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Leveraging Structural Complexity to Enable a Lean Supply Base

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Abstract. The Zero Carbon Humber (ZCH) project, formed to create the UK's largest decarbonised industrial cluster, requires a robust and lean supply base, which must meet the complex requirements for building a blue hydrogen production plant, including Carbon Capture & Storage (CCS). This study addresses the theoretical challenges of optimising supplier selection within a complex, dependency-prone network. The research examines the structural complexity of the supply base network, to assess dependency risks and inform decision makers of the ideal configuration of suppliers. Findings reveal areas of high dependency on certain suppliers for critical components, highlighting the need to expand the supply base. Furthermore, the study suggests that a carefully managed supplier network can balance lean efficiency with robustness, supporting the scalability required for the ZCH project's long-term sustainability. The insights offer practical implications for policymakers and supply chain managers aiming to mitigate risks within complex industrial ecosystems.

Keywords: Supplier Selection, Carbon Capture, Lean Supply Base.

1 Introduction

The UK government is targeting carbon-intensive regions for transformation to significantly lower their emissions by 2050. The Humber region is the most carbon-intensive area in the country and is responsible for approximately 40% of the UK's industrial emissions. Local communities have historically depended on energy-intensive industries, such as refining, steelmaking, and chemicals, for jobs and skill development. To reduce emissions without causing adverse economic or social impacts, a partnership has been established to transform the Humber region into the world's first carbon-neutral industrial cluster by 2040.

To achieve this ambitious goal, an initiative known as Zero Carbon Humber (ZCH) has been launched, comprising a collection of low-carbon and decarbonisation projects. The anchor project of ZCH is the establishment of the world's largest hydrogen production plant, equipped with carbon capture technology. This plant will convert natural gas into hydrogen while capturing at least 95% of the resulting carbon dioxide (CO_2). The captured emissions will be transported via pipeline to an aquifer beneath the North Sea for permanent storage. As part of this initiative, industrial plants in the Humber region will transition to using hydrogen, facilitated by a new pipeline network, while power generation will shift to a blend that includes 30% hydrogen. These efforts are expected to reduce the region's emissions by 900,000 tonnes CO_2 per year.

To realise this aim, it is essential to establish a robust supply base capable of delivering the necessary components, materials, and infrastructure with the right quality, quantity, and timing of delivery. The primary objective is to create a well-balanced supply base that minimises dependency on any single supplier, by ensuring multiple options for critical components and materials, while avoiding an oversized and inefficient supplier base.

In this paper, we use the term supply base to refer specifically to the suppliers able to provide the components required in the construction of the hydrogen production, carbon capture and storage (CCS), and distribution network facilities.

Several researchers have tackled the challenge of supply base optimisation, emphasising key themes such as supplier rationalisation, supplier diversification, upstream supply chain complexity, and relationship management. However, these approaches typically require substantial data, often obtained through direct contact with suppliers. For the ZCH project traditional frameworks proved impractical. The available information is very limited as the supply base has not been consolidated and there are no existing agreements with the potential suppliers. The scale and intricacy of the task necessitated a more pragmatic approach—one that leverages publicly available data to identify critical components, assess potential suppliers, dependencies, and address the operational inefficiencies that may arise from supplier proliferation. This approach aims at identifying the optimal number of suppliers and how the demand could be spread among them to minimise dependency, maintain visibility and control, and create an effective supply base.

A promising solution to this challenge was found in the work of Ruiz-Hernández et al. [1], who introduced the *pars*-Complexity metric which quantifies structural complexity within supply networks This metric can also be interpreted as a measure for diversification that is particularly useful for our objectives. In summary, our goal is to deploy the *pars*-Complexity metric to shape a lean and robust supply base for the ZCH project.

This study provides a comprehensive analysis of the structural complexity of the supply base needed to build the ZCH industrial cluster. The insights gained in terms of dependency, robustness, and optimal number of suppliers will contribute to more informed decision-making regarding supplier management, risk mitigation, and supply optimisation.

Section 2 presents a literature review. The *pars*-Complexity theoretical framework is presented in Section 3. Section 4 outlines our analytical approach and presents our results. Section 5 summarises our findings, discusses limitations, and identifies areas for future research.

