-carbon innovations in current operations.

In this regard, the operational stabilization and energy visibility can be an absorptive infrastructure to facilitate sustainability transition. Such capabilities as hydrogen-readiness modelling, carbon monitoring integration, and efficiency benchmarking require the presence of reliable and accurate operational data. Thus the extent of decarbonization will depend on the previous establishment of P-digital-based stabilization and transparency.

Organizational Enablers as Mediating Mechanisms

Although digital infrastructure does add informational capacity, it does not necessarily result in strategic change. In line with the views of innovation and corporate entrepreneurship, the technological capabilities should be integrated into organizational frameworks in order to be reconfigured effectively (Bojesson and Fundin, 2020).

The digital signals are converted into the co-ordinated action through the use of organizational enablers: digital PMOs, IT-OT integration teams, performance management systems and structured upskilling programs (Dubey et al., 2024; Chen et al., 2025). Such governance mechanisms formalize the decision-making process based on the data and focus the operational metrics on strategic goals (Imran et al., 2021).

In this context, organizational enablers will be a mediating process between digital affordances and sustainability outcomes. Digital technologies create visibility and the governance structures dictate whether this kind of visibility can be translated into performance discipline and strategic alignment. In the absence of such embedding, digital systems are confined to the periphery and they are underutilized. This has led to the fact that any given technological investments could produce different results due to the intensity of governance integration.

Structural Constraints as Moderating Conditions

Development of capability takes place in a wider infrastructural and institutional framework. The specialization of assets, capital-intensity, and dependence on regulations are typical of the heavy industry (Appiah et al., 2022). Old blast furnace systems make technological retrofitting more expensive and risky (Dziecio Lewpacz, 2022), and uncertainty in the policies on pricing carbon and hydrogen markets has an impact on investment decisions (Boldrini et al., 2023).

The ownership structure also has an impact on the procedural flexibility and risk tolerance. The constraints as pertinent to the public sector firms are more restrictive in terms of rigidity of procurement and continuity in operations as compared to the private firms which might be more flexible in terms of strategic aspects and yet be sensitive to the ambiguity in the policies.

These drivers are moderating conditions, which determine the pace and intenseness of digital integration of green capabilities. With favorable institutional environments, companies will have higher chances of developing beyond the stabilization of operations to strategic experimentation. Conversely, constraining conditions can force the firms to make only modest gains in efficiency rather than decarbonize (Raineri, 2025).

Notably, the use of structural constraints in the framework eliminates technological determinism and puts the development of capability in context of socio-technical regimes, as highlighted in the sustainability transition theory. It is possible that firms of comparable technological capabilities therefore have divergent transformation paths since institutional and infrastructural environments vary.

