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Green Hydrogen

Strategic Frameworks for Technology Selection, Infrastructure Integration, and Partnership Optimization Across the Hydrogen Value Chain Through 2035

May 2025

Green Hydrogen: A clean alternative

Green hydrogen's pivotal role in global decarbonization

- Planned green and blue hydrogen production through 2030 now exceeds 26 million metric tons annually — a 4x increase since 2020.
- Global demand for clean hydrogen could reach ~660 million metric tons per year by 2050.
- Clean hydrogen production costs are expected to decline rapidly over the next decade.
- At a production cost of ~$2/kg, clean hydrogen could become cost competitive across many applications.
- In 2050, hydrogen could contribute more than 20 percent of annual global emissions reductions.

Source: McKinsey & Company, "Five charts on hydrogen's role in a net-zero future", 2022.

Market Drivers

While each stage of the green hydrogen value chain - production, storage, transportation, end-use, and system integration - faces its own unique challenges and drivers, there are five overarching forces shaping progress across the entire ecosystem

- Technological Advancements Across the Value Chain
- Declining Renewable Energy Costs
- Policy Support and Regulatory Standardization
- Emerging Infrastructure and System Integration
- Corporate Commitments and Sector-Specific Adoption

Understanding the Hydrogen Infrastructure Value Chain

Electricity Generation
Renewable Energy Generation

Hydrogen Production
- Biothermal Chemical Processes
- Biological Processes
- Photoelectrochemical Water Splitting
- Electrolysis Water Splitting
- Solar Thermochemical Water Splitting

Logistics

Storage
- Compression
- Chemisorption
- Physisorption
- Liquefaction

Transportation
- Pipelines
- Rail
- Trucks
- Ships

Long Term Storage

Applications
- Refineries
- Chemical Industry
- Ammonia Production
- Steel Industry
- Power Sector
- Transport Sector
- Heating Sector

ICP Highlight

Major Energy Players
- For all applications, demand for green hydrogen increases demand for renewable and low-carbon energy

Industrial Manufacturing & Heavy Industry
- The physical form and logistics of hydrogen delivery will determine the complexity and design of on-site operations in heavy industry.

Infrastructure in buildings & Utilities
- The adoption of hydrogen technologies will disrupt standardized HVAC systems in buildings.

Critical Interfaces-Economics

Electricity Generation – Hydrogen Production
- Electricity is the largest input cost for hydrogen production; the price, availability, and reliability of renewable electricity ultimately determine whether green hydrogen is cost-competitive.

Hydrogen Production – Logistics
- Methods to prepare hydrogen for storage and/or transport are energy-intensive and capital-heavy.

Logistics – Applications
- Inefficiencies in storage, transportation, and preparation methods can increase delivered hydrogen costs by 30–50%.

Infrastructure

Electricity Generation – Hydrogen Production
- Proximity to renewable energy sources reduces transmission losses and grid ~~reliance~~ dependence.

Hydrogen Production – Logistics
- Connecting hydrogen production to storage and transportation networks requires investment in preparation units and storage tanks

Logistics – Applications
- Different applications require hydrogen in specific states or formats, each with transport challenges and infrastructure demands.

Project Development

Green hydrogen, provides a zero-carbon, high-efficiency energy carrier that enables the decarbonization of hard-to-electrify sectors such as long-haul freight, steel, cement, and petrochemicals. Compared to other decarbonization pathways such as carbon capture or electrification, green hydrogen allows for direct replacement of fossil fuels in industrial heat, transportation fuels, and feedstocks without legacy infrastructure dependency.

Green hydrogen strengthens grid resilience by acting as both a clean fuel and a flexible energy storage medium. Electrification-only strategies can worsen grid congestion and need transmission upgrades. Green hydrogen provides demand flexibility and load balancing: supporting non-wire alternatives, optimizes grid and reduces dependency on centralized infrastructure - lowering complexity for hard-to-electrify applications.

