The Future of Energy Value Chains in the Transition to a Low-Carbon Economy: An Evaluation Framework of Integration and Segmentation Scenarios

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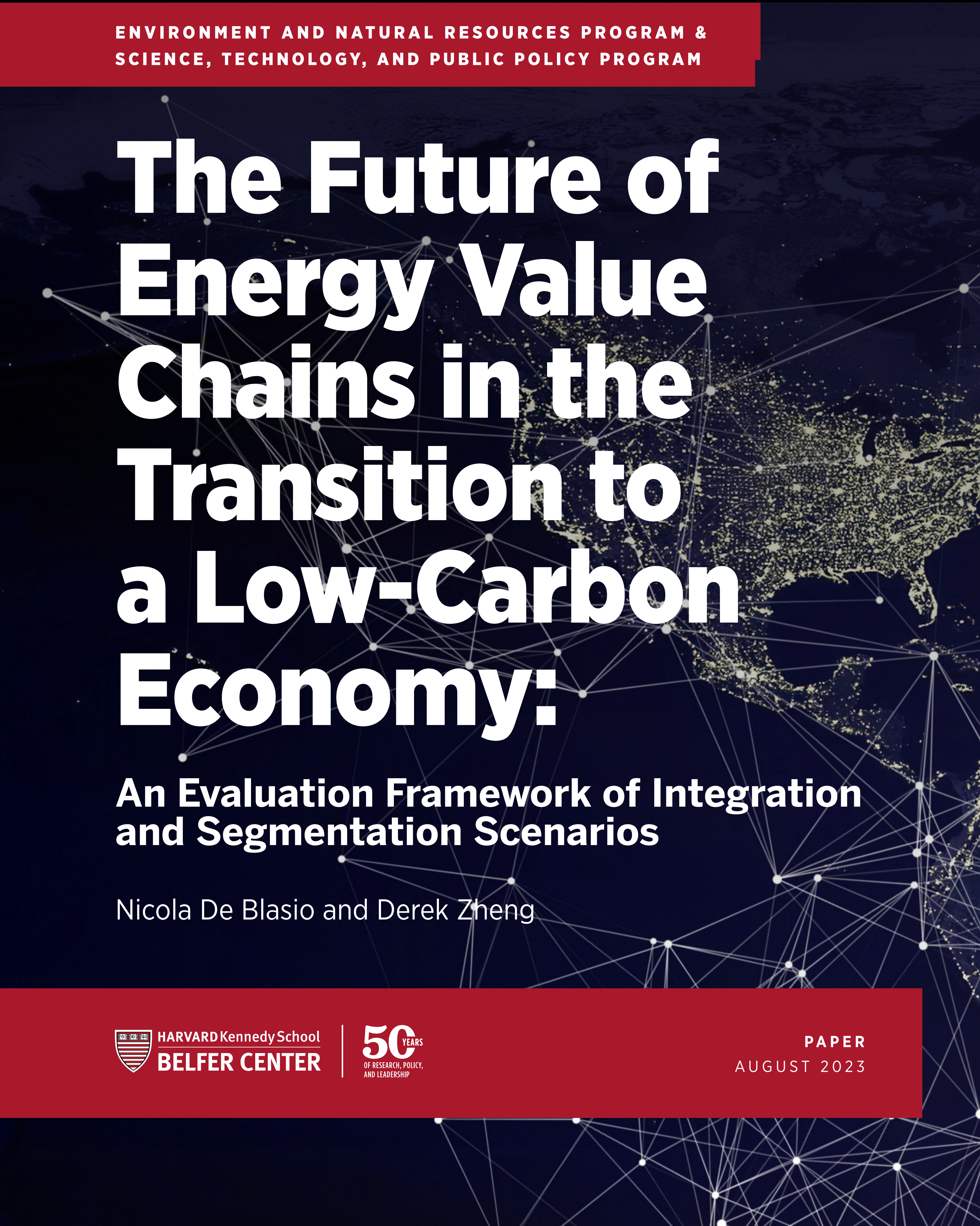

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An Evaluation Framework of Integration and Segmentation Scenarios

Nicola De Blasio and Derek Zheng

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50 YEARS
OF RESEARCH, POLICY, AND LEADERSHIP

PAPER
AUGUST 2023

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About the Authors

Nicola De Blasio is a Senior Fellow leading Belfer Center research on energy technology innovation and the transition to a low-carbon economy. With more than 25 years of global experience in the energy sector, Dr. De Blasio is an expert in navigating the challenges of strategic development and technology innovation toward sustainable commercial success at scale. Through his research and experience, he has gained considerable insight into the impact of institutional development and innovation activities on other facets of business strategy.

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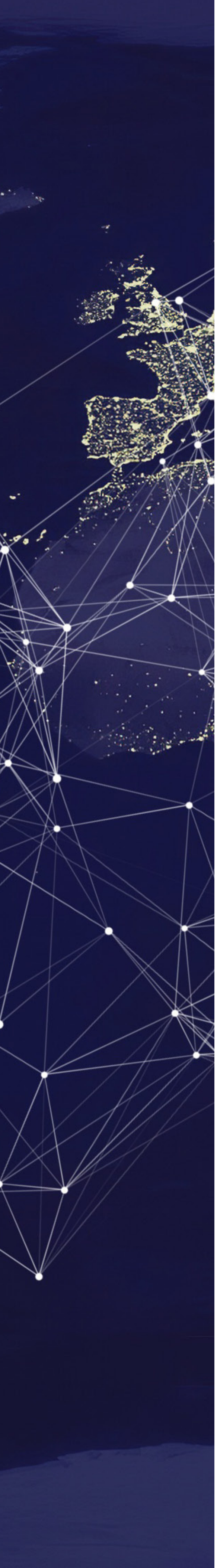

Introduction

The transition from energy systems dominated by fossil fuels[1] to ones based on renewable electricity and "green" molecules will significantly impact existing value chains[2] and forge new pathways, interactions, and transformation steps from production to consumption. Regulatory and business models must rapidly evolve to manage the resulting substantial cost challenges and dramatic shifts in stakeholder interactions while continuing to create value.

Fossil fuels have paved the way for rapid industrialization and economic growth for many decades, but business-as-usual would only exacerbate existing socioeconomic imbalances. Due to these disparities, we tend to divide the world into Global North and Global South, which from a semantics perspective seems to imply that the former has already reached the achievable and the latter only need to catch up. But if the rest of the world were to attain the same per capita energy consumption (and associated emissions) as the Global North, the results would be environmentally catastrophic.

The critical question is how to navigate the delicate balance of sustaining growth while achieving prosperity for all and accelerating the transition to a low-carbon economy. The answer must lie not only in globalization but increasingly in technology innovation.

Innovation is everywhere - policy, finance, technology, and business - driving dynamics not seen in the energy sector

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[1] Today, coal, oil, and natural gas still account for 80% of global energy demand.

[2] Unlike the term supply chain, which is typically used to define a set of operational relationships designed to benefit a single stakeholder and deliver products or services, the term value chain refers to a more conceptual design of business relationships between stakeholders that support the development and adoption of a market or technology at scale.

since the Industrial Revolution. As new technologies and processes develop to sustain growing energy needs, understanding how these will impact existing energy value chains or cause new ones to emerge is crucial for navigating the energy transition successfully.

The first step in this process is identifying key technologies driving disruptive change and understanding how they create value. To do this, it is critical to recognize that a technology by itself is not necessarily valuable for all stakeholders. Technologies, no matter how innovative, can offer little to no value unless contextualized to a specific company and its asset portfolio because technologies cannot be decoupled from their applications. In other words, the actual value of a technology lies in its potential to drive business opportunities rather than its overall innovative content. This is why a game-changing technology in one sector may hold little or no use in another. For example, a lumber company will derive little to no value from a medical artificial intelligence imaging technology, even if extremely valuable for the healthcare sector.

Elucidating the role of innovation in shaping future value chains also requires understanding who could best leverage a specific technology – and how. The key to maximizing overall value and accelerating the transition to a low-carbon economy can be found only by understanding the opportunities and challenges of deploying technology at scale and the complex role that different stakeholders could play. Analyzing existing energy value chains highlights the many ways stakeholders position their offerings—including adopting sustainable business models, specializing in key technologies to gain a competitive advantage, or responding to regulatory constraints. These decisions generally result in two outcomes: integration or segmentation.

As we move toward a more decarbonized and decentralized future enabled by technological innovation, the public and private sectors must work together to rethink their roles. To facilitate this discussion, we propose a framework to guide the understanding of how innovation can drive integration or segmentation scenarios and why stakeholders may want to pursue a specific outcome.

While it is challenging to encapsulate in this framework all the factors influencing the process, we have identified three criteria encompassing the key determinants:

Strategic Value, Techno-Economic Relatedness, and Risk. We apply the proposed framework to three technologies that, if adopted at scale, could significantly change energy systems as we know them: renewable hydrogen[3]; carbon capture, utilization, and storage (CCUS)[4]; and blockchain.[5]

Only a cohesive and collective understanding of how energy value chains will evolve can enable each participant to best prepare for and succeed in the energy transition. Stakeholders who can embrace the new energy landscape will gain significant competitive advantages, while the others risk fading into obsolescence.