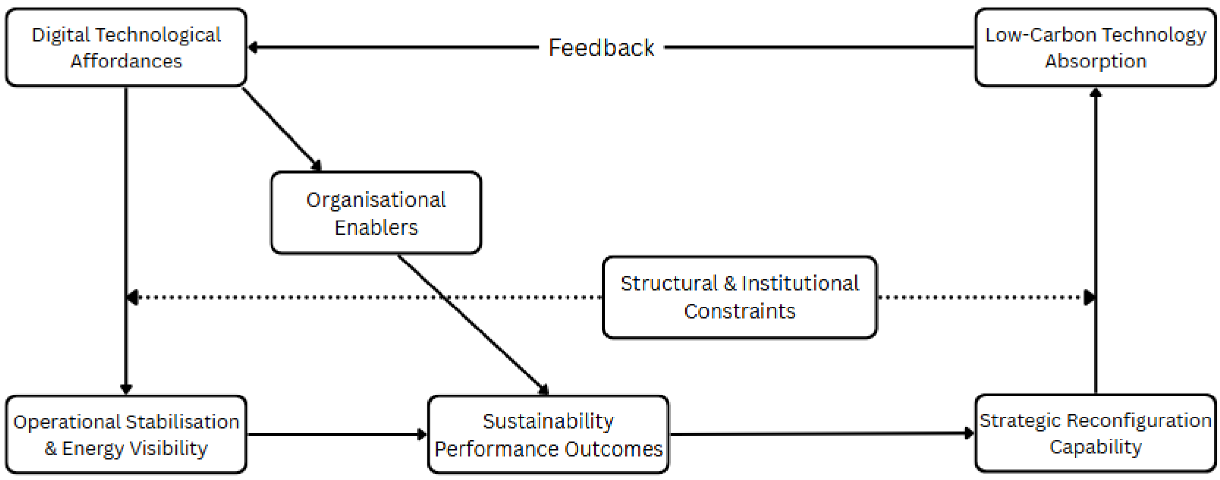

Figure 1: Digital Green Capability Co-Evolution Conceptual Model.

Figure 1 shows that there is a mediated and moderated pathway involving digital and sustainability transformation. The ability to stabilize operations and have visibility of energy in a digital technological form provides the base layer of capability development. For this process, organizational enablers play an intermediate role in transforming informational visibility into strategic action. The rate and the intensity of integration is mediated by structural and institutional constraints. Feedback loops over time represent capability stacking and augment the co-evolution of digital and sustainability capabilities. It describes how digital technological affordances provide intermediate functional capabilities, which are then put to sustainability effects via organizational governance, and facilitated by structural and institutional restriction.

In particular, the operational stabilization and energy visibility are made possible by such digital technological affordances as predictive maintenance, digital twins, and energy analytics. These medium-level abilities are the basis on which the transformations that are driven by sustainability are possible. Nonetheless, these capabilities are not automatically converted to strategic outcomes. This relationship is mediated by organizational enablers such as governance structures, performance management systems as well as cross-functional integration which converts informational visibility into coordinated strategic action.

Meanwhile, the capacity and dynamics of this channel is determined by structural and institutional limitations, including legacy infrastructure, capital intensity, policy uncertainty, and ownership structure. Such limitations moderately regulate the rate and intensity of the integration of the digital and sustainability capabilities. When institutional environments are favorable, then companies have a greater likelihood of moving towards high levels of sustainability experimentation, but when they are constraining, companies may be prevented in changing to more incremental gains in efficiency.

The framework also includes feedback loops that are used to denote the capability stacking process with time. The higher the level of digital and organizational capabilities that firms have built, the greater their ability to absorb low-carbon technologies and, therefore, reconfigure their strategies at higher orders and experiment with them. These recursive relations support the realization of the interrelation between digital and sustainability capabilities.

In relation to this framework, the hypotheses are as follows:

Hypothesis 1: Digital technological affordances have a positive effect on the operational stabilization and the energy visibility as the foundational layer to the formation of sustainability capabilities.

Hypothesis 2: This is because organizational enablers are a mediator of the linkage between digital technological affordances and the development of sustainability capabilities by generating operational visibility into strategic reconfiguration.

Hypothesis 3: Structural and institutional constraints mediate the association between digital and sustainability capabilities, which affect their rate and depth of integration with one another.

Collectively, these propositions would constitute a process of co-evolution of digital and green change in capital-intensive sectors. Digital maturity, therefore, does not appear as an efficiency-enhancement tool, it is rather a structural condition, which facilitates and determines the direction of sustainability transition.

3. Methodology

Research Design and Case Selection

The research was a qualitative multi-case study that took an abductive reasoning. In this manner, the empirical observation and theoretical explanation can be taken to alternate between each other until it is evident how digital maturity preconditions the decarbonization capacity. Abductive reasoning helps to formulate explanations by constant interaction between data and theory.

Multi-case approach has been adopted in order to allow cross-case comparisons across ownership structure, infrastructural legacies, and the degree of digital maturity. Such a design facilitates more generalization of the analytic findings, as it is concerned with patterned associations as opposed to single cases. Four important Indian steel manufacturers were sampled purposely so as to maximize theoretical variance. It contains a traditional public-sector combined producer, large-scale private producers, and a greenfield facility with built-in automation.