Company	Technology	Specification	Impact
Shell	Electrolyzer (Germany)	10 MW electrolyzer in refinery	15–20% CO_2 reduction vs. 2016 levels
First Hydrogen	Green H_2 production + vehicle assembly	50 MW green H_2 plant + 25,000 vehicle/yr capacity	800k tonnes GHG reduction annually in Québec
World Energy G2	Wind-powered H_2 → Green ammonia	4 GW onshore wind, 280k t/y H_2 → 1.6M t/y green ammonia	850k tonnes GHG offset annually
TES Canada	H_2 for mobility + synthetic gas	Project Mauricie: H_2 split — 1/3 for FCEVs, 2/3 for RNG	800k tonnes GHG reduction (3% of Québec total)
Irving Oil	PEM electrolyzer blending in SMR	5 MW PEM electrolyzer installed at refinery	30% GHG reduction by 2030
Dow + Linde	Clean H_2 + CCS for ethylene cracker	\$2B+ H_2 facility with CCS at Fort Saskatchewan, 2M+ tons CO_2 captured	World's first net-zero ethylene cracker
Hydro-Québec	Grid storage using green hydrogen	Stores excess hydropower as H_2; reuses when demand increases	Boosts energy availability & reliability (figures not disclosed)
Enbridge Gas	Power-to-gas blending	2.5 MW facility, ~3,600 households, up to 2% H_2 blend	Grid stability + reduced emissions
ATCO + Suncor	CCS + low-carbon H_2	CCS-based H_2 for refining; ATCO handles infra, Suncor operates production	>2M tonnes CO_2 reduction annually in Alberta

Production

Hygreen energy
EVERWIND FUELS
AATRAL H_2
CPH2 CLEAN POWER HYDROGEN
HY2GEN
ohmium
H2APEX
Z·E·G
VERDAGY
sunfire
elogen
Lhyfe
PLAGAZI GREEN HYDROGEN FROM WASTE
H_2PRO
ITM
ceres
SH
PEREGRINE

Utilization

Transport & Industry

H2greensteel
TECO 2030
NAMX
ZEROAVIA
hps
azolla HYDROGEN
TITAN HYDROGEN
KEYOU
Fly-Box

Fuel Cells

BALLARD
SYMBIO
FTXT 未势能源
HDF ENERGY
XYDROGEN
HydroLite
AFC Energy
NUVERA
Helion by ALSTOM
Horizon
NOWOGEN
REFIRE

Systems and Integration

hypion
HydroGain
HYGENCO
hydgenfuel
HRS
KAIZEN Clean Energy
Hydrogen Optimized
PowiDian Energy
h2 green
nel
HYREX
H2 Core Systems

Storage and Distribution

NPROXX
H2 vector
Immaterial
STEELHEAD COMPOSITES
GKN HYDROGEN
PROVARIS
H2M
VOYEX
Hynion
CARBON 280
KONTAK
HEXAGON PURUS
AVRTON

