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A Theory of Rapid Transition

How S-Curves Work and What We Can Do to Accelerate Them

By Laurens Speelman and Yuki Numata
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Series Overview

In our *Peaking Series*, we introduced *The Peak, Plateau, and Decline* and presented historical examples to show how demand for fossil fuels faces inevitable decline.

In this article, we describe the dynamics behind the S-curve growth that underpins the adoption rate of innovations.

1. Summary

The adoption rate of innovations is non-linear; it is slow at first, then rapidly rises before flattening out again as it reaches market saturation. Such trajectories of growth are commonly known as the S-curve. The rapidly rising part of the S-curve is often underestimated in projections and expectations of new technologies. This is exactly what has happened with wind, batteries, and solar technologies in the past decade, with prices dropping faster and further than many believed possible. The rapid rise of these technologies is now leading to the peaking and decline of fossil fuel demand.

The shape of the S-curve is a result of system feedbacks such as learning curves, economies of scale, technological reinforcement, and social diffusion. The process of an S-curve is complex and context specific, and some innovations are more likely to scale than others, but all transitions follow the same pattern of shifting dynamics:

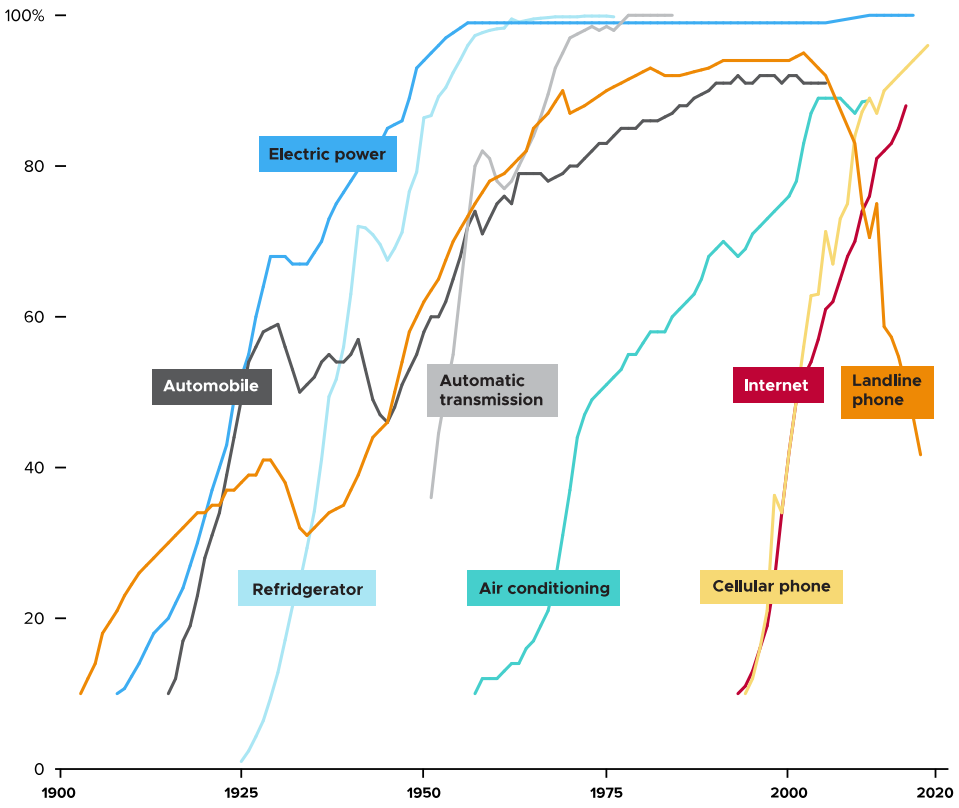
- **Phase 1:** Visionaries recognize a problem or opportunity and conceptualize a better way to do things.
- **Phase 2:** Innovators move the concept from the laboratory, models, and sketches to working prototypes or pilots.
- **Phase 3:** Early adopters form niche markets, connecting supply and demand. Performance increases and costs decline but the innovation remains at a premium and not widely available.
- **Phase 4:** The innovation reaches mass market as it outperforms incumbents in costs and performance. This is the steep part of the S-curve.
- **Phase 5:** Growth slows as the innovation reaches market saturation. The innovation may be transferred to new markets or serve as the basis for further innovations.