This paper is structured as follows: after a literature review, Section 2 defines the concepts of value chains, value-chain analysis, and integration and segmentation scenarios. Section 3 introduces a comprehensive framework to explain innovative technologies' role in the transition to a low-carbon economy based on the three criteria mentioned above. Section 4 applies the framework to the three indicated technologies. Finally, Section 5 offers recommendations for catalyzing innovation's successful development and deployment in an accelerated transition to a low-carbon economy.

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[3] Renewable or green hydrogen refers to hydrogen produced using renewable energy through water splitting.

[4] Carbon capture, utilization, and storage (CCUS) encompasses methods and technologies to remove carbon dioxide (CO_2) from the atmosphere, followed by either recycling for utilization or safe and permanent storage.

[5] A blockchain technology is a shared, decentralized, immutable digital ledger that securely stores single or multi-party transactions.

1. Literature Review

The debate on the geopolitical and market implications of the energy transition has significantly intensified over the past few years, focusing on how adopting renewable energy at scale might affect economic markets and international relations.[6,7,8,9,10,11,12,13] Most studies have focused on the geopolitical dimension of this issue using a classical definition of geopolitics, thus analyzing the "influence of geography on the power of states and international affairs with [...] emphasis on [...] the strategic importance of natural resources, their location, transportation routes, and chokepoints."[14] Very few have moved beyond geographical boundaries to include technological, economic, political, and cultural considerations which are by definition "changeable over time."[15,16,17]

Using an approach rooted in critical[18] geopolitics, this paper shows how, in the energy transition to a low-carbon economy, technological innovation adoption at scale will dynamically affect global value chains over time and illuminates the role stakeholders in the private and public sectors will need to play.

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[11] Blondeel, M., et al. (2021) "The geopolitics of energy system transformation: a review," *Geography Compass* 15 (7).

[12] IRENA (2019) *"A New World. The Geopolitics of the Energy Transformation," Global Commission on the Geopolitics of Energy Transformation,* Abu Dhabi.

[13] Goldthau, A., et al. (2019) "Model and manage the changing geopolitics of energy," *Nature* 569 (7754) 29–31.

[14] Overland, I. (2019) "The geopolitics of renewable energy: debunking four emerging myths," *Energy Research & Social Science* 49, 36–40.

[15] Pflugmann, F., and De Blasio, N. (2020) "The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets," *Geopolitics, History, and International Relations* 12(1): 9–44. doi:10.22381/GHIR12120201

[16] Amineh, P.M. (2003) "Globalisation, Geopolitics and Energy Security in Central Eurasia and the Caspian Region," IAEA.

[17] Eicke, L. and De Blasio, N. (2022) "Green hydrogen value chains in the industrial sector—Geopolitical and market implications," *Energy Research & Social Science* 93, 102847 https://doi.org/10.1016/j.erss.2022.102847

[18] While classical geopolitics refers to the study of the impact or influence of certain geographic features - such as the positions and locations of regions, states, and resources - as an objective perspective of the external world, critical geopolitics is based on a subjective spatial and political perspective.

In current literature, only a few articles hint at the importance of value chains for international relations,[19,20,21,22] or examine in detail the geopolitical implications of the adoption at scale of innovative technologies and the associated impact on value chains.[17,23] Some studies explore technological and cost improvements[24] or address value-chain impacts in country-specific case studies, e.g., looking at hydrogen technologies in the United States,[25] Japan,[26] and Germany.[27] Furthermore, the current body of literature examines global value chains in terms of repositioning by focusing on the strategies of firms, with very little attention on the public sector and state policymaking.[28,29] We suggest a more comprehensive, empirically driven analysis of stakeholders' role in emerging value chains driven by technological innovation.

We address this gap using insights from global value-chain literature and technological innovation's role in the energy sector. Our research advances understanding of this dynamic by addressing the key research question of how technological and policy innovation impact energy value chains. Furthermore, it provides stakeholders in both the public and private sectors with the tools to evaluate the role they can play. This perspective offers new insights into the required realignment among stakeholders. We argue that a detailed understanding

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[19] Van de Graaf, T., et al., (2020) "The new oil? The geopolitics and international governance of hydrogen," *Energy Research & Social Science* 70, 101667.

[20] Noussan, M., et al., (2021) "The role of green and blue hydrogen in the energy transition—a technological and geopolitical perspective," *Sustainability* 13 (1) 298.

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[23] IRENA (2022) "Geopolitics of the Energy Transformation: The Hydrogen Factor," Abu Dhabi.

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[26] Nagashima, M. (2018) "Japan's Hydrogen Strategy and Its Economic and Geopolitical Implications," Ifri.

[27] Coleman, D., et al. (2020) "The value chain of green hydrogen for fuel cell buses–a case study for the Rhine-main area in Germany," *International Journal of Hydrogen Energy* 45 (8) 5122–5133.

[28] De Marchi, V., and Alford, M. (2022) "State policies and upgrading in global value chains: A systematic literature review," *Journal of International Business Policy* 5, 88–111.

[29] Eicke, L., and De Blasio, N. (2022) "The Future of Green Hydrogen Value Chains: Geopolitical and Market Implications in the Industrial Sector," Belfer Center for Science and International Affairs, Harvard Kennedy School.

of the role of technological innovation on global value chains can help to accelerate the transition to a low-carbon economy more efficiently and effectively while overcoming the dichotomy of winners and losers and providing a more granular understanding of the diverse roles stakeholders can embrace.[30]

The literature on global value chains incorporates several disciplines, including business and management studies, geography, and political economy.[31] Key concepts that we draw upon are upgrading, downgrading, integration, and segmentation along value chains.

Upgrading is defined as a shift "to higher value-added activities to improve technology, knowledge, and skills, and to increase the benefits or profits deriving from participation in global value chains."[32] Four types of upgrading are usually identified: product, process, functional, and inter-sectoral.[33,34] Existing literature on global value chains highlights how a product or a service's final value varies along value-chain segments. Resource extraction is the least profitable segment of a value chain, whereas the value-added of industrial applications is much higher.[35,36]

In contrast to upgrading, the concept of downgrading has received limited attention, and it is generally used with a negative connotation. Value-chain downgrading may be a passive,[37] adaptive,[38] or strategic process.[39] Most studies examine upgrading and downgrading repositioning by focusing on the private sector with very little attention to the public sector.

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[30] De Blasio, N., and Zheng, D. (2022) "Technological Innovation and the Future of Energy Value Chains," Policy Brief, Belfer Center for Science and International Affairs, Harvard Kennedy School.

[31] Kano, L., Tsang, E.W., Yeung, H.W. (2020) "Global value chains: a review of the multi- disciplinary literature," *Journal of International Business Studies* 51 (4) 577–622.

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[33] Humphrey, J., and Schmitz, H. (2002) "How does insertion in global value chains affect upgrading in industrial clusters?" *Regional Studies* 36 (9) 1017–1027.

[34] Ponte, S., and Ewert, J. (2009) "Which way is 'Up' in upgrading? Trajectories of change in the value chain for South African wine," *World Development* 37, 1637–1650.

[35] Pipkin, S., and Fuentes, A. (2017) "Spurred to upgrade: a review of triggers and consequences of industrial upgrading in the global value chain literature," *World Development* 98, 536–554.

[36] Gereffi, G., Lee, J. (2012) "Why the world suddenly cares about global supply chains," *Journal of Supply Chain Management* 48 (3) 24–32.

[37] Kaplinsky, R., Terheggen, A., Tijaja, J. (2011) "China as a final market: the Gabon timber andThai cassava value chains," *World Development* 39, 1177–1190.

[38] Plank, L., and Staritz, C. (2015) "Global competition, institutional context, and regional production networks: up- and downgrading experiences in Romania's apparel industry," *Cambridge Journal of Regions, Economy and Society* 8, 421–438.

[39] Blazek, Jiri (2016) "Towards a typology of repositioning strategies of GVC/GPN suppliers: the case of functional upgrading and downgrading," *Journal of Economic Geography* 16, 849–869.

In this context, it is essential to remember that it is beneficial for countries to improve their value-chain positioning by moving from lower- to higher-value activities.[32,40] China is a successful example of value-chain upgrading. In recent decades, Beijing has supported the renewable energy sector with policies tailored to growing global market shares and the required skilled labor force.[41,42,43] Driving green industrialization has been vital for Global South countries more broadly, where policymakers have implemented strategic industrial policies to upgrade a nation's value chain position.[34,44] Several studies have also highlighted the importance of technology transfer and knowledge spillovers from related industries to enable upgrading processes in renewable value chains.[34,45,46,47,48,49,50,51]

Furthermore, evolving value chains have substantial implications for the distribution of gains and losses, especially concerning varying degrees of segmentation or integration. Analyzing existing energy value chains is critical in highlighting how stakeholders position their offerings, for example, by adopting sustainable business models, specializing in critical technologies to gain a competitive advantage, or responding to regulatory constraints.

Combining the research streams on global value chains, the energy transition's geopolitics, and technological innovation's role can provide original and more

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[40] Gereffi, G. (2005) "The global economy: organization, governance and development," in the *Handbook of Economic Sociology*, Princeton University Press and Russell Sage Foundation, Princeton, NJ.

[41] Chen, G.C., and Lees, C. (2016) "Growing China's renewables sector: a developmental state approach," *New Political Economy* 21 (6) 574–586.