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Green Hydrogen

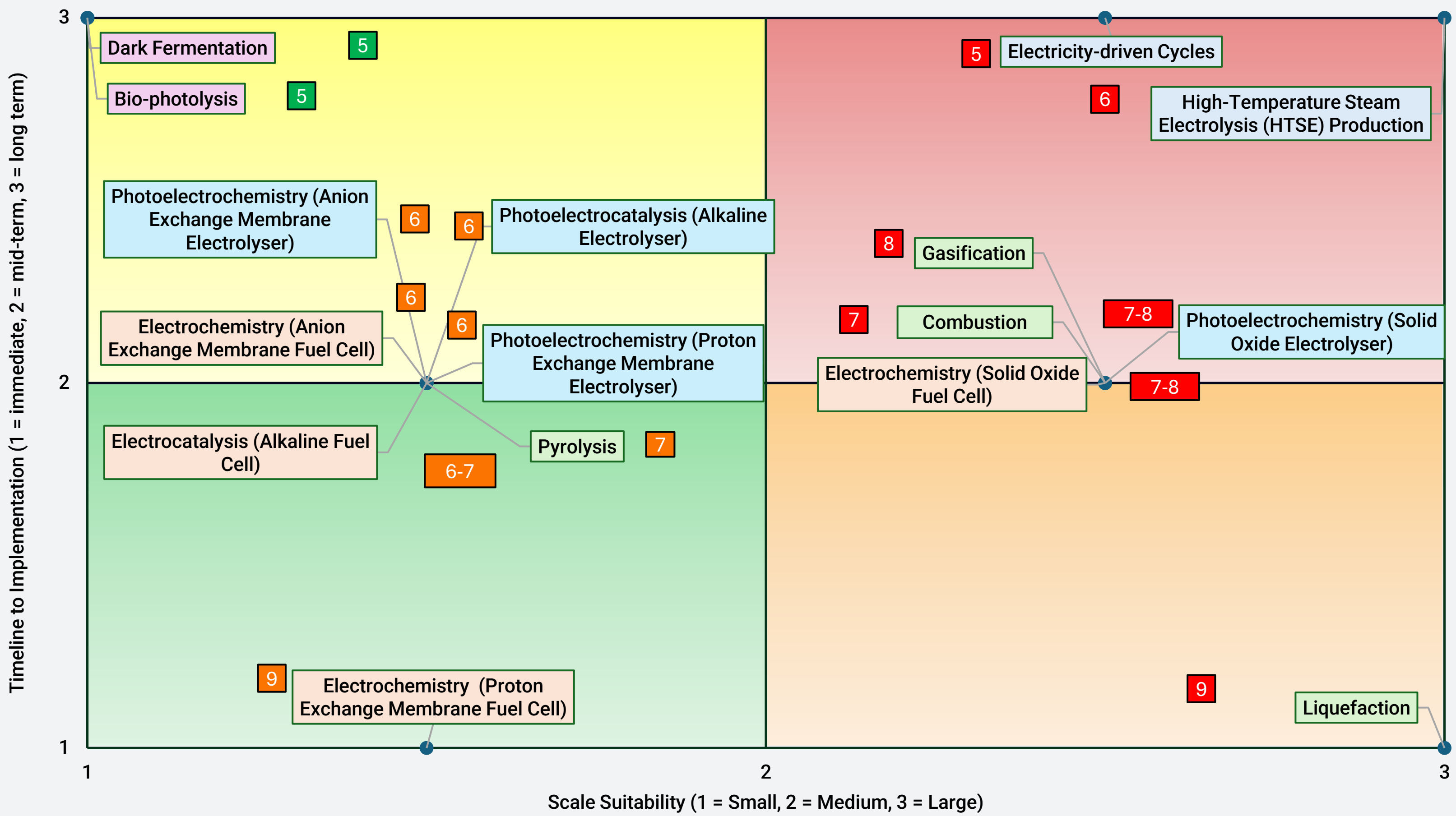
Source: Climate Insider Intelligence Platform

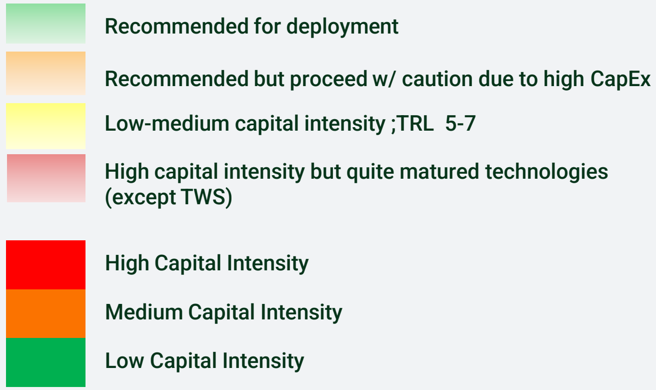
(non exhaustive, focused on startups)