Barriers and system dynamics are predictable, manageable, and solvable through each of these phases. This means that as transitions unfold, stakeholders who have a good understanding of various innovations and their phases can develop targeted strategies to stay ahead of, and take advantage of, new markets. Generally, the fastest movers will stand to capture the biggest rewards, and the slowest movers will be left with the biggest losses.

2. What Is the S-Curve?

Innovations typically follow an S-curve pattern of growth: slow at first, then rapidly rising, before flattening out again as they reach market saturation. The curve is typically described in market share and size and has been observed in many transitions, including cars replacing horses, electric lighting replacing gas lighting, and more.

Exhibit 1. A sample of historical S-curves



Source: Hannah Ritchie and Max Roser

3. Why S-Curves Matter

Ultimately, S-curves mean that change can be fast, beneficial, and inevitable once market tipping points are reached. The S-curve is simultaneously a warning for slow movers and an opportunity for fast movers. Slow movers risk overestimating their future sales and prices and will face higher capital costs as well as a higher risk of stranded assets in a shrinking market. Fast movers who are willing to take initial risks will be rewarded with rapidly growing market opportunities.

For instance, in the information revolution, IBM invested in upcoming technologies and became the market leader in the late 1980s. Computer makers such as Commodore and Atari were left behind. Denmark is now a market leader in offshore wind, while China dominates the solar photovoltaic market. Tesla Motors leads the electric vehicle industry, and by some metrics, the entire automobile industry.

S-curves can also provide us with hope. By accelerating clean energy innovations through their S-curves, we pave viable pathways to avoid climate disaster.

4. The Drivers of S-Curve Growth

S-curve growth is driven by key system dynamics that make the innovation more affordable and accessible. The following are four common examples:

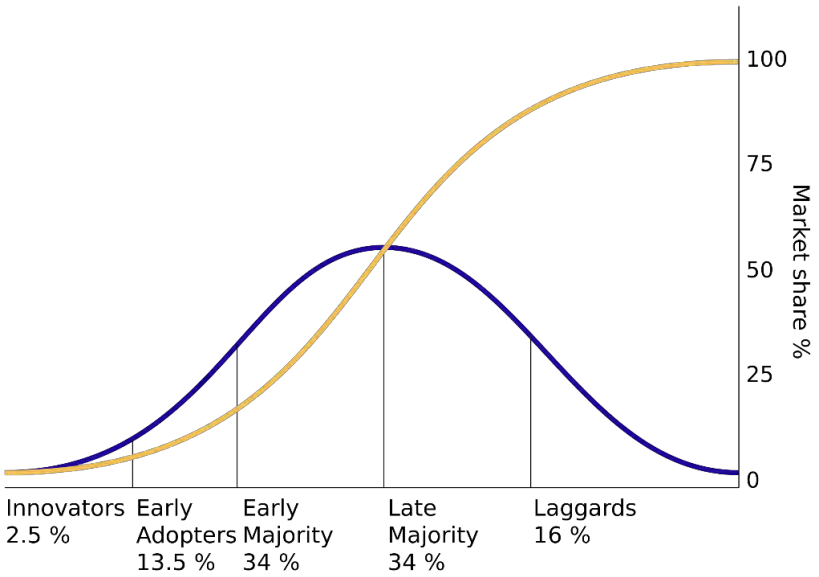
1. *Learning curves*
   The more experience producers accumulate with an innovation, the more productivity improves, and the cheaper (and often, faster and better) it becomes.

2. *Economies of scale*
   The higher the quantity of products or services, the cheaper the per-unit cost becomes. This is because fixed costs can be spread over a larger number of outputs. In turn, as per-unit costs become cheaper, scale can increase.