2 Literature Review

The debate between lean supply chains and supplier proliferation has been longstanding. Agrawal and Nahmias [2] highlight the risks of single sourcing, as evidenced by the 2023 semiconductor shortage. Over-reliance on key suppliers, such as Taiwan's TSMC for computer chips, makes industries vulnerable to disruptions like natural disasters. Additionally, single suppliers may struggle with fluctuating demand, creating bottlenecks, as seen in the 2021 rubber shortage [3]. Expanding the supplier base can mitigate such risks, improving negotiation power, quality, and innovation, but also increases complexity and management challenges [4][5].

Managing supplier proliferation is crucial, as excessive expansion can reduce profitability and complicate logistics, quality control, and coordination [6]. The balancing of flexibility and control is key to minimising risks associated with both over-reliance and fragmentation [7]. While lean supply chains improve efficiency and cost control [8][9], excessive reductions in inventory and lead times can cause instability [10].

Supply chain complexity has been studied through multiple theoretical lenses, including systems theory, complex adaptive systems, entropy theory, and network science [11]. Complexity is influenced by supplier numbers, interconnectivity, and unpredictability [12][13]. The structural complexity of supply bases has been quantified using network science [14] and entropy-based models [15].

A key metric for assessing complexity is *pars*-Complexity (C_p), derived from entropy theory [1]. C_p quantifies structural complexity within supply networks by evaluating supplier diversity and system variability [16]. It helps firms identify inefficiencies and streamline operations while maintaining flexibility [17]. The next section outlines the application of this metric in our study.

3 Theoretical Framework

Under the assumption that structural complexity arises from the proliferation of products, suppliers, markets, etc. Ruiz-Hernández et al. [1] introduced the *pars*-Complexity (C_p) metric. The C_p metric measures complexity based on the contribution of each uniquely identified product i to the total plant cost (p_i); and it is represented by equation (1):

$$C_p = \sum_{i=1}^{n} -p_i log_2 p_i \quad (1)$$

where $\boldsymbol{n}$ is the number of unique products.

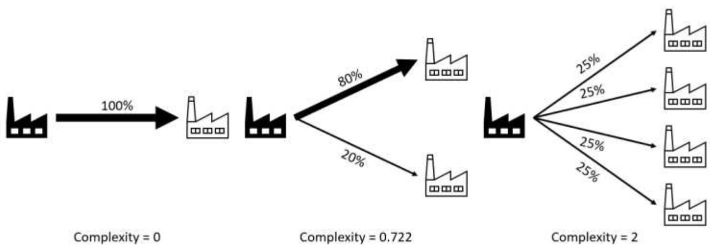

Fig. 1. Complexity score of each supply option for the hypothetical company.

This metric serves as a tool to compare alternative procurement configurations. For example (see Fig. 1), a manufacturer can choose between one (option 1), two (option

2), or multiple suppliers (option 3). In this context, having only one supplier would pose a significant risk to the project's success; while a larger number of them would increase managerial complexity and hinder visibility, it also suggests increased resilience, enabling the manufacturer to cope with disruptions. For configurations with the same number of suppliers, those cases where the demand is more concentrated have lower complexity values, while those with a more evenly distributed demand will show higher complexity values.

As the *pars*-Complexity (C_p) value depends on the network's size, a normalised version (henceforth *n*-Complexity) has been proposed that removes the influence of network size and renders the complexity values for different numbers of suppliers comparable (2).

$$n\text{-Complexity: } \tilde{C}_p = \frac{C_p}{log_2 n} \quad (2)$$

The modified metric reports a score on a scale of 0-1, where 1 is an even distribution and zero will reflect concentration in only one supplier.

4 Methodology

This study applies the *pars*-Complexity (C_p) metric to assess the structural complexity of the supplier network within the ZCH project, providing an answer to the following research questions.

1. **What are the dependency levels in the supplier network?**
   The C_p metric is used to quantify the level of dependency within the ZCH supply base. This helps identify potential vulnerabilities, particularly where there are single-source dependencies that could disrupt operations if a key supplier fails.
2. **What are the components at risk?**
   Some components within the project may be more vulnerable due to high dependency levels within their supply network. Using the C_p metric, the study identifies components with low structural complexity that are at greater risk of disruption.
3. **What are the structural vulnerabilities?**
   The study seeks to identify those components that may be at risk due to either the absence of enough suppliers or to the limited capacity of the existing supply base. To do so, we propose an alternative use of the C_p metric referred to as *substitutability score*.
   As a byproduct of this score, we propose a mechanism to identify the number of suppliers that can better guarantee a balance between efficiency and risk management.