Hydrogen Production Technologies – Strategic Summary

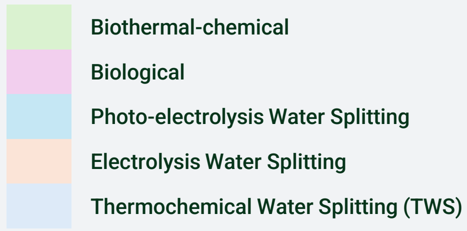
Technology Pathway	Readiness & Efficiency	Key Advantages	Primary Challenges	Use Cases	Example Deployment
1. Biothermal-Chemical (Gasification, Pyrolysis, Combustion, Liquefaction)	• Early to Mid-Stage • High Temp: 250–1500°C • Pressure: 10–30 MPa	• Renewable waste feedstock • Potential for carbon neutrality • Value-added byproducts (e.g. biochar, syngas)	• Expensive, complex equipment • Logistics-sensitive • Inconsistent product quality	• Waste-to-energy • Industrial CHP • Distributed conversion	SGH2 Energy Global (plasma gasification), Air Liquide (bio-H_2 + liquefaction)
2. Biological Processes (Dark Fermentation, Bio-photolysis)	• Very Early Stage • Low Temp: 30–50°C	• Zero-emission potential • Low energy input • Versatile organic feedstocks	• Low H_2 yield • Scale-up difficulty • Bioreactor complexity	• Municipal/agricultural waste conversion • Algae/biohybrid systems	Alps Ecoscience (biohythane via waste streams)
3. Photoelectrolysis (Various photoelectrochemical cells)	• Early-StageEff. ~60–90% (tech-dependent)	• High purity H_2 • Solar-ready integration • Low emissions	• Durability issues • Cost & scalability • Sensitive to environmental conditions	• Off-grid, solar-aligned production • Portable and modular setups	None listed (R&D level)
4. Electrolysis (Water Splitting) (PEM, Alkaline, Solid Oxide, AEM)	• Mid to Commercial • Eff. ~40–60% (up to 85%) • Durability: 20k–90k hours	• Mature supply chains • High efficiency • Modular, decentralized options	• Thermal & water management • Durability risks • Material cost	• Grid-connected or off-grid H_2 • Industrial and mobility sectors	Hydro-Québec Green H_2 Plant Sunfire – MultiPLHY project
5. Thermochemical Water Splitting (HTSE, Electrolytic Cycles)	• Early-stage Demo • Temp: 500–2000°C	• Integrates with nuclear/solar • High theoretical efficiency • Continuous H_2 production	• Material degradation • Complex thermal recovery • Requires high-temp heat	• Large-scale industrial use • Hybrid with nuclear/solar • Power-to-X (P2X)	NTPC – India (HTSE pilot with power plant integration)

From Lab to Launch: Visualizing Readiness Across Hydrogen Pathways





TRL	Definition	Key Criteria
5–6	Lab-scale or small-scale pilot testing. Technology has been validated in a simulated or limited environment.	Pilot <1 MW- Focus on component R&D- No commercial deployments
7–8	Pre-commercial demonstration. Integrated system tested in operational environment at meaningful scale.	Pilot 1–10 MW- At least one full system demo- Deployment confirmed but limited
9	Fully commercialized. Technology deployed in real environments at commercial scale across multiple use cases.	≥2 commercial systems >10 MW- TRL validated by OEMs and regulators- Deployed across industries/geographies



Greenfield Hydrogen Infrastructure Conversion Roadmap

Phase 1: Strategic Site Framing (2025–2026)

Identify optimal project sites with access to low-cost renewables, water, and end-use demand. Ensure locational synergies that reduce logistics and interconnection risk.

Activity
- GIS + techno-economic site modeling
- Engage offtakers for early MoUs
- Analyze interconnection and grid support options

Go/No-Go Trigger
- No competitive land access or zoning approvals
- RE intermittency too high for stable H_2 output
- Anchor demand too fragmented or uncertain

Alternative Pathway
- Co-locate near existing industrial zones
- Use hybrid solar/wind for better supply profile
- Shift to export-only model (e.g., ammonia)

Phase 2: Infrastructure Stack Design (2026–2027)

Define the full hydrogen production-to-delivery system architecture based on project scale, energy profile, and cost targets. Ensure technical compatibility and flexibility from the outset.

Activity
- Tech selection (PEM, SOEC, AEM, etc.) based on scale and timeline
- Integrate water treatment, compression, storage tech
- Simulate system-level energy efficiency

Go/No-Go Trigger
- Electrolyzer supply lead time exceeds build schedule
- Water source inadequate or costly to treat
- No viable downstream transport model

Alternative Pathway
- Use distributed H_2 clusters instead of centralized hubs
- Deploy modular electrolyzer skids
- Switch to LOHC or ammonia transport formats

Phase 3: Permitting & Funding Gate (2027–2029)

Secure critical regulatory approvals, close financing gaps, and confirm offtake to move toward Final Investment Decision (FID). De-risk early-stage exposure before construction.

Activity
- Secure EIA + hydrogen-specific permits
- Submit grant proposals and investor decks
- Finalize EPC bid packages and risk insurance

Go/No-Go Trigger
- Delays in major permits or stakeholder opposition
- Funding gap exceeds de-risking buffer
- No offtake lock-in to support FID

Alternative Pathway
- Phase project into 10–30 MW tranches
- Switch to BOO or PPP model with infra partners
- Seek export pre-orders to guarantee demand

Phase 4: Phased Build & Commissioning (2030–2032)

Execute pilot-scale builds and validate real-world performance across electrolyzer, storage, and transport systems. Establish reliability, safety, and integration readiness.