[42] Gandenberger, C., et al. (2015) "The international transfer of wind power technology to Brazil and China," *Working Paper Sustainability and Innovation,* Fraunhofer ISI, Karlsruhe.

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[45] Tajoli, L., and Felice, G. (2018) "Global value chains participation and knowledge spillovers in developed and developing countries: an empirical investigation," *European Journal of Development Research* 30 (3) 505–532.

[46] Eicke, L., and Weko, S. (2022) "Does green growth foster green policies? Value chain upgrading and feedback mechanisms on renewable energy policies," *Energy Policy* 165, 112948.

[47] Lema,R., and Lema, A. (2012) "Technology transfer? The rise of China and India in green technology sectors," *Innovation and Development* 2 (1) 23–44.

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[49] Ockwell, D., and Byrne, R. (2016) "Improving technology transfer through national systems of innovation: climate relevant innovation-system builders (CRIBs)," *Climate Policy* 16 (7) 836–854.

[50] Pueyo, A., et al. (2011) "The role of technology transfer for the development of a local wind component industry in Chile," *Energy Policy* 39 (7) 4274–4283.

[51] Zhang, F., and Gallagher, K.S. (2016) "Innovation and technology transfer through global value chains: evidence from China's PV industry," *Energy Policy* 94, 191–203.

granular insights into stakeholders' roles in future clean energy markets. The synergies deriving from the integration of these segments will enable stakeholders to leverage and compound the intrinsic value of each segment while increasing control and reducing dependencies without falling into the inefficient behaviors of the past.[52]

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[52] Poorly designed and deployed energy policies and infrastructure, not taking into consideration system-level dynamics, have consistently failed to satisfy users' needs and lead to 'performance gaps' that are both energy and economically inefficient.

2. Value-Chain Definitions and Reference Scenarios

Before analyzing how the adoption of innovative technologies at scale could affect existing energy value chains in the transition to a low-carbon economy, it is important to define core concepts behind value chains, value-chain analysis, and the role of integration and segmentation scenarios.

2.1 Value Chains

Traditionally, the term "value chain" refers to a series of consecutive business activities and processes that result in creating a product or performing a service. Each link in the chain identifies a step at which value is added - from design to manufacturing, distribution, use, recycling, upcycling, or disposal. This differs from the term "supply chain," which is typically used to define a set of operational relationships designed to benefit a single stakeholder and the delivery of products or services. In the energy sector, value is derived from activities like hydrocarbon production, refining and marketing, transportation and shipping, electricity generation and distribution, renewable energy, research and development, and policymaking. We use the term value chain to mean a sequence of business relationships among stakeholders that support the development, deployment, and adoption of a market or technology at energy-system scale.

Value Chain Upgrading vs. Downgrading

In this paper, we define *value chain upgrading* as a process by which stakeholders acquire knowledge and skills that can be translated into innovations or improvements that increase the value of their products or services. We define *value chain downgrading* as a process by which stakeholders push to secure a better positioning within more confined markets by abandoning lower-strategic value activities or deciding to exit markets altogether.

2.2 **Value Chain Analysis**

A value-chain analysis aims to optimize system-level efficiencies so that stakeholders can extract maximum value. Stakeholders conduct a value-chain analysis by evaluating the detailed processes and interactions involved in each chain step. Expanding beyond simple resource availability, a comprehensive value-chain analysis can unlock crucial insights about global markets and geopolitical implications, contextualizing direct, clear consequences for policymakers regarding financing, technological, and infrastructural needs. As we will show, moreover, this process can help to accelerate the transition to a low-carbon economy and identify the roles nations might want to play in future energy markets.[53,54]

2.3 **Reference Scenarios**

An analysis of existing energy value chains highlights many reasons for how stakeholders position their offerings—including adopting sustainable business models, specializing in key technologies to gain a competitive advantage, or responding to regulatory constraints. However, these decisions generally result in one of two outcomes: integration or segmentation.

Value-Chain Integration

Value-chain integration is a process by which multiple stakeholders at different points along a value chain form sustained collaborations and create value by leveraging system-level efficiencies to optimize returns.[55] Integration is usually associated with higher value accumulation and a more substantial degree of control. Furthermore, from a critical geopolitics perspective, integration could

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[53] De Blasio, N., and Eicke, L. (2023) “Green Hydrogen Industrial Value Chains: Geopolitical and Market Implications.” Policy Brief, Belfer Center for Science and International Affairs, Harvard Kennedy School.

[54] Nuñez-Jimenez, A., and De Blasio, N (2022) “Competitive and secure renewable hydrogen markets: Three strategic scenarios for the European Union,” *International Journal of Hydrogen Energy*, 47, pp. 35553-35570 https://doi.org/10.1016/j.ijhydene.2022.08.170

[55] Gereffi, G., Humphrey, J., Sturgeon, T., (2005) “The governance of global value chains,” *Review of International Political Economy* 12 (1) 78–104.

increase the local added value, create jobs, and reduce dependencies resulting in vulnerability. Overall, integrated scenarios generally occur when there is a need for coordination between stakeholders to develop and adopt a market or technology at scale.

For example, the creation of liquefied natural gas (LNG) markets demonstrates how joint planning, construction, and operation of enabling infrastructure is key to transforming an inherently regional commodity into a global one.

Liquefied Natural Gas Markets – The Role of Integration in Achieving Global Reach

Natural gas can be transported by land, via pipelines, or by sea, via ships. Today, most of the world's natural gas is transported by pipelines, but this is a highly rigid approach since delivery points are unchangeable once built. Shipping by tanker provides much more flexibility, but natural gas must first be converted (liquefied) to LNG through a cryogenic process. This liquefaction process is expensive, and transportation requires specially designed tankers to limit re-vaporization (boil-off) and losses. Furthermore, even if intrinsically more flexible, this approach hinges on the availability of re-gasification terminals where LNG can be converted back to its gaseous form before being injected into pipeline systems for its distribution to final users (Figure 1).

The overall challenge resides in the fact that, unlike the cost of transporting crude oil, which is usually a fraction of crude oil costs, the cost of liquefying and transporting natural gas in the form of LNG can, in some cases, cost as much or more than natural gas itself. Hence, the high cost and complex logistics of transporting natural gas have hindered natural gas trade over long distances and helped to keep regional markets isolated.[56,57]

But energy security, flexibility of supply, and market considerations have driven integration along value chains, forcing stakeholders to come together to finance,

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[56] Brauers, H., Braunger, I., Jewell, J. (2021) "Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions," *Energy Research & Social Science* 76, 102059 https://doi.org/10.1016/j.erss.2021.102059

[57] IEA (2019) "LNG Market Trends and Their Implications" IEA, Paris https://www.iea.org/reports/lng-market-trends-and-their-implications

build, and operate the needed LNG infrastructure. This is because building highly capital-intensive liquefaction plants to bring natural gas to global markets can only be justified if off-takers – owners of regasification terminals in target markets – are willing to sign long-term contracts.[58]

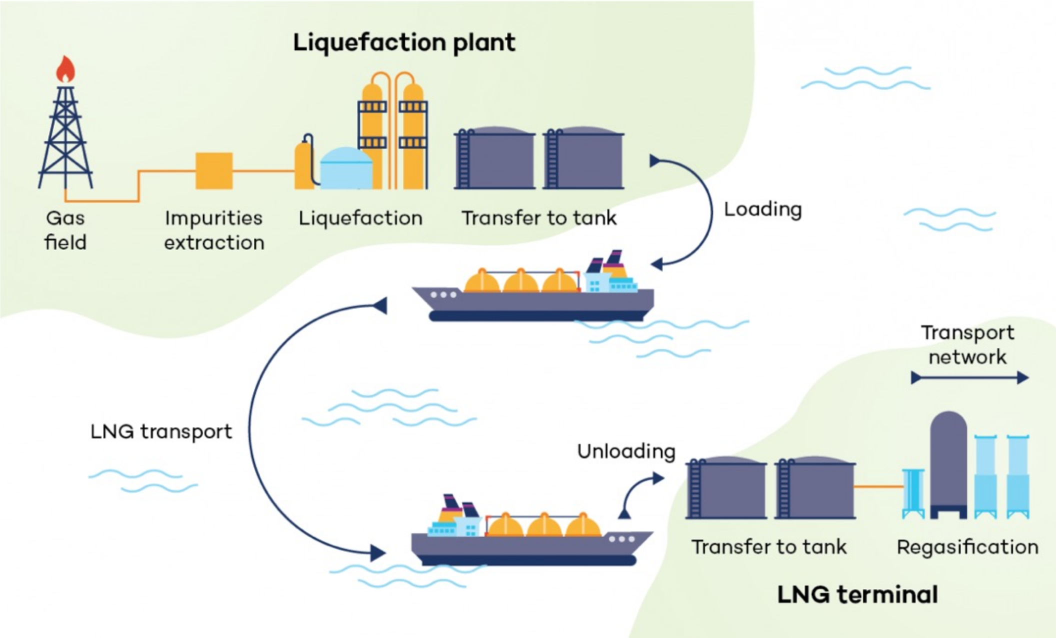

Figure 1. Liquefied Natural Gas Value Chain
(Source: International Institute for Sustainable Development)

Value Chain Segmentation

Value chain segmentation refers to activities that create unique markets or differentiation in services, where individual stakeholders realize a competitive advantage through specialization in single segments of a value chain. In segmented areas of a value chain, competitors maximize profits by offering unique products or services to multiple clients. This approach creates value by focusing on producing a limited range of products or services to gain greater efficiency and maximize productivity. Service agreements are a typical example.