Certain criteria were taken into consideration when choosing it. The companies had to show the presence of Industry 4.0 and/or the investments in decarbonization. The different institutional conditions were captured by varying the age of plants and the nature of their ownership. Also, the presence of archival and sustainability-related data was taken into consideration so that triangulation could be done. Such a design allows investigating how digital green capability integration occurs in different institutional and infrastructural contexts.

Data Collection

The triangulation of three sources, that is, semi-structured interviews, documentary evidence, and performance measures, was used to collect data. The major source of information was semi-structured interviews. Four5 interviews were done with top executives, head of digital transformation, head of operations of plants, energy managers and project personnel. Technological establishment, embedded governance, performance impacts, financing logic, and perceived barriers were also discussed in the interviews. All the interviews were on tape, transcribed verbatim, and anonymised. Informed consent was used to conduct the interviews and sensitive information was given in aggregated form to maintain confidentiality.

The data provided through the interview were complemented and validated with the documentary evidence. Annual reports, sustainability reports, investor reports, technical project reports, policy reports of 2018-2024 were used as sources. These records were reviewed with a view of establishing timelines of initiatives, strategic framing, and measures of performance.

Secondly, contextualization of qualitative statements was also done by operational performance measures including reduced downtime, reduced mean time between failures, reduced energy intensity and reduced pilot outcomes. These indicators were used to facilitate triangulation and were utilized to illustrate and not to make a causal conclusion.

Data Analysis

The coding was inductively coded and structured abstraction was used in the analysis in keeping up with the logic of the Gioia methodology. It started with open coding of documents and transcripts to identify first-order concepts using informant terms. This made the analysis to be kept on the positions of the respondents.

After this, cases were compared to bring out second-order themes through the clustering of similar ideas. These themes were subsequently abstracted into four aggregate dimensions which are namely technological affordances, organizational enablers, structural constraints and capability stacking. The emerging patterns were repeatedly contrasted with dynamic capabilities theory, absorptive capacity theory, and socio-technical transition theory in an attempt to come up with theoretically informed propositions.

The analysis of the data was supported with the help of NVivo software, which provides a clear audit history. All the constructs were well defined and included criteria with representative quotations being recorded in the codebook.

Research Rigor and Validity

Various processes were used to give more credibility to the analytical procedures. Two raters were used in intercoder reliability where a calibration subset of transcripts was coded by the two raters. Disagreements were solved by discussing and Cohen kappa showed there was a high agreement (0.71). The calibration sample consisted of 28 percent of the data containing 362 coded blocks of 13 interviews. In order to have variation in the ownership type and levels of digital maturity, these interviews were chosen.

Triangulation was carried through cross-validation of the results of interviews, documentary evidence, and performance data. Where there was a partial convergence the results were given with due reservations. Member validation was also done with the presentation of early interpretations and the developed data structure to selected informants so as to help in checking the accuracy and clarifying the interpretations.

A trail of audit was done within the research process. To promote transparency, all the coding iterations, analytical memos and construct refinements were documented systematically.

4. Results

Corpus of Data and Structure of Analysis. The foundation of it is 45 semi-structured interviews (43 hours) and 162 documentary materials (annual reports, sustainability reports, technical project briefs, policy documents) in 4 steel manufacturers in the year between 2018 and 2024. The individuals interviewed included plant heads, leaders of digital transformation, engineers in the maintenance area, energy managers, project management officers and strategy executives. The coding produced 1286 segments which were grouped into 48 first order concepts, 14 second order themes and four aggregate dimensions. Individual firms which include JSW and Tata in Table 1 show to be more intensive in predictive control systems, energy analytics, and governance embedding as compared to the legacy units which include SAIL and show higher levels of skill resistance.