4.1 What is the dependency level of the supplier network?

The ZCH project analyses 278 unique components, grouped into 21 component families and 11 plant facilities. Given the phased development and the independence between different plants, our results will be presented both at a component family level (aggregated results for all components within each family) and at the plant level. The component family perspective provides a strategic view for policymakers, while the plant-level analysis offers a practical insight for individual companies. This dual approach ensures relevance for both high-level planning and facility-specific decision-making.

Two demand allocation strategies are considered: one that assumes an even distribution of the demand among suppliers, and another one where allocation is based on estimated capacities obtained from companies' turnover information.

Even demand allocation. Starting with the first approach (even demand distribution), Table 1 shows the *pars*-Complexity values for the different families of components. The component family with smaller *n*-Complexity score, and therefore more dependent, is the Instrumentation family. This could be expected due the specialist nature of the equipment within the broader family. Likewise, Electrolysers and Boilers present the scores closest to 1, reflecting higher availability.

Table 1. Complexity at the component family level (even demand allocation).

Component Family	*pars*-Complexity	*n*-Complexity
Boilers	3.61	0.98
Civil	3.85	0.89
Compressors	3.40	0.83
Electricals	4.68	0.92
Electrolysers	2.32	1.00
Exhaust	3.57	0.94
Fans	2.79	0.93
Filters	4.18	0.97
Heat Exchangers	4.71	0.86
Instrumentation	3.60	0.73
Mechanical Handling	3.72	0.95
Miscellaneous	4.84	0.91
Mixers	2.79	0.84
Pipes & Pigging	3.73	0.89
Power Generation	4.06	0.96
Pumps	4.03	0.86
Safety Equipment	3.30	0.87
Separators	3.79	0.85
Valves	3.94	0.88
Vessels	4.29	0.82

Shifting the focus of the analysis from the component to the plant's perspective, Table 2 presents the corresponding scores of *pars*-Complexity and *n*-Complexity at the plant level. The table suggests little variability in complexity among plants.

Table 2. Complexity at the plant level (even demand allocation).

Plant	*pars*-Complexity	*n*-Complexity
1	4.87	0.82
2	5.40	0.75
3	6.13	0.9
4	6.72	0.94
5	5.83	0.83
6	6.04	0.89
7A	6.14	0.9

7B	6.48	0.91
8	4.34	0.87
9A	5.72	0.85
9B	5.66	0.83

Demand allocation based on estimated capacities. For our second approach we used the supplier turnover as a proxy for capacity, splitting demand accordingly. This measure can be interpreted as the percentage deviation from an optimal scenario with no capacity constraints. Table 3 presents results at component family level while Table 4 focuses on plant level. Additionally, a dependency score, measured as the percentage difference in *n*-Complexity between the estimation based on even demand and the one obtained with the turnover data has been calculated (value between brackets in the third column).

The analysis conducted for the ZCH supply base reveals mixed levels of dependency across different component families and plants. It can be seen, for example, that the dependency of Boilers is among the lowest. The Electrolysers family however appears to be highly dependent. This may be explained by the fact that most companies in this area are emerging and so have a very small turnover; at the same time some of the larger and more well-established companies from other sectors are also investigating the possibility of supplying electrolysers and so appear dominant in a potentially misleading way. i.e., the much larger turnover of such global companies may only reflect their aggregate size, rather than indicating a specific production capacity of electrolysers. Therefore, further investigation would be required at supplier selection stage.

Before concluding the section, it is worth noting that, although the second approach is clearly preferable, in early stages of project development it is unlikely that detailed information about the potential suppliers' turnover would be available; in such circumstances the first approach can still provide valuable insights on the dependency level of the supply network.

Table 3. Complexity at the component family level (turnover-based allocation).