In the energy sector, oilfield service companies (Figure 2) are known for their highly standardized, specialized, and efficient offerings, which reveal the role of segmentation.

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[58] Bresciani, G., Heiligtag, S., Lambert, P., et al. (2020) "The future of liquefied natural gas: Opportunities for growth," McKinsey https://www.mckinsey.com/industries/oil-and-gas/our-insights/the-future-of-liquefied-natural-gas-opportunities-for-growth

The Oilfield Equipment and Service Industry: The Power of Segmentation

The oilfield equipment and services (OFS) industry refers to all products and services associated with oil and gas exploration and production – the so-called upstream sector. The range of offerings that service companies provide is broad. It includes technology-based services vital for successful field operations, such as seismic testing (formation evaluation), well construction, and production and completion services.

Due to cost-opportunity considerations, upstream companies do not usually own the needed equipment or possess the required skills but outsource these activities to service companies supporting the entire upstream sector. Service companies are compensated for the time and costs associated with their services, not by a production revenue share. Therefore, the high level of operational and technological efficiency and specialization provided by service companies drives segmentation scenarios.

Figure 2. Oilfield Service Companies

3. Value-Chain Evaluation Framework

As the world moves toward a more decarbonized and decentralized future spurred by technological innovation, the public and private sectors must work together to rethink their roles within value chains. To facilitate this discussion, we propose a framework to guide understanding of how innovation can drive integration or segmentation scenarios. While it is challenging to encapsulate all the factors influencing stakeholders' decisions to push for integration or segmentation, we have identified three criteria encompassing the key determinants: Strategic Value, Techno-Economic Relatedness, and Risk. We use these three criteria to draw Value Chain Evaluation Maps and assess the key strategic options available to stakeholders.

3.1 Strategic Value

A traditional, dictionary-definition of "strategic value" is the degree to which a particular action or planned action is important or useful in relation to something that it intends to achieve.

But what is the strategic value of a technological opportunity? To answer this question, it is critical to recognize that technologies cannot be decoupled from their applications. A technology by itself is not necessarily valuable - no matter how innovative - and it can offer little to no value unless contextualized to a specific asset portfolio. In other words, the actual value of a technology lies not in its absolute innovative content but in its potential to drive business opportunities.

In summary, embracing any novel innovation requires a strong business proposition, such as a new market opportunity or regulatory push. At the same time, its overall strategic value lies in the alignment with current or future business strategy and a complementary asset portfolio. The higher the strategic value of a business opportunity, the higher the drive for specialization and, thus, segmentation scenarios. On the other hand, the lower the strategic value of a business opportunity, the higher the drive for integration.

3.2 **Techno-Economic Relatedness**

To execute a strategically valuable opportunity, stakeholders must evaluate its techno-economic feasibility to identify needed core competencies, compare costs and benefits, and evaluate any sustainability or regulatory implication. This process also requires assessing the relatedness of an opportunity compared to ongoing activities.

The concept of relatedness refers to the consideration that while two activities might not be identical, they could still share techno-economic commonalities which can be leveraged for successful execution. In the literature, relatedness is often described in terms of similarity, and complementarity[59] activities are identified as similar when the same knowledge can be used in multiple technologies, services, or products.[60]

This paper defines techno-economic relatedness as the percentage of complementary activities present in a particular strategic opportunity. Comparatively high techno-economic relatedness will most likely drive a segmentation scenario – as stakeholders will want to embrace specialization to capitalize on unique opportunities. On the other hand, low techno-economic relatedness will drive integration scenarios.

3.3 **Risk**

Risk relates to future deviations from the expected outcomes of an endeavor and measures the uncertainty that stakeholders are exposed to due to internal and external variables. For example, economic risk may be the chance that macroeconomic conditions like exchange rates, government regulation, or political stability will affect a stakeholder's prospects. In the context of value-chain analysis, risk encompasses a series of factors, including market, technology, and regulatory and policy risk.

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[59] Makri, M., M.A. Hitt and P.J. Lane (2010) "Complementary technologies, knowledge relatedness, and invention outcomes in high technology mergers and acquisitions," *Strategic Management Journal* 31, 602-628

[60] Breschi, S., F. Lissoni and F. Malerba (2003) "Knowledge-relatedness in firm technological diversification," *Research Policy* 32, 69-87

- Market or systematic risk refers to uncertainties that would affect all investment decisions. Sources of market risk include adverse price movements, changes in interest and exchange rates, consumer preferences, recessions, political turmoil, natural disasters, and terrorist attacks.
- Systematic risk contrasts with specific risk, also known as unsystematic risk, which is tied to a particular market sector or the performance of a particular company or technology.
- Technology risk is a type of specific risk involving unfavorable circumstances that may affect a specific technology's successful development and deployment.
- Regulatory and policy risk – another type of specific risk – is the risk that a change in regulations or legislation will affect a company, a sector, or an industry by impacting the associated markets and value chains. Examples include introducing carbon pricing and green molecules certification requirements, subsidizing specific commodities (such as renewables or corn ethanol), and incentivizing the adoption of specific technologies (such as supporting electric vehicle adoption and banning internal combustion ones). Regulatory and policy risk also impacts project financing by de-risking specific technological or infrastructural projects.

Overall, more significant uncertainties and, thus, higher risks will drive integrated scenarios to spread liabilities between stakeholders, thereby de-risking a strategic opportunity for all players. For example, higher-risk opportunities, such as entering a new market where a specific company has little experience, warrant increased collaboration to reduce investment risk and improve the chance of success by pooling resources, expertise, and capital. In other words, high-risk opportunities generally push stakeholders into an integrated scenario approach. Vice versa, lower-risk opportunities, where stakeholders are confident that they have a competitive advantage and the ability to execute successfully, will drive for segmentation scenarios.

3.4 **Value Chain Evaluation Map**

To understand how innovation can drive integration or segmentation scenarios and to explain the key strategic options available to stakeholders, we propose a Value Chain Evaluation Map (Figure 3) based on the described criteria of Strategic Value, Techno-Economic Relatedness, and Risk.

By plotting Strategic Value (SV) on the horizontal axis and Techno-Economic Relatedness (TER) on the vertical axis, the first step identifies four quadrants, each representing a strategic option available to stakeholders: in-house execution (Execute), buying or developing the needed competencies (Buy/Develop), exiting an activity or a sector (Stop), and outsourcing or selling (Sell). The second step introduces the Risk variable so that lower to higher risk profiles are proportional to the area of the central diamond. Specific examples using the three identified technologies are described in the following section.

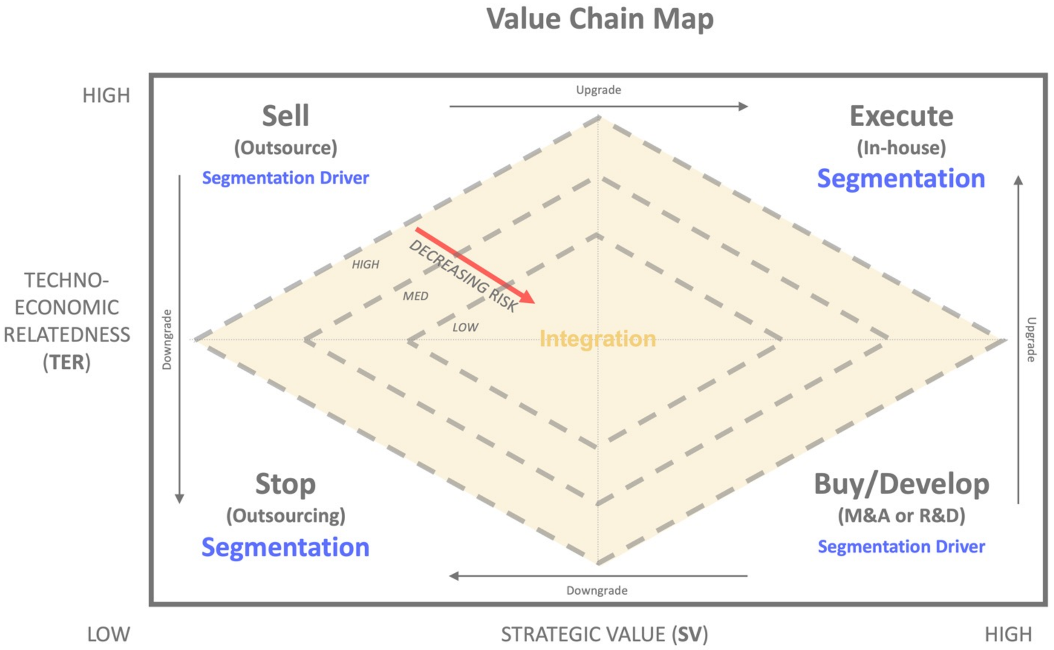

Figure 3. Value Chain Evaluation Map (Source: Authors' Elaboration)

High Strategic Value, High Techno-Economic Relatedness

Opportunities with high strategic value and strong alignment with core activities provide little incentive for stakeholders to form collaborative endeavors and will result in segmentation scenarios. This is the typical situation of companies having substantial competitive advantages and the means to develop and deploy products and services independently. However, if we introduce the risk variable, different dynamics come into play. If risk levels for specific stakeholders are above acceptable internal thresholds (and thus fall within the central diamond in Figure 3), participants will strive for more integrated scenarios to de-risk the endeavor for all players.