Activity
- Construct initial MW-scale pilot plant
- Test end-to-end output, storage, and dispatch
- Calibrate controls, safety, and contingency plans

Go/No-Go Trigger
- Interoperability failures across subsystems
- Safety violations during testing
- Initial CapEx overrun >15%

Alternative Pathway
- Lock in backup OEMs and tech suppliers
- Segment operations into manageable zones
- Re-design with simplified process layout

Phase 5: Market Activation & Backbone Integration (2033–2035)

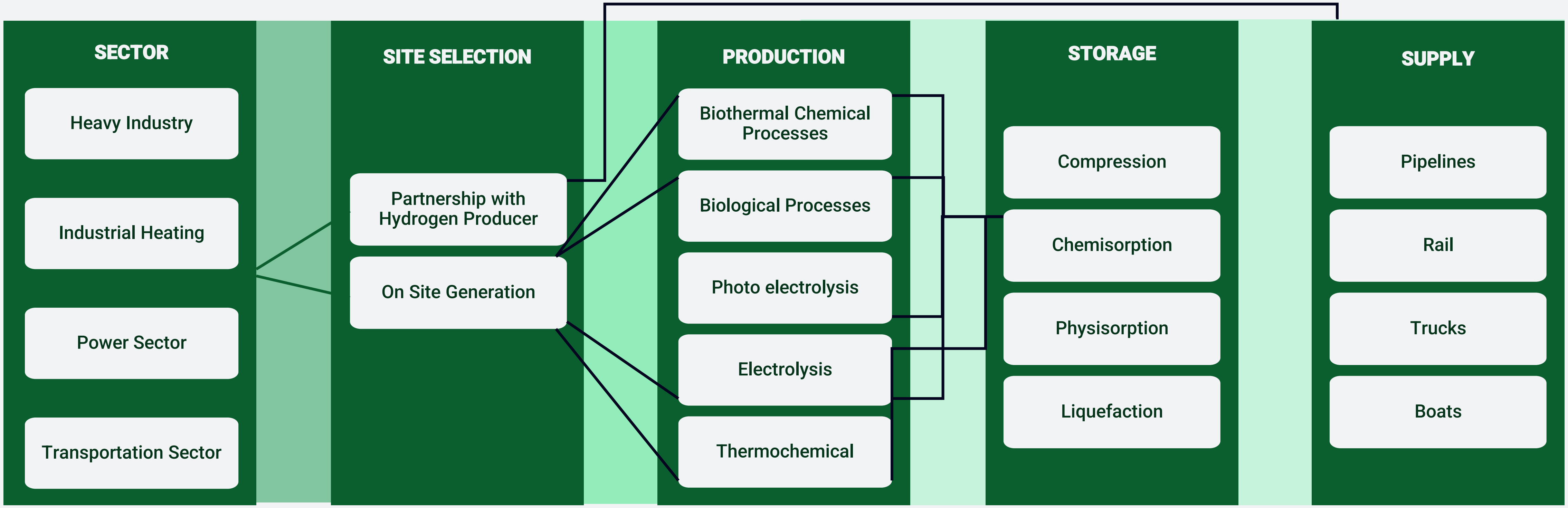
Activate supply routes to mobility hubs, industrial users, or export markets. Enable long-term scalability via pipeline, port, or backbone infrastructure connectivity.

Activity
- Enable dispatch to industrial clusters, mobility hubs, or ports
- Build or link into regional H_2 backbone
- Certify export-grade purity & compliance

Go/No-Go Trigger
- No domestic uptake at viable price point
- Pipeline connection delayed or infeasible
- Regulatory blocks on cross-border sales

Alternative Pathway
- Create “H_2 islands” for industrial use only
- Shift to trucking or ammonia export
- Enable storage buffering until infra catches up

Practical Hydrogen Solutions Integration Roadmap



Decision 1:
Where will the hydrogen supply come from?