Table 1. Distribution of Second-Order Themes Across Cases

Second-Order Theme	JSW	Tata	SAIL	NMDC	Total References	Interpretive Pattern
Predictive Control Systems	48	39	21	12	120	Deep integration in advanced private firms
Energy Analytics	36	41	18	14	109	Energy visibility concentrated in JSW & Tata
Governance Embedding	44	38	25	16	123	Strong mediation in private firms
Skill Resistance	15	19	31	12	77	Resistance concentrated in legacy units

Policy Uncertainty	18	22	14	26	80	Institutional moderation prominent in private strategy discussions
Hydrogen Experimentation	29	24	9	17	79	Early-stage experimentation asymmetry

Theme intensity has more patterns of integration in JSW and Tata and has more resistance-related coding frequency in SAIL. This element of policy uncertainty is particularly applicable when it comes to strategic planning of the private sector.

Technological Affordances: Operational Stabilization and Quantified Performance Effects

In all the instances, the digital technologies meant the conversion of the time-logic of the functioning of the reactive correction into the predictive intervention. One of the heads of the blast furnace optimization of JSW Steel, the person who monitors the shift, described it in the following way: We used to respond to the alarms in the past. we come in, and preclude losses with the help of the digital twin to predict deviations. Equally a Chief Energy Manager in Tata Steel explained the importance of energy dashboards in revolutionizing the supervisory discipline: Energy dashboards changed behaviour. The supervisors can see per-heat consumption. The visibility was the only field of decisions. Quantified performance indicators are used to support these accounts. The reduction in the downtime of digitally advanced units was 5-8 percent, increase in the mean time between failure was 6-9 percent, and the intensity of energy at the unit level was lowered by 2-4 percent. One of the Maintenance Heads of the integrated plant of JSW stated: At one of the units, the Maintenance Head stated that the mean-time-between-failures increased by nearly nine percent after the introduction of AI. Digitalisation influenced project implementation in the public sector in legacy situations. As one of the Project Management officers in the headquarters of SAIL stated, DPMS did not focus on the physics of furnace, but it changed how capital projects were done through reduced number of overruns and having a higher sense of responsibility. Table 2 indicates that the improvements in the operations and more developed sustainability integration can be observed in the case of the private companies, including JSW and Tata, and SAIL is at its initial steps and NMDC is at the transitional level.

Table 2. Comparative Operational and Sustainability Indicators.

Case	Downtime Reduction	MTBF Improvement	Energy Intensity Reduction	Carbon Monitoring Integration	Hydrogen Readiness	Primary Data Source
JSW	High (5–8%)	High (6–9%)	Moderate–High (3–4%)	Full dashboard integration	Simulation stage	Interview + Document
Tata	Moderate–High (4–6%)	Moderate (4–6%)	Moderate (2–4%)	ESG-linked dashboards	Pilot modelling	Interview + Document
SAIL	Low–Moderate (1–3%)	Emerging (<4%)	Low (<2%)	Limited integration	Conceptual stage	Interview dominant
NMDC	Stabilization phase	Structural reconfiguration	Waste heat optimization	Early integration	Feasibility stage	Interview + Project brief

Digital systems stabilized processes and measured the energy in granular steps. The energy was taken out of an aggregated accounting variable into an operational control metric. The green transformation digitally was therefore founded on the stabilization of operations and visibility of energy.

Enablers in an Organization: Governance as Translation Mechanism

The introduction of technology alone did not create long term returns. Presence created visibility with strategic outcomes based on existence of organizational embedding. The integration of governance was pointed out by one of the Group Strategy Executive of Tata steel: Digital is not an IT initiative. It became serious when we linked it with KPI at the board level. Mandatory cross-functional ownership was illustrated by a Director of an Integrated Operations Centre (IOC) at JSW: We needed IT-OT integration. None had unanimous ownership in any of the systems. It was critical in alignment of the workforce. According to one Tata steel HR and Digital Capability Lead, operators were initially sceptical. They viewed their own furnace information when they were in training and that provided them with trust. Quite on the contrary, absence of governance structures lead to underutilisation. One of the plant engineers at one of the SAIL units reported, we planted sensors and no one responded to alerts. Technology is a spectacle that lacks an actor. In the cross-case analysis, it is found that the intensity of governance is closer to integration of sustainability than capital expenditure. Informational capacity has been developed by utilising digital tools; coordinated strategic action has been developed by establishing structures of governance.