3. *Technological reinforcement*
   The more an innovation is used, the more supporting technologies emerge that make it even more useful. For example, electric vehicle users can now easily search for charging stations along their planned route.

4. *Social diffusion*
   Put simply, people are more likely to adopt a new behavior or technology when they see others around them doing the same. As a result, the more an innovation is adopted, the more interested people become. In the 1960s, Everett Rogers outlined five categories of adopters of an innovation and how they are generally distributed on an S-curve:

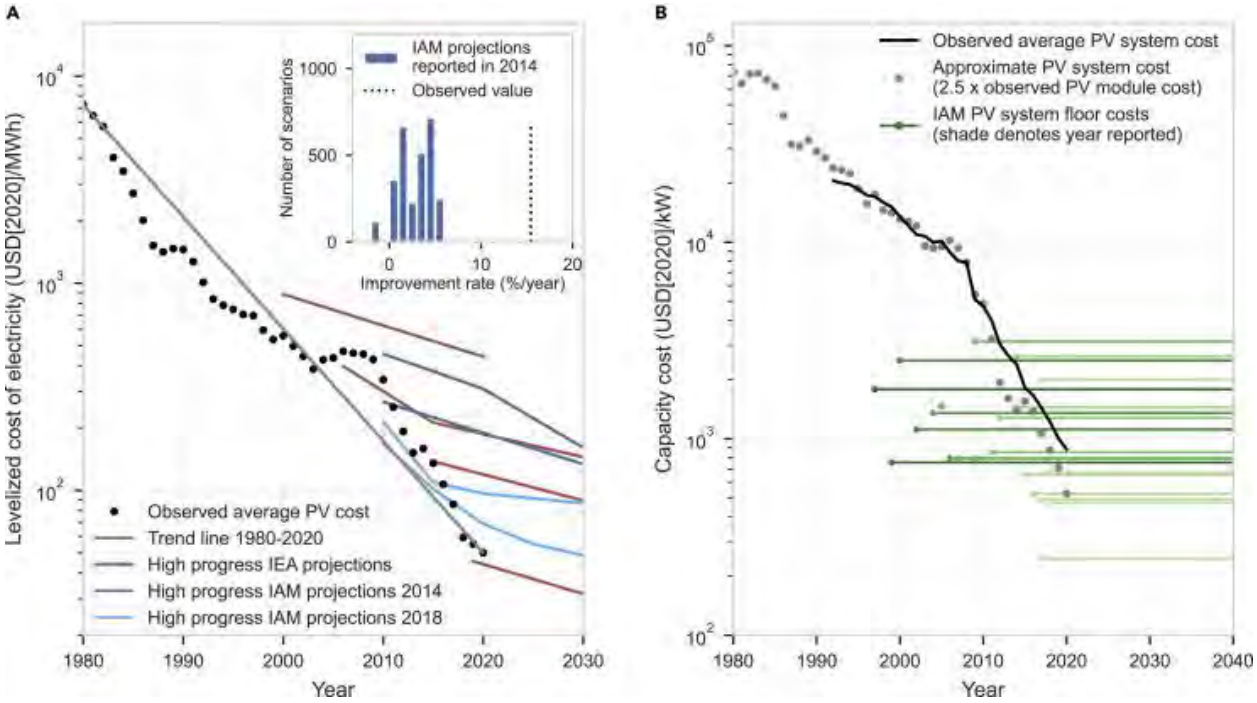
Exhibit 2. A bell curve of adopters in five categories



Source: E.M. Rogers, Diffusion of Innovations (1962)

As a result of these processes, the cost declines of innovations and the speed of adoption are frequently underestimated as they approach the steep part of the S-curve. For example, actual solar photovoltaic costs dropped not only faster, but also further, than models predicted:

Exhibit 3. Historical PV cost projections and floor costs



Source: Way et al., Empirically grounded technology forecasts and the energy transition (2022)

The macro trends both influence and are a collective result of decisions by individual consumers, corporations, governments, and other actors.