Assessment Criteria
- Availability of partner
- Available Funding
- Conditions (Pressure, Temperature, State) Hydrogen can be supplied in

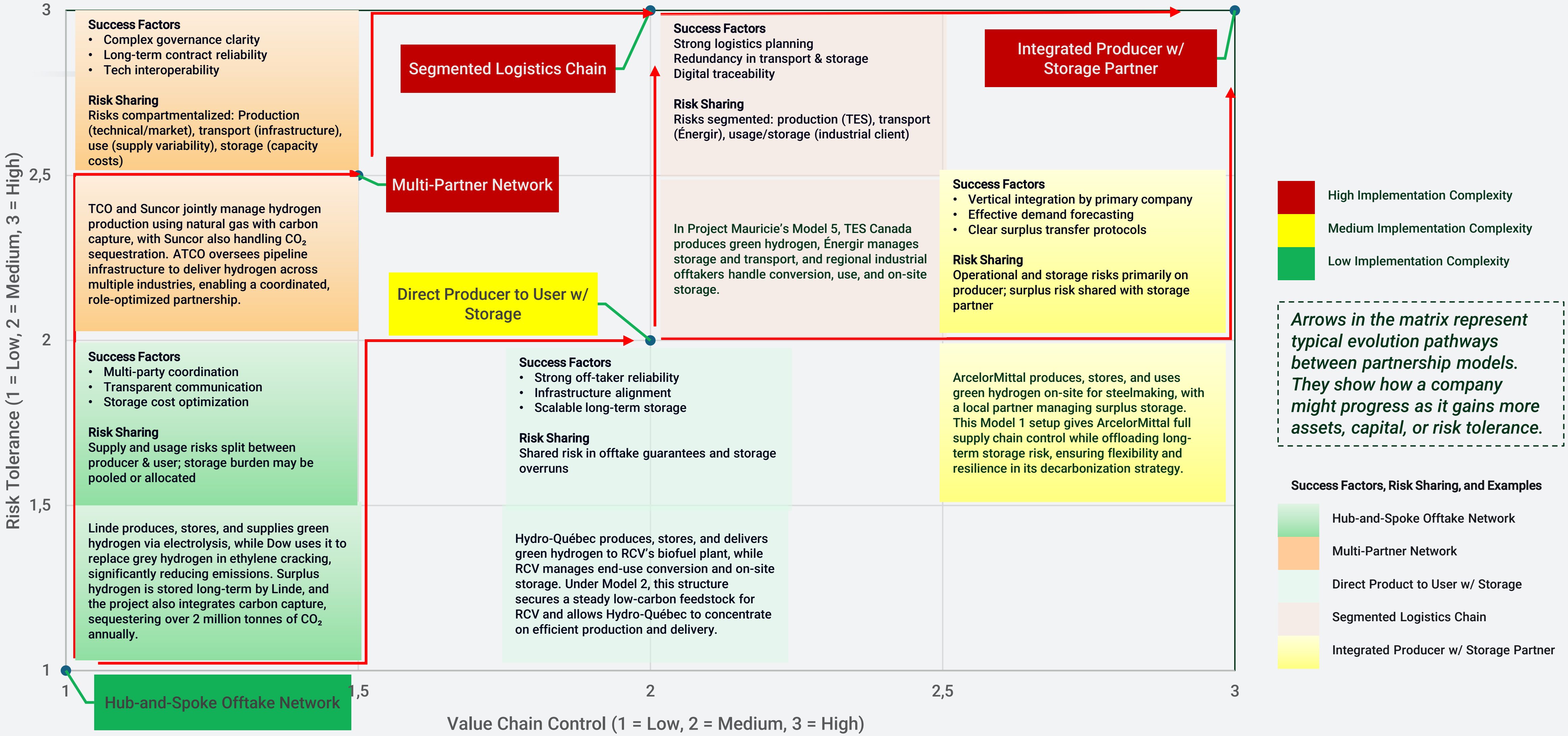
Decision 1.5:
Choose Production Type

Assessment Criteria
- Raw Hydrogen Purity
- Contaminates and Postproduction Cleaning
- Feedstock Integration into Circular Economy
- Scalability (Equipment Availability, Integrations)
- Long Term Operational Stability

Decision 2: Choose hydrogen state for transportation and transportation method (choices are interconnected)

Assessment Criteria
- Conditions (Pressure, Temperature)
- Transportation Risks
- Scalability (Equipment Availability, Integrations)
- Long Term Operational Stability

Green Hydrogen Partnership Models: Strategic Fit & Evolution Pathways



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