Structural Constraints: Intermediating depth of Integration

The level of change was varied with regards to infrastructural and institutional requirements. There were noticed dilemmas of retrofitting in a Plant Head at a SAIL legacy plant: Retrofitting means shutdown. Shutdown means lost output. That is always contested." The companies of the privatized sector were undergoing strategic hesitation of regulatory uncertainty. One of the Vice Presidents-Strategy of JSW Steel says that the pilots of hydrogen must know about the issue of pricing and grid support. Increment is dangerous when there are no indications of policy. There was also the asymmetry of skills which slowed down things. Among the Leaders of NMDC Digital Transformation, an observation has been made: Senior operators are working and familiar with the furnace more than model-wise. The process of overcoming that confidence gap is cumbersome. Table 3 below indicates that structural constraints differ between public and private firms, whereby legacy infrastructure and procurement inflexibility hinder transformation in the public sector and capital sensitivity and policy uncertainty have greater influence on experimentation in the private sector.

Table 3. Structural Constraints and Moderation Effects of Capability Stacking.

Constraint	Public Sector Emphasis	Private Sector Emphasis	Moderation Effect on Stacking
Legacy Infrastructure	High	Moderate	Delays transition from stabilization to experimentation
Capital Sensitivity	Moderate	High	Slows hydrogen scaling decisions
Policy Uncertainty	Moderate	High	Limits Stage 4 experimentation depth
Skill Asymmetry	High	Moderate	Weakens governance mediation
Procurement Rigidity	High	Low	Extends digital deployment timelines

Structural conditions influence the rate of progression but not dismissal of transformation.

Contradictory Evidence: Technology Without Absorption

Investments in the digital world are not sustainable. One of the already existing SAIL units applied an AI predictive maintenance model in the correct way but overused. One Shift Operations Manager said: The model had not been wrong, but experience of operation had been utilized. Alerts were often ignored." Similarly, a non-governmental producer could not develop hydrogen-ready regardless of technical feasibility. According to one of the Corporate Sustainability Directors, they are technically ready to simulate hydrogen blending, but without pricing signals and regulation, the board is not proceeding. Table 4 reveals that digital initiatives do not necessarily have sustainability outcomes, with the distrust of operators and policy ambiguity proving to be the causes of underutilization and slow scaling.

Table 4. Delayed or Underutilized Initiatives

Initiative	Primary Barrier	Observed Outcome	Theoretical Implication
AI Predictive Maintenance (Legacy Unit)	Operator distrust	Underutilized for 12 months	Weak governance mediation
Hydrogen Simulation Pilot	Policy ambiguity	Scaling postponed	Institutional moderation boundary

These instances demonstrate that there is need, though poor, digital maturity. Moderation of developing operational visibility into sustainability capability is done by the adoption of behavior and institutional stability.

Capability Stacking: Sequenced Integration

The development of advanced companies was graded. One of the JSW Chief Digital Officer described it in this way: First we had reduced the downtime through predictive maintenance. Thereafter the energy optimization was improved. Now, it is possible to model hydrogen. The dependency was supported by another Carbon Management Lead of Tata Steel: "Reduction of carbon intensity with no relevant data base is a mere guess. The Capability Stacking Progression Index is indicated as in Table 5 below. The 03 progression scores represent semantic cross-case synthesis of the themes intensity bar coding, and documented depth of governance integration as opposed to quantitative harmonic cutting. As Table 5 demonstrates, JSW and

Tata have more extensive capability stacking than SAIL and NMDC, which mean that they integrate more digital, governance, and sustainability aspects.