Component Family	***pars*-Complexity**	***n*-Complexity (Dependency)**
Boilers	3.34	0.90 (−0.08 Δ)
Civil	3.50	0.81 (−0.09 Δ)
Compressors	2.45	0.60 (−0.28 Δ)
Electricals	3.48	0.68 (−0.26 Δ)
Electrolysers	0.62	0.31 (−0.69 Δ)
Exhaust	3.24	0.85 (−0.09 Δ)
Fans	2.29	0.76 (−0.18 Δ)
Filters	3.08	0.71 (−0.26 Δ)
Heat Exchangers	4.10	0.75 (−0.13 Δ)
Instrumentation	2.40	0.48 (−0.33 Δ)
Mechanical Handling	3.28	0.84 (−0.12 Δ)
Miscellaneous	4.32	0.81 (−0.11 Δ)
Mixers	2.25	0.68 (−0.19 Δ)
Pipes & Pigging	2.61	0.63 (−0.30 Δ)
Power Generation	3.26	0.77 (−0.20 Δ)
Pumps	3.02	0.64 (−0.25 Δ)
Safety Equipment	2.62	0.69 (−0.21 Δ)
Separators	3.44	0.77 (−0.09 Δ)

Valves	2.77	0.62 (−0.30 Δ)
Vessels	3.99	0.77 (−0.07 Δ)

Table 4. Complexity at the plant level (turnover-based allocation).

Plant	*pars*-Complexity	*n*-Complexity (Dependency)
1	4.45	0.75 (−0.09 Δ)
2	4.56	0.63 (−0.16 Δ)
3	5.28	0.77 (−0.14 Δ)
4	5.77	0.81 (−0.14 Δ)
5	5.07	0.72 (−0.13 Δ)
6	5.19	0.77 (−0.14 Δ)
7A	5.30	0.78 (−0.14 Δ)
7B	5.73	0.81 (−0.12 Δ)
8	3.48	0.70 (−0.20 Δ)
9A	4.83	0.72 (−0.15 Δ)
9B	4.88	0.71 (−0.14 Δ)

4.2 Are there specific components within the project that are at risk?

A challenge presented by the approaches in the previous section was that assigning demand in terms of physical units obscures the sheer differences in the values of the components. A component that is worth only a few thousand pounds does not entail the same risk as one that is worth tens of millions. To address this, an alternative approach was to use the value of each component to calculate the total monetary value of the demand instead of the number of demand units for the calculation. A fraction of this value was assigned to each potential supplier based on its turnover.

As before, complexity and dependency scores for each component family within ZCH with the components value are reported in Table 5. Most product families now sit around 0.7, with the most resilient being Boilers, Mechanical Handling, and Civil - which are established industries with many large companies. At the other end of the spectrum the most dependent component families are Filters, Electrolysers, Pipes and Compressors. This is because of the emerging nature of hydrogen production and CO_2 storage, and the requirement for large scale pipework to transport the CO_2 to the North Sea. The largest change in score corresponds to Filters (-0.58 Δ), due to the CO_2 dehydration filter costing £20M has a much higher risk than the rest of the filters, more common types only costing £20K.

Table 5. Complexity at the component family level (component values applied).

Component Family	*pars*-Complexity	*n*-Complexity (Dependency)
Boilers	3.27	0.88 (−0.02 Δ)
Civil	3.50	0.81 (0.00 Δ)
Compressors	2.13	0.52 (−0.13 Δ)
Electricals	3.50	0.69 (+0.01 Δ)
Electrolysers	0.62	0.31 (0.00 Δ)
Exhaust	2.51	0.66 (−0.22 Δ)
Fans	2.25	0.75 (−0.02 Δ)
Filters	1.29	0.30 (−0.58 Δ)
Heat Exchangers	3.87	0.70 (−0.06 Δ)
Instrumentation	2.99	0.60 (+0.25 Δ)
Mechanical Handling	3.28	0.84 (0.00 Δ)

Miscellaneous	3.60	0.68 (−0.17 Δ)
Mixers	1.62	0.49 (−0.28 Δ)
Pipes & Pigging	1.86	0.45 (−0.28 Δ)
Power Generation	3.00	0.71 (−0.08 Δ)
Pumps	3.26	0.69 (+0.08 Δ)
Safety Equipment	2.56	0.67 (−0.02 Δ)
Separators	3.04	0.68 (−0.12 Δ)
Valves	2.77	0.62 (0.00 Δ)
Vessels	3.74	0.72 (−0.06 Δ)

Complexity and dependency scores for each plant within ZCH with components values weighting applied are visible in Table 6. Plants 6 and 8 show the highest vulnerability probably due to their requirement for large scale pipelines into the North Sea, and the dependency on limited suppliers to provide this.

Table 6. Complexity at the component family level (component values applied).