High Strategic Value, Low Techno-Economic Relatedness

In the case of opportunities with high strategic value but lacking the necessary competencies to execute, stakeholders can upgrade or downgrade along value chains. As discussed, the former requires specializing by acquiring the needed knowledge and skills, while the latter involves intentionally exiting a market altogether to facilitate a strategic realignment. Both dynamics are explicit segmentation scenarios. However, high risk levels might warrant stakeholder collaboration to de-risk implementation and increase success opportunities.

Low Strategic Value, High Techno-Economic Relatedness

This is the case of stakeholders owning a technology or competence not strategically aligned to current core activities or asset portfolios. Stakeholders in this quadrant may either sell these assets to more strategically aligned players or pivot by strategically upgrading to capitalize on the opportunity. In both cases, these processes result in segmentation scenarios. At the same time, stakeholders pivoting into new business lines will face considerable risks, which might drive integration scenarios.

Low Strategic Value, Low Techno-Economic Relatedness

If an opportunity arises in which stakeholders neither derive strategic value nor own the needed competencies, no further action should be taken. However, a segmented scenario may arise in which activities are outsourced to more strategically and techno-economically aligned players if needed. An example of this is the previously discussed case of oil and gas companies outsourcing activities to the oilfield and services industry.

4. Energy Value Chains and Adoption of Innovative Technologies – Case Studies

To clarify how adoption at scale of innovative technologies could drive integration or segmentation scenarios along value chains, we focus on three cases that have the potential to significantly change energy systems as we know them by disrupting value chains, upending stakeholders, and reshaping the way that energy, products, and services are produced, transported, and delivered. These technologies are renewable hydrogen; carbon capture, utilization, and storage (CCUS); and blockchain.

4.1 Renewable Hydrogen

Hydrogen is often described as the "missing link" in global decarbonization efforts.[61] It can be used in both stationary and mobility applications[62] (Figure 4), and, as a readily dispatchable means of storing energy, it can help address growing intermittency and curtailment challenges associated with expanded renewable energy capacity. It can serve as a fuel in stationary systems for buildings, backup power, distributed generation, or high-temperature industrial heat. As a sustainable mobility energy carrier, hydrogen can power fuel-cell electric vehicles or be the base for synthetic fuels, thus complementing ongoing efforts to electrify road and rail transportation and provide a scalable option to decarbonize the shipping and aviation sectors. But this versatility also creates significant uncertainties that must not be overlooked. The infrastructure needed in an economy where hydrogen is used as a transport fuel differs significantly from one whose primary value is as a heating fuel for buildings.[63]

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[61] De Blasio, N., Pflugmann, F., Lee, H., et al. (2021) "Mission Hydrogen: Accelerating the Transition to a Low Carbon Economy," Edited by Nicola De Blasio, A G20 Report, Belfer Center for Science and International Affairs, Harvard Kennedy School.

[62] De Blasio, N., Hua, C., Nuñez-Jimenez, A. (2021) "Sustainable Mobility: Renewable Hydrogen in the Transport Sector," Policy Brief, Belfer Center for Science and International Affairs, Harvard Kennedy School.

[63] Berstad, D., Gardarsdottir, S., Roussanaly, S., et al. (2022) "Liquid hydrogen as prospective energy carrier: A brief review and discussion of underlying assumptions applied in value chain analysis," *Renewable and Sustainable Energy Reviews* 154, 111772 https://doi.org/10.1016/j.rser.2021.111772

On the one hand, stationary applications drive integration scenarios because the development and deployment of hydrogen at scale requires close coordination between all stakeholders from production to consumption. For example, during the emergence of liquefied natural gas markets, players along regional natural gas value chains had to work together to deploy the necessary infrastructure and drive adoption globally. On the other hand, hydrogen technologies will drive segmentation scenarios in the mobility sector. While lithium-ion battery-powered electric vehicles will dominate the light-duty vehicle market, the heavy-duty segment will be powered by hydrogen or hydrogen derivatives like ammonia.[29]

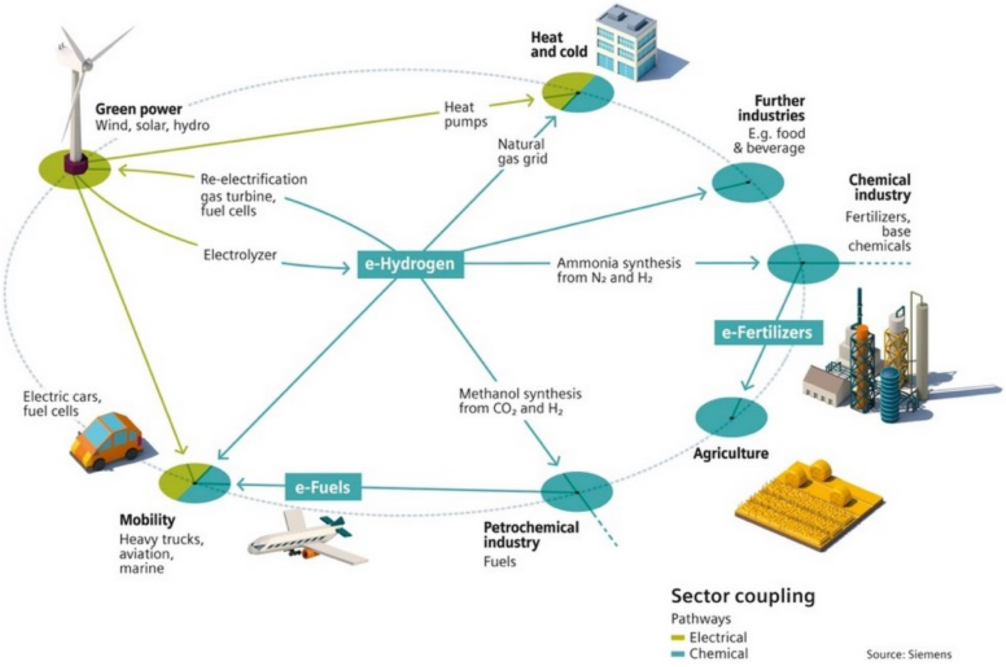

Figure 4. Hydrogen Value Chains (Source: Siemens)

4.2 **Carbon Capture, Utilization, and Storage**

Carbon capture, utilization, and storage (CCUS) refers to a suite of technologies for carbon abatement that could become key in tackling global warming.[64,65,66] CCUS is a three-step process in which the first step involves capturing carbon dioxide (CO_2) from large point sources, such as power generation, or industrial activities, such as steel or cement making, that use fossil fuels. Alternatively, the CO_2 could also be captured directly from the atmosphere by a process called direct air capture (DAC).[67,68] In the second step, the captured CO_2 is compressed and transported by pipeline, ship, rail, or truck. Finally, the CO_2 is injected into deep geological formations (including depleted oil and gas reservoirs or saline aquifers), which can trap it for permanent storage. In the case of utilization,[69] instead of storing the CO_2, the carbon could be re-used in industrial processes by converting it into products such as plastics, concrete, or biofuels (Figure 5). Today CCUS is mainly used for enhanced oil recovery (EOR)[70] applications.

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[64] Raza, A., et al. (2019) "Significant aspects of carbon capture and storage – A review," *Petroleum* 5 (4) 335-340 https://doi.org/10.1016/j.petlm.2018.12.007

[65] Roussanaly, S., Berghout, N., Fout, T., et al. (2021) "Towards improved cost evaluation of Carbon Capture and Storage from industry," *International Journal of Greenhouse Gas Control* 106 https://doi.org/10.1016/j.ijggc.2021.103263

[66] Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N. et al. (2020) "The climate change mitigation potential of bioenergy with carbon capture and storage," *Nature Climate Change* 10, 1023–1029 https://doi.org/10.1038/s41558-020-0885-y

[67] McQueen, N., et al (2021) "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future," *Progress in Energy* 3, 032001 DOI 10.1088/2516-1083/abf1ce

[68] Realmonte, G., Drouet, L., Gambhir, A. et al. (2019) "An inter-model assessment of the role of direct air capture in deep mitigation pathways," *Nature Communications* 10, 3277 https://doi.org/10.1038/s41467-019-10842-5

[69] Mikulčić, H., Skov, I.R., Dominković, D.F., et al. (2019) "Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO_2," *Renewable and Sustainable Energy Reviews*, 114 https://doi.org/10.1016/j.rser.2019.109338

[70] Enhanced oil recovery is an advanced process for extracting oil from reservoirs.