Table 5. Capability Stacking Progression Index

Case	Digital Depth (0–3)	Governance Depth (0–3)	Sustainability Integration (0–3)	Overall Stack Depth	Representative Evidence
JSW	3	3	3	9	IOC integration + ESG dashboard + hydrogen simulation
Tata	2	3	2	7	Executive ESG linkage + pilot modelling
SAIL	2	2	1	5	DPMS integration + conceptual hydrogen discussion
NMDC	3	1	1	5	Greenfield automation + early feasibility studies

Scoring System: 0 = Ubiquitous, 1 = Ubiquitous, but unit-level implementation, 2 = Ubiquitous, but embedded in the organization. The scores are not statistical, but interpretive and analytically derived synthesis according to the level of synthesis of themes that were coded and recorded regarding governance. Digital maturity was an absorbent infrastructure. They became visible, by means of stabilization; governance brought in policies; and experimentation followed.

Cross-Case Synthesis

The analysis results in two groups of structural imbalances. First, the advantages of efficiency do not always go in tandem with the advancement in the direction of sustainability. Second, weak commitment to governance leads to compliance-based sustainability and not optimisation-based decarbonization. These trends demonstrate that the depth of capability stacking is more useful in explaining the outcome of transformation as opposed to the size of capital investment.

There is also an indication of a gradual process of integration: The integration is facilitated by digital affordances, which allow operational stabilization and energy visibility, which are succeeded by governance embedding, resulting in the capacity to reconfigure strategically, and finally, the ability to experiment with low carbon. This development is influenced by the structural limitations, and its level is derived by the level of behavioral embracement in organizations. These factors, with time, consolidate the other via recursive interactions.

In this, digital mechanisms restructure informational structure of the company, which establishes the environments of decarbonization possibility. Instead of being a manifestation of a specific technological displacement, decarbonization turns out to be an opportunity-conditioned change that is made possible by digital maturity.

5. Discussion

Even though the frequency patterns are a clear tool of analysis, the focus of the study is not on the establishment of a statistical causality, but the depth of transformation is informed by patterned relationships amongst cases. The results suggest that the concepts of digitalization and decarbonization of the heavy industry do not occur simultaneously but form structurally dependent capability building. The implementation of Industry 4.0 as an efficiency agenda and decarbonization as technological substitution ignores the mechanism that exists behind the two.

This is supported by a stratified process whereby operational stabilization and energy visibility are created by digital technological affordance, governance by embedding translates this visibility to strategic discipline and structural constraint influences the evolution of integration. With time, the stacking of iterative capability makes it possible to reconfigure strategies. To this end, decarbonization comes out as an ability-contingent change, rather than a specific technological one.

Digital Maturity as Dynamic Capability

Using throughput improvement and reduced downtime are often used to determine success in Industry 4.0 scholarship. Such framing is, however, imperfect. Online systems restructure the informational structure of companies that work in the conditions of constant processes. Predictive maintenance, digital twins, and real-time dashboards are technologies that increase the capacity of sensing because they enable visualizing variability in the process and improving response time.

This change allows moving toward reactive correction to anticipatory intervention. Sustainability indicators can be introduced in the production governance, which makes the reconfiguration possible. The concept of digital maturity is therefore a dynamic capability since it reorganizes the way companies sense, make sense, and act to operational and environmental cues.

When the energy consumption is reduced to granular and real-time measurements, the environmental performance can be manageable. The carbon intensity is no longer an intangible compliance variable but a working variable which can be manipulated. The strategic value of digitalization, thus, is not only in the improvement of efficiency but also flexibility. This repositions Industry 4.0 as a functional betterment agenda to a structural facilitator of environmental change.

Capability-Contingent Transition as Decarbonization

Hydrogen-based production, electrification and carbon capture are technological avenues that are frequently highlighted in sustainability transition research at regime level. The strategies imply organizational preparedness. The results of this paper demonstrate that this preparedness depends on the background of digital stabilization.