Plant	*pars*-Complexity	*n*-Complexity (Dependency)
1	4.18	0.70 (−0.06 Δ)
2	4.01	0.55 (−0.12 Δ)
3	4.72	0.69 (−0.11 Δ)
4	4.98	0.70 (−0.14 Δ)
5	4.95	0.71 (−0.02 Δ)
6	3.18	0.47 (−0.39 Δ)
7A	4.75	0.70 (−0.10 Δ)
7B	4.75	0.67 (−0.17 Δ)
8	2.41	0.48 (−0.31 Δ)
9A	4.52	0.67 (−0.07 Δ)
9B	4.84	0.71 (−0.01 Δ)

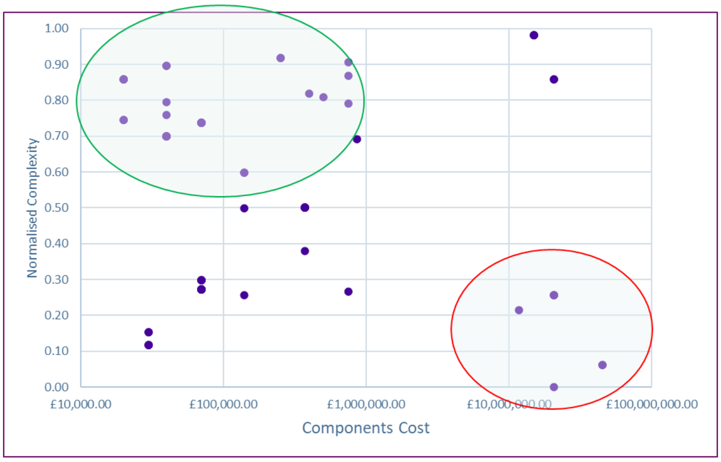

Fig. 2. Component *n*-Complexity for each item in Plant 6.

Fig. 2 shows an example of the weighting of components within Plant 6. In the previous section, Table 4 shows this facility to be one of the least dependent plants within ZCH, with an *n*-Complexity score of 0.77. However, whilst the average component may have a high *n*-Complexity (low dependency), these are in general within a £10,000 - £1,000,000 price interval. At the other end of the scale there is a cluster of highly dependent items that are within a £10,000,000 - £100,000,000 range. This results in a drop in *n*-Complexity of around 40% (see Table 5) when the component value weighting is applied, making it one of the most dependent facilities.

4.3 **What are the structural vulnerabilities?**

The final stage of the analysis shifted from assessing dependencies in the UK supply base to evaluating risks associated with the existing supply base.

In order to assess vulnerability of the supply base, we further introduce the notion of substitutability, which reflects -in one single figure- the availability of alternative suppliers for any given components. Following the same rationale behind the *pars*-Complexity metric, we developed a real-valued substitutability score. A component is classified as "at risk" if its substitutability score is below 1 (equivalent to not having at least two backup suppliers). A 'critical risk' component has no alternative suppliers. Alternatively, the higher the score, the more resilient is the supply base of that specific component. The critical risk components are reported in Table 7.

There are two main risk-drivers for a component. First, there is insufficient remaining capacity amongst the existing suppliers; or second, there are no alternative suppliers.

Table 7. List of critical risk components identified by the down-selection analysis.

Component	Reason
ASU Package	Only 2 suppliers identified, one does not have the required capacity.
CO_2 Compressors	The suppliers do not have the capacity to fulfil the requirement for compressors across ZCH.
Ion Exchange Packages	Specialised equipment.
CO_2/N_2 Storage Skid	Specialised equipment.
Gas Turbine	Specialised equipment, where the suppliers that were able to be assigned to other components didn't have the remaining capacity.
Steam Turbine	Specialised equipment, where the suppliers that were able to be assigned to other components didn't have the remaining capacity.
Electrolyser Package	Specialised equipment.

We can say that addressing supply risks in the ZCH project involves identifying alternative suppliers for components with limited or no remaining capacity. For standard components, new suppliers can often be found based on turnover and capability. However, specialised components pose a greater challenge, sometimes requiring unique solutions. In some cases, equipment like Electrolyser Packages or CO_2/H_2 Pipes could be split among multiple suppliers rather than relying on a single provider, depending on the company's risk tolerance.