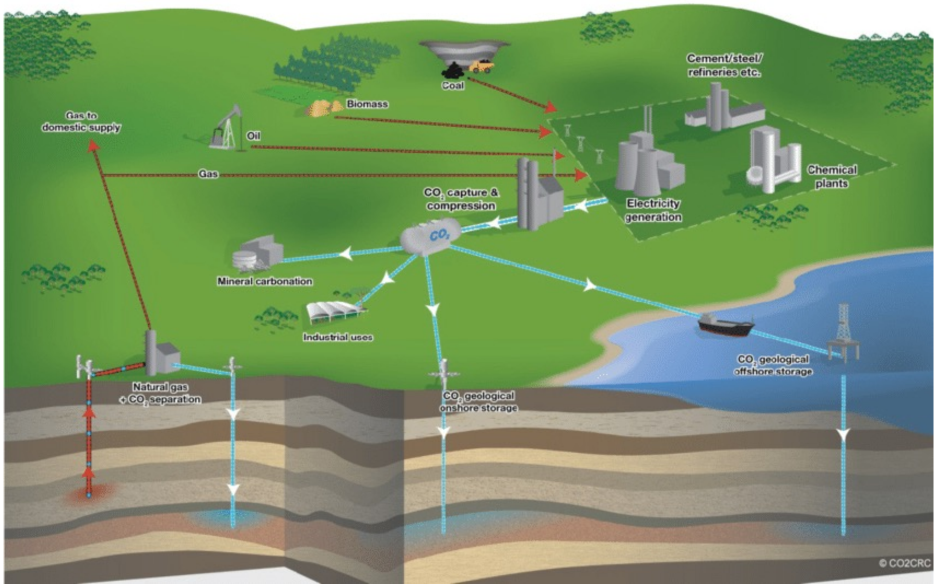

Figure 5. Carbon Capture, Utilization, and Storage Value Chains (Source: CO2CRC 2012)

We believe deploying CCUS technologies will start from large-scale applications to leverage economies of scale. Due to the associated high costs and technological and regulatory uncertainties, players along the impacted value chains must work together to deploy the required technology and enabling infrastructure from capturing to storage. Since large-scale applications - such as power plants - are often located far away from oil and gas reservoirs or saline aquifers, accomplishing storage at the capture site will not be generally feasible. Hence adoption will drive integrated scenarios to de-risk adoption and deployment.[71]

On the other hand, DAC technologies – which are still in the early development stages – will push for segmentation scenarios. This is because while potential customers will span multiple industries, most would derive little to no strategic value from trying to develop proprietary carbon capture technologies. Stakeholders will, therefore rather, hire highly specialized players with the needed technological and engineering know-how, thus replicating the business model of oilfield service companies.

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[71] Quarton, C.J., and Samsatli, S. (2020) "The value of hydrogen and carbon capture, storage and utilisation in decarbonising energy: Insights from integrated value chain optimization," *Applied Energy* 257, 113936 https://doi.org/10.1016/j.apenergy.2019.113936

4.3 **Blockchain Technology**

A blockchain is a shared, decentralized, and immutable[72] digital ledger that securely stores transactions and enables the automated execution of "smart contracts"[73] among parties without a central authority or intermediaries.[74,75,76] At its core, the technology consists of a distributed network of independent computers, or nodes, that manages the blockchain; the nodes receive new transactions, review their legitimacy based on consensus protocols, and integrate them into a chain (Figure 6). Blockchain technology has already demonstrated its innovation potential in the financial sector thanks to its unique structural advantages of immutability, efficiency, control, and security.[77] These properties make blockchain well-suited to optimize processes, enable novel business solutions,[78] and promote greater access to services for a broader range of users by significantly reducing costs. However, significant challenges must be addressed to foster adoption, such as interoperability between blockchain networks, user trust, and energy consumption.[79]

Thanks to the above characteristics, blockchain technology could be key in accelerating the transition to a low-carbon economy and the adoption of innovative technologies at scale. For example, as energy systems increasingly evolve from centralized to decentralized, from "grey" to "green," stakeholders will need to efficiently account for and track emissions and green molecules in a transparent, secure, and standardized way and to do so along value chains from production to consumption. This will require the ability to process large volumes of multi-party transactions in a scalable, secure, and efficient manner. Today, the

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[72] In a distributed ledger, a hypothetical hacker would need to be able to modify the recorded information on multiple nodes simultaneously.

[73] Smart contracts are programs stored on a blockchain that run when predetermined conditions are met. They are typically used to automate the execution of an agreement so that all participants can be immediately certain of the outcome, without any intermediary's involvement or time loss. They can also automate a workflow, triggering the next action when specific conditions are met.

[74] Swan, M. (2015), "Blockchain: Blueprint for a new economy," O'Reilly Media Inc.

[75] Ali, O., et al. (2021) "A Comparative Study: Blockchain Technology Utilization Benefits, Challenges and Functionalities," in *IEEE Access*, vol. 9, pp. 12730-12749 doi: 10.1109/ACCESS.2021.3050241.

[76] Javaid, M., et al. (2021) "Blockchain technology applications for Industry 4.0: A literature-based review," Blockchain Research and Applications 2 (4) https://doi.org/10.1016/j.bcra.2021.100027

[77] Guo, H., and Yu, X. (2022) "A survey on blockchain technology and its security," Blockchain: Research and Applications 3 (2) https://doi.org/10.1016/j.bcra.2022.100067

[78] Morkunas, V.J., Paschen, J., Boon, E. (2019) "How blockchain technologies impact your business model," Business Horizons 62 (3) 295-306 https://doi.org/10.1016/j.bushor.2019.01.009

[79] Sedlmeir, J., et al. (2020) "The Energy Consumption of Blockchain Technology: Beyond Myth," *Business Information Systems Engineering* 62, 599–608 https://doi.org/10.1007/s12599-020-00656-x

origin of a commodity is certified through certificates of origin. However, the process is complex, requiring many intermediaries that add time, labor, and cost burdens. Furthermore, concerns over whether commodities are accurately counted and traded pose challenges to scalability.[80]

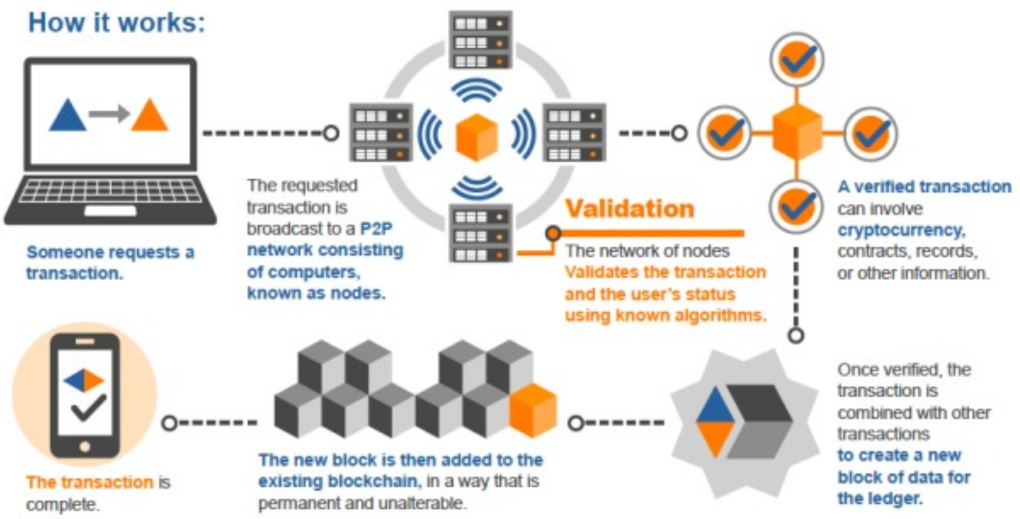

Figure 6. Blockchain Technology (Source: PwC)

But what does this mean in practice? In green hydrogen value chains, stakeholders must be appropriately credited for investing in the current premium required to produce carbon-free hydrogen. Therefore, the ability to verify a hydrogen molecule's origin from clean energy sources amidst a dynamic energy landscape presents a crucial and strategic value proposition central to success. Hence the actual value of these blockchain applications lies in the ability to integrate disparate stakeholders to create unified, reliable, and accessible depositories. Integrating digital sensors to track green molecules and securely validate data from multiple stakeholders will therefore drive integration scenarios.

While the true value proposition of blockchain technologies in the energy sector lies in their ability to integrate stakeholders, which are becoming increasingly decentralized, there are still components of the value chain that will drive segmentation. As the Internet of Things (IoT) and blockchain applications proliferate in the energy sector,[81] the deployment of digital sensors will be crucial

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[80] De Blasio, N. and Hua, C. (2021) "The Role of Blockchain in Green Hydrogen Value Chains," Policy Brief, Belfer Center for Science and International Affairs, Harvard Kennedy School.

[81] Alsharari, N. (2021) "Integrating Blockchain Technology with Internet of Things to Efficiency," *International Journal of Technology, Innovation, & Management* 1 (2) pp. 01–13 https://doi.org/10.54489/ijtim.v1i2.25

to tracking, monitoring, and operating energy infrastructure. Still, as in the case of the oilfield equipment and service industry, current players assign low strategic value to developing proprietary advanced IoT device technologies and particularly have little incentive and substantial risks to implement custom blockchain interfaces. As a result, specialized players possessing the required blockchain and IoT-related competencies will emerge, leading to segmentation scenarios.