The high variability in operation inhibits experimentation because companies oriented towards downtime do not have the managerial capacity in which to operate the sustainability programs. Digital stabilization eliminates variability, and energy visibility allows establishing consistent baselines. This enables the complex programs like hydrogen-readiness modelling to become possible.

This task of decarbonization of heavy industry is then not purely a technological one, but a sequencing issue. It relies on the existing infrastructure development of digital maturity that is absorptive. Without this ability, sustainability efforts are still pilot-based or symbolic instead of being transformative.

Governance as a Process of Translation

The transformation does not occur because of the only implementation of digital technologies. The results indicate that different technologies are yielded by similar technologies in different cases that are influenced by the intensity of governance embedding. In systems of governance that feature digital metrics in the executive decision-making and cross-functional accountability systems, there is greater integration in sustainability. In cases where there is low embedding, the digital systems are peripheral.

Governance is a process that acts as a translating process to ensure that knowledge of visibility is translated into strategic action. The digital PMOs, IT-OT integration and ESG-related dashboards convert the data into action-oriented information. Adoption of behavioral behavior is also vital, since predictive alerts and digital systems can only be used in a scenario where they are embraced in organizations.

This mediation reasoning disputes techno-deterministic views on digital transformation, insisting that digital ability is not consequential at all until it is integrated into organizational forms of authority.

Institutional Conditioning and Structural Moderation

The infrastructural and institutional constraints influence the development of capability. There are variables like retrofit risk, capital sensitivity and policy uncertainty that determine how fast and in what order the transformation will occur. The infrastructural rigidity limits public sector firms but the uncertainty of investment is experienced by the private firms in case of the emergence of a new technology like hydrogen.

These conditions of structure are not the ones that inhibit transformation but determine its depth and time. The consideration of moderation influences in the model disputes the linear transition narratives. The digital maturity does not presuppose decarbonization; on the contrary, it depends on the institutional consistency and flexibility of the infrastructure.

Capability Stacking and Co-Evolution

The digital and green transformations complement each other, as time goes on. Operational stabilization allows optimization of energy, energy transparency allows practitioners to monitor carbon, governance embedding allows practitioners to experiment, and experimentation enhances the requirements of digital precision. Such feed-back mechanisms help in the process of adapting capacity.

Capability stacking builds on the theory of absorptive capacity by defining how internal digital infrastructure can be used to facilitate the identification and assimilation of sustainability innovations. It also narrows down on dynamic capability theory in locating stratified capability building pathway in capital intensive context that is characterized by infrastructural inertia. The two are therefore closely interconnected, namely, digital maturity as an absorptive infrastructure and decarbonization as an experiment-driven capability.

Theoretical Consolidation

The results systematize digital green transformation as three processes which are related to one another. To begin with, technological affordances generate operational stabilization and have an energy visibility. Second, organizational governance facilitates the process of transforming these capabilities into strategic reconfiguration. Third, there is a moderating effect of structural constraints on the intensity and course of integration.

The results of transformation depend on the intensity of the capability stacking, as opposed to the magnitude of capital investment. Digital-green integration is a recursively reinforced institutionally conditioned process that is determined by the intensity of governance. Decarbonization in the heavy industry should not thus be viewed as a specific technological replacement, but as a mediated, moderated, and sequenced ability formation as a part of socio-technical regimes.

Theoretical Implications

This paper reinvents the concept of digital maturity as a structure requirement in capital regime transition to sustainability. Digital technologies have been widely conceived by Industry 4.0 studies as instruments of efficiency enhancement, but the results show that they are an absorptive infrastructural potential that predisposes the potential of low-carbon transformation. Digital affordances reorganize the informational architecture of companies, making energy use measurable and manageable, thus, making it possible to incorporate environmental performance into the operations.

The findings go beyond the sustainability transition theory by demonstrating that technological substitution processes depend on the previous capability layering. Carbon tracking, the experiment of decarbonization and hydrogen modeling is only possible once they have the capacity to stabilize and provide energy transparency. Decarbonization is capability-dependent as opposed to technology-independent.