Managers can also use the substitutability score, together with the *pars*-Complexity metric, as a tool for identifying the optimal number of suppliers for a given component (provided that the supply base is large enough). This is illustrated in Table 8, where we show five different configurations for Plant 3. These configurations differ on the priority given to either *pars*-Complexity or substitutability. Substitutability comes at the price of higher *pars*-Complexity through expanding and diversifying the supply base, while reducing *pars*-Complexity may increase the number of components at risk; potentially endangering the availability of certain components due to supply constraints. Efficient configurations would have either a substitutability or complexity orientation, minimising *pars*-Complexity, without increasing the presence of components at risk. This is further illustrated in Fig. 4.

Table 8. Comparison of supplier selection strategies.

Supplier Assignment	Plant Complexity	Average Substitutability	Components at Risk	Critical Risk
Maximum Substitutability	4.52	2.63	0	0
Substitutability Orientation	3.74	2.56	0	0
pars-Complexity Orientation	3.20	1.62	0	0
Low pars-Complexity Orientation	2.80	0.89	30	0
Minimum pars-Complexity (Critical Risk)	2.77	0.35	37	21

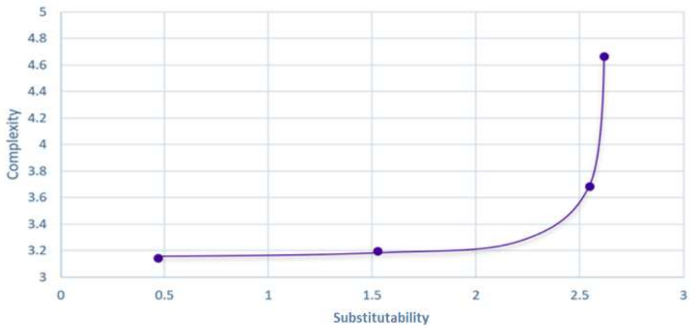

Fig. 4. Complexity vs. Substitutability trade-off visualisation for the Plant 3 facility.

The same exercise was repeated for all the plants in ZCH cluster. Table 9 presents the calculated values for the *pars*-Complexity orientation alternatives. It can be noticed that, although the risk is reduced, there is no guarantee that all components will be free of risk in all cases.

Table 9. Optimised complexity, substitutability values, and components at risk for each plant.

Plant	Plant *pars*-Complexity	Average Substitutability	Components at Risk	Critical Risk
1	2.05	1.50	1	0
2	2.85	1.34	5	0
3	3.20	1.61	0	0
4	4.23	1.29	3	0
5	3.98	1.65	19	3
6	2.88	1.21	7	0

7A	3.13	1.36	1	0
7B	3.62	1.33	11	3
8	2.23	1.29	2	0
9A	3.82	1.55	13	2
9B	3.58	1.52	15	1

The table shows that the optimal number of suppliers varies by component type. For highly specialised items like electrolysers or compressors, a smaller, well-managed supplier base is preferable due to the limited number of qualified suppliers. Conversely, for more commoditised components like valves or piping, a larger supplier base helps distribute risk without excessive management complexity.

Ultimately, these calculations help decision-makers determine the ideal supplier count by identifying the point where additional suppliers no longer enhance resilience but instead introduce unnecessary complexity. This ensures a supply network that is both robust and operationally efficient.

5 Conclusions

In this paper we utilise the theory of structural complexity to analyse the capabilities of the UK industrial base to supply for building a large-scale low-carbon and decarbonisation initiative and to explore its resilience and existing vulnerabilities.

The study identifies key supply chain capabilities and risks; for example, Instrumentation components show medium risk due to their specialised nature, while the Electrolysers family is highly dependent on a limited supplier base. The highest-risk components include filters, electrolysers, pipes, and mixers, with two plants (6 and 8) facing the greatest challenges.

By applying *pars*-Complexity and *n*-Complexity metrics, this research helps assess supply chain robustness early in the planning process. It offers a framework that can be applied to other industrial clusters, balancing supplier diversification with operational efficiency. The study underscores the need for continuous updates as industry capabilities evolve, ensuring the supply chain remains resilient in a rapidly changing market.

Notwithstanding that our analysis provides valuable insights, it is subject to several limitations due to data assumptions. The Bill of Materials (BoM) was estimated from public CCS and hydrogen power data, making component details uncertain. Supplier capacities were inferred from turnover and employee data, which may not accurately reflect production capabilities, especially for large firms with diverse operations. Additionally, the analysis assumed a linear relationship between turnover and capacity, which does not account for operational constraints.

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