4.4 **Summary Comparison**

In summary, the three criteria of Strategic Value (SV), Techno-Economic Relatedness (TER), and Risk are crucial to elucidating the key strategic options available to stakeholders. It should be noted that the selected case studies (Table 1) are essential for the energy transition and were explicitly chosen for relevance. The strategic value ranking for each reflects this selection bias as we consider each technology from the perspective of its most relevant stakeholder. Furthermore, the classification in each column (SV, TER, and Risk) highly depends on the specific stakeholder and the opportunity at hand. For example, CCUS technology may have little to no value for stakeholders active only in green hydrogen[82] value chains and vice versa.

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[82] Green or renewable hydrogen refers to hydrogen produced from renewable energy sources like wind and solar through a process known as water electrolysis, where an electrolyzer splits water molecules into oxygen and hydrogen. There are no CO_2 emissions generated during the production process. Today, green hydrogen costs are significantly more than those from fossil fuels even with CCUS.

Technology	Application	Scenario	SV	TER	Risk
Hydrogen	Stationary	Integration	High	Function of Stakeholder	Technology, cost, infrastructure, regulatory
	Mobility	Segmentation	High	Function of Stakeholder	Cost, infrastructure
CCUS	Sequestration	Integration	High	Function of Stakeholder	Cost, infrastructure, regulatory
	DAC	Segmentation	High	Function of Stakeholder	Technology, cost, infrastructure, regulatory
Blockchain	Emissions & Green Molecules Tracking	Integration	High	Function of Stakeholder	Technology, regulatory
	IoT and Smart Sensors	Segmentation	High	Function of Stakeholder	Technology

Table 1. Case Studies on Technology Innovation Adoption and Energy Value Chains

4.5 **Value Chain Evaluation Mapping**

Qualitative Value Chain Evaluation Maps (VCEM) can help better clarify the dynamics at play and the resulting integration or segmentation scenarios. VCEMs can be drawn from either a technology or a company/stakeholder perspective (Figures 10-11). However, the former is better suited to representing the impact of innovative technologies adoption on value chains. On the other hand, the latter provides stakeholders with the means to better assess innovation portfolio opportunities. The following section focuses on three technological and two stakeholder perspectives. Stationary hydrogen (Figure 7), CCUS (Figure 8), and blockchain for emission and green molecules certification and tracking (Figure 9) for the former and service (Figure 10) and energy companies (Figure 11) for the latter.

Technology Perspective – Stationary Hydrogen

A VCEM analysis of stationary hydrogen applications results in different outcomes depending on the stakeholder: independent execution in the case of energy companies and either a push for know-how development and acquisition or exiting the market opportunity in the case of service companies. This is because service companies have significantly lower expertise and presence in today's hydrogen markets than energy companies. Regardless, adoption at scale would drive for a segmentation scenario, although, in the case of service companies, higher risk factors could significantly increase the push for integration.

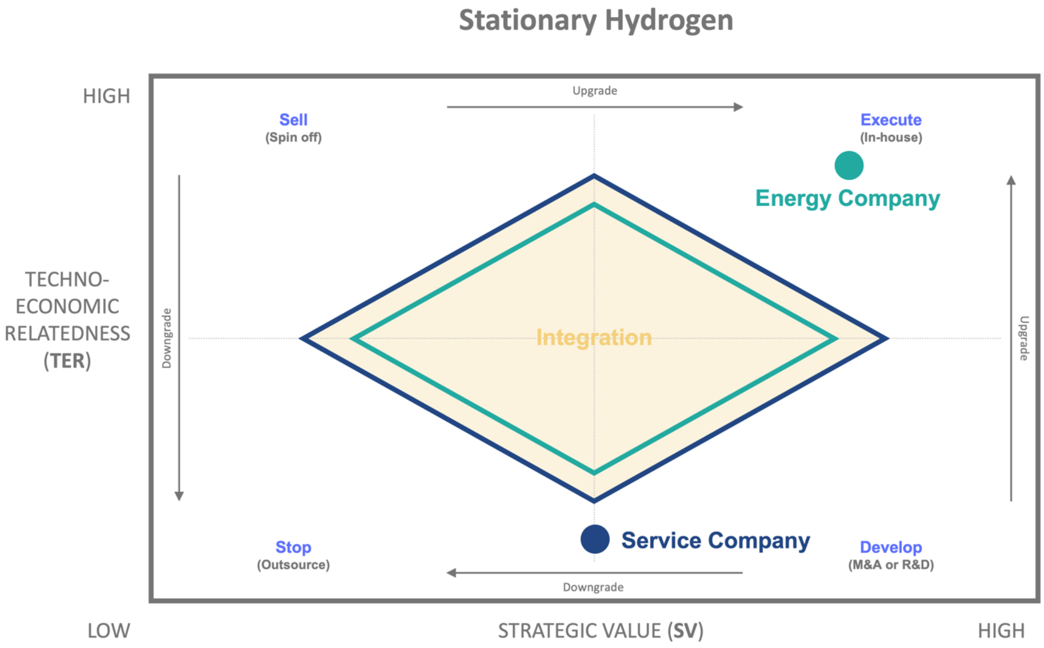

Figure 7. Stationary Hydrogen Value Chain Opportunity Map (Source: Authors' Elaboration)

Stationary H_2	SV	TER	Risk	Result
Service Company	Med	Low	Med	Segmentation
Energy Company	High	High	Med-Low	Segmentation

Technology Perspective – CCUS

While energy and service companies both hold extensive presence and expertise in CCUS technologies and applications, a VCEM analysis results in integration scenarios regardless of the stakeholder due to the high infrastructure, regulatory, and cost-risk profiles.

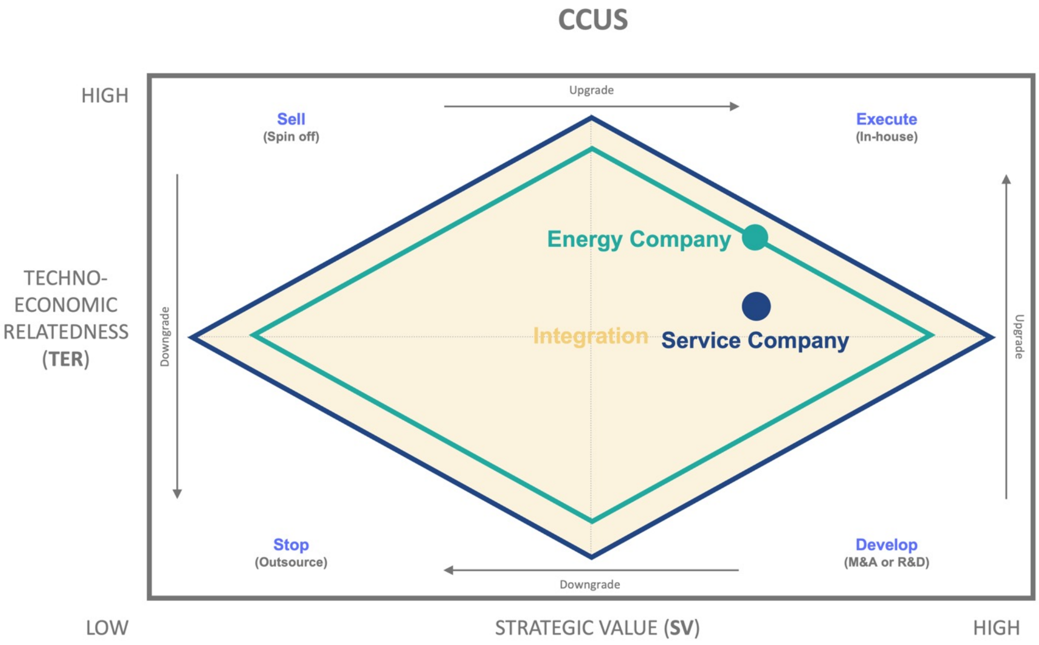

Figure 8. CCUS Value Chain Opportunity Map (Source: Authors' Elaboration)

CCUS	SV	TER	Risk	Result
Service Company	High	Med-High	High	Integration
Energy Company	High	High	Med-High	Integration

Technology Perspective – Blockchain for emission and green molecules certification and tracking

Due to the technological, infrastructural, and regulatory challenges associated with blockchain applications in the energy sector, a VCEM analysis results in integration scenarios for all stakeholders. At the same time, energy companies should evaluate know-how development or acquisition to deploy applications at scale.