Another aspect that is also incorporated in the study is that of institutional moderation to dynamic capability theory. Governmental frameworks convert digital visibility into reconfiguration of the strategy, and infrastructural legacy and policy ambiguity limit the richness of the integration. The results of transformation are, therefore, more explicable as a consequence of the stacking of capabilities within the institutional boundaries, as opposed to the fact of merely installing technology. This polymorphic approach offers a mechanistic incorporation of Industry 4.0, sustainability transition and institutional theory.

Managerial Implications

The results show that digital and sustainability strategies cannot be considered two autonomous investment streams. Environmental governance is an enabling infrastructure, which is digital. Operational stabilization is the precursor to strategic experimentation in decarbonization, and predictive maintenance, energy visibility is the precursor needed to give credible sustainability initiatives a solid foundation.

Without this base, it is also probable that low-carbon projects will not go beyond symbolic or modest. Digital investment is a strategic asset with regard to its incorporation into governance systems. The alignment at the board level, IT and OT integration, and institutionalization of performance measures are important in the translation of the informational capacity into a coordinated action. Without integration, digital tools will probably remain unexploited.

Capability development is then crucial to be sequenced. Even though the stalled projects and organizational opposition can result, firms should take into account the digital granularity before making advanced decarbonization initiatives. The process of adaptive capacity occurs in stages of stabilization, optimization, monitoring and experimentation.

Policy Implications

The results propose that the building of digital capabilities would be integrated as a fundamental element of the policy of decarbonization of industries. Absorptive capacity at the firm level is needed to make large-scale efforts to create hydrogen infrastructure, price carbon, and integrate renewables.

Clarity in regulations is also very critical in determining the rate of change. Although hydrogen technologies have a lot of potential, the ambiguity in policy in terms of pricing and regulatory frameworks may slow experimentation and investment decisions. Uninterrupted and predictable signals in terms of policies can decrease uncertainty and increase development of capabilities.

Secondly, parallel institutional ecosystems should be developed. The adoption of digital systems has skill gaps that reduce the level of decarbonization. Organized digital-industrial education and training initiatives can have an impact on sector-wide absorptive capacity and eliminate inequality between first-mover and late-comer companies.

It may be expected that the process of capability-layering which is evidenced in the steel industry will be generalized to other carbon-consuming sectors which are typified by infrastructural lock-in and capital intensity. Digital transformation restructures the process of the measurement, control, and integration of environmental performance into production systems. Companies that build digital absorptive infrastructure are in a position to adjust to climate-bounded surroundings. Digital maturity must be perceived, consequently, not as an efficiency-driven investment, but as a structural state that facilitates a practical implementation of sustainability transition.

7. Conclusion

The digitalization and decarbonization of the heavy industry are not on parallel paths, but they create a self-enhancing ability structure. The case of the Indian steel industry indicates that the digital maturity restructures informational structure of the firm, which makes the operations stable and seen, which prepare the feasibility of low-carbon experimentation. Digital technologies like predictive maintenance, digital twins, and energy analytics do not only help to optimize throughput, but develop absorptive infrastructures needed by carbon monitoring, hydrogen modelling, and sustainability governance. Decarbonization as such, then, turns out to be a contingent capacity adjustment, as opposed to a technology substitution process. Operational visibility is translated into strategic reconfiguration and hinges on governance embedding, whereas the tenor and the velocity of evolution are influenced by the infrastructural legacy and uncertainty about the policy. Deepening firm differences of the capability stacking is more effective in explaining differences between firms; stabilization, visibility, governance integration, and experimentation rather than capital intensity alone. Digital maturity is therefore not to be seen as a complementary efficiency investment, instead it is a structural precondition to environmental transformation. Correlation between sustainability ambition and digital capability depth comes out as a decisive factor of competitiveness in carbon intensive industries that continue to operate within climate limits. In general, the digital and green capabilities that are developing are a mediated, moderated, and reinforced process of industrial transition by which sustainability becomes an operation practice and not an ideation.

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