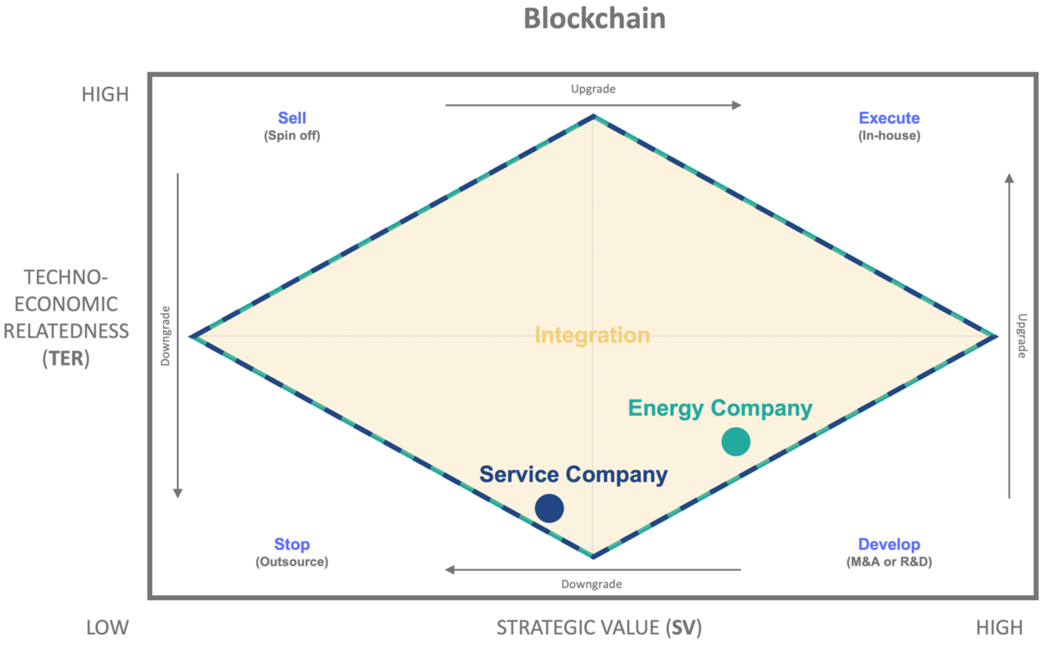

Figure 9. Blockchain Value Chain Opportunity Map (Source: Authors' Elaboration)

Blockchain	SV	TER	Risk	Result
Service Company	Med	Low	High	Integration
Energy Company	Med-High	Low	High	Integration

Stakeholder Perspective – Service Companies

An innovation portfolio analysis shows how for service companies, CCUS adoption would align with today's expertise and market positioning; securing the potential benefits of stationary hydrogen and blockchain applications would require a significant change in business strategy.

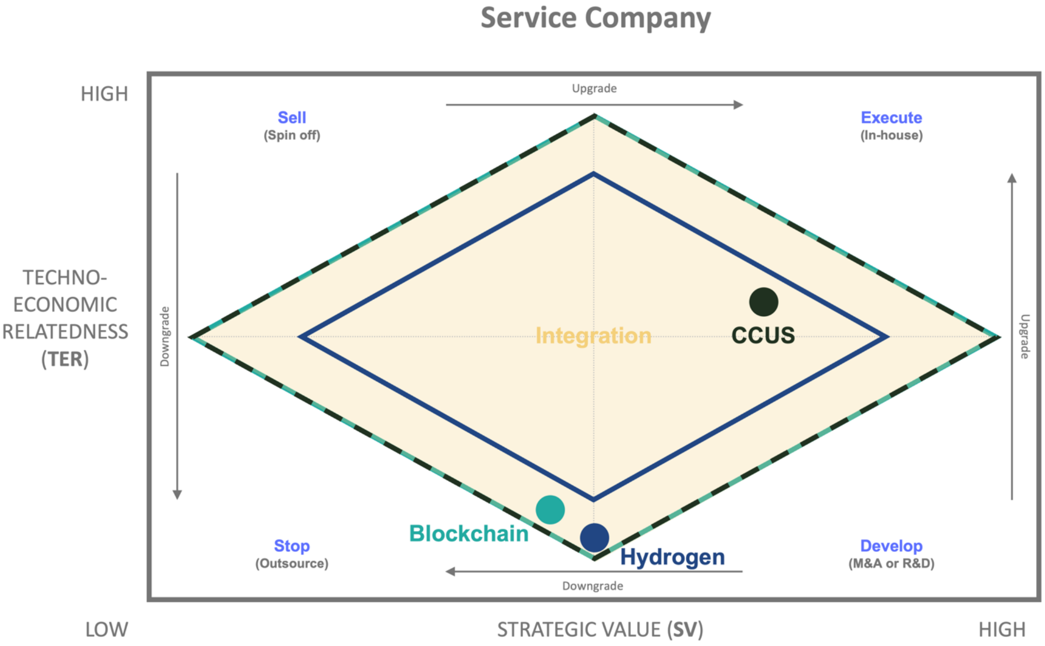

Figure 10. Service Company Value Chain Opportunity Map (Source: Authors' Elaboration)

Service Company	SV	TER	Risk	Result
Stationary H2	Med	Low	Med	Segmentation
CCUS	High	Med-High	High	Integration
Blockchain	Med	Low	High	Integration

Stakeholder Perspective – Energy Companies

An innovation portfolio analysis shows how energy companies could leverage significant opportunities in all three areas, with hydrogen being the clear potential outlier. This is because CCUS and blockchain applications would require integrated scenarios due to the higher risk factors.

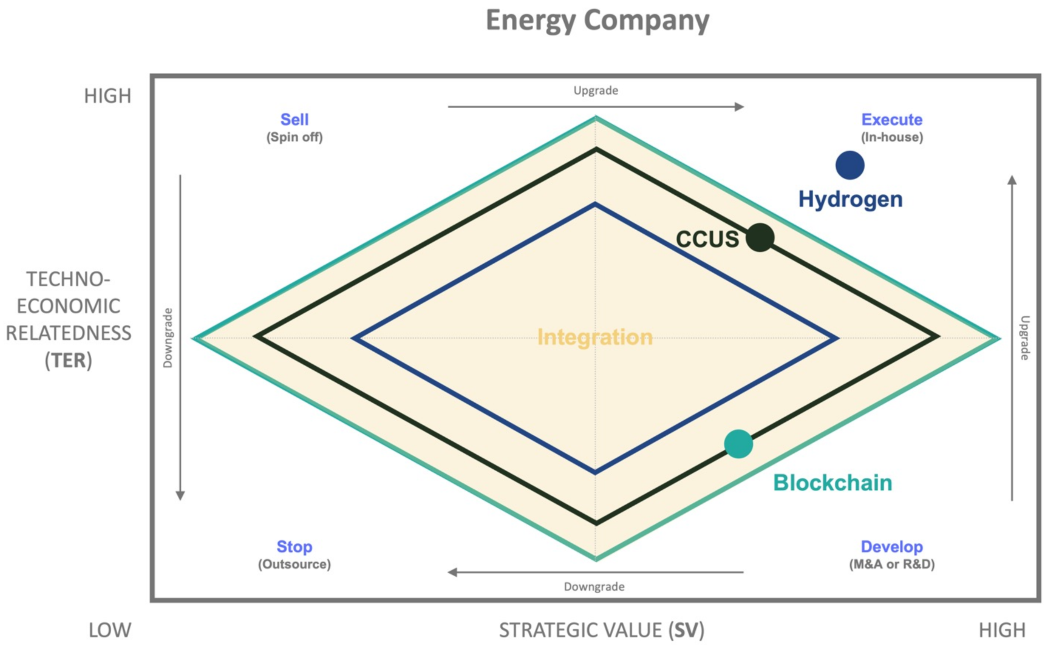

Figure 11. Energy Company Value Chain Opportunity Map (Source: Authors' Elaboration)

Energy Company	SV	TER	Risk	Result
Stationary H2	High	High	Med-Low	Segmentation
CCUS	High	High	Med-High	Integration
Blockchain	Med-High	Low	High	Integration

5. Conclusions & Recommendations

The transition toward a more decarbonized and decentralized future spurred by technological innovation requires the public and private sectors to work together to rethink their roles. As new technologies and processes develop to sustain growing energy needs, understanding how these will impact existing value chains or cause new ones to emerge is crucial for navigating the energy transition successfully. To catalyze the development and deployment of innovation at scale, we have identified the following necessary steps:

- **Recognize and address the new geopolitical dynamics of a world less reliant on fossil fuels and the political push for self-sufficiency and strategic independence.** For example, if renewable hydrogen were to be adopted at scale, future market dynamics would likely resemble today's regional natural gas markets—with the corresponding potential for geopolitical conflict. On the one hand, nations must evaluate which role they will want to play in emerging energy systems. Resource-rich countries must implement policies to trigger technology innovation and infrastructure investments. In contrast, importing countries must prepare and embrace strategic long-term supply diversification to increase national security. In both cases, the private sector must assess key strategic options and adapt to new market dynamics to achieve long-term value creation and resilience.

- **Identify key technologies driving disruptive change and examine how value chains will evolve or how new ones will emerge.** This will require recognizing integration and segmentation scenarios and their impact on market dynamics and infrastructure needs. To do so, we propose the Value Chain Evaluation Framework, which provides a comprehensive analysis tool based on three key variables: Strategic Alignment, Techno-Economic Relatedness, and Risk.

- **Define clear government policies and regulations based on the detailed analysis of value chain scenarios.** Only a more profound understanding of

> these dynamics will allow policymakers and corporate investors to better navigate the opportunities that decarbonization will bring. In order to build the resilient energy systems of the future and tackle climate change, countries will need to develop industrial policies designed to leverage their comparative advantages while incentivizing internal competition in high-value-added sectors. Policymakers will need to facilitate the creation and growth of new markets, address capital misallocation across sectors, help de-risk investments, promote innovation to drive robust growth and strengthen participation and integration in global value chains.

Success is possible, but only a cohesive and collective understanding of how energy value chains will evolve will enable each participant to take the best course of action to prepare for and succeed in the energy transition. Stakeholders who can embrace the new energy landscape will gain significant competitive advantages, while the others risk fading into obsolescence.

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