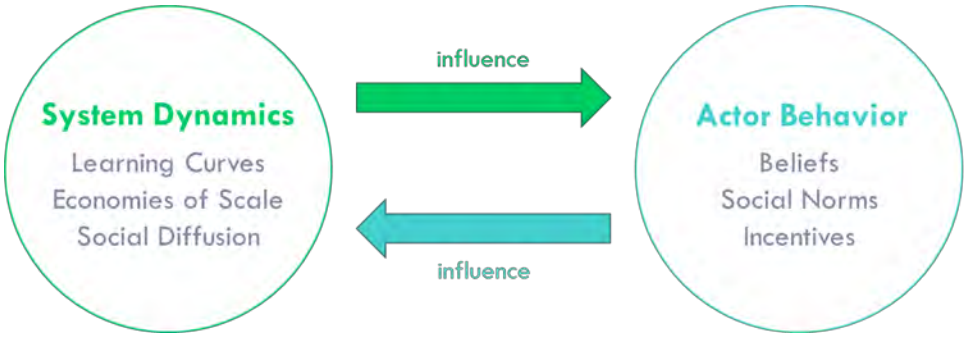
Actor behavior is well understood from academic literature and consist of a combination of economic arguments, social pressure, individual beliefs, and external controls and incentives.

For example, actors are more likely to adopt if:

- There is a business case. The calculus and thresholds to invest differs by group. Innovators or early adopters believe in a faster speed of change and expect a higher return on investment than those that expect no or slow change.
- They are connected to trusted leaders or peers who are adopting/advocating adoption.
- There is plenty of information from trusted sources about the innovation.
- The innovation is accessible, with plenty of resources available to support adoption.
- The perceived level of risk associated with adopting an innovation is within their risk threshold.
- There is a clear vision for the future of the innovation.
- There are penalties (legal, financial, social, or otherwise) for those that do not adopt.

Conversely, actors are less likely to adopt if they believe in slow change, perceive a high level of risk, are relatively isolated in their social networks, and have no information or resources to access the innovation.

Exhibit 4. The relationship between system dynamics and actor behavior



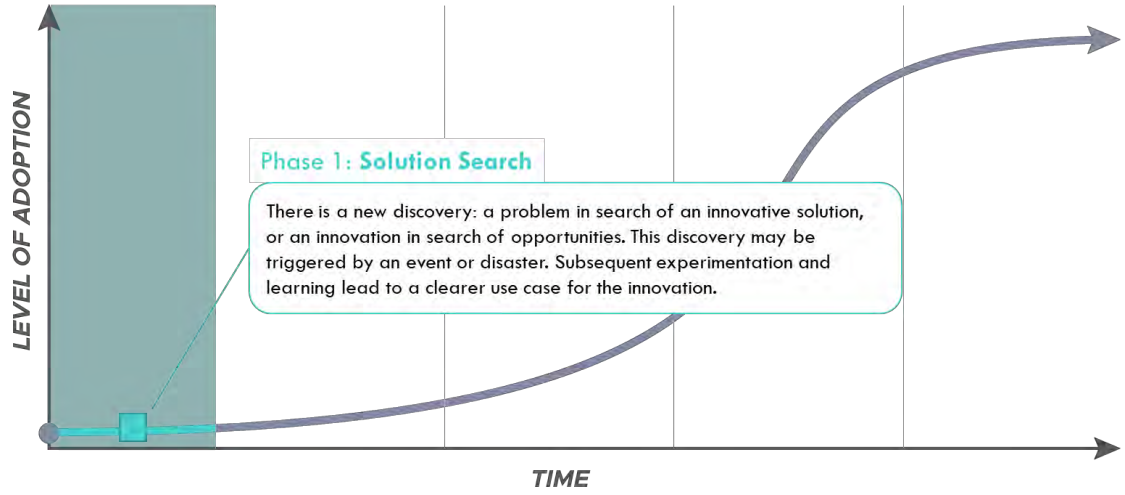
5. The Five Phases of the S-Curve

Transitions occur when these incentives and dynamics evolve and the innovation scales. Transitions through S-curves can be understood in five phases (see Exhibit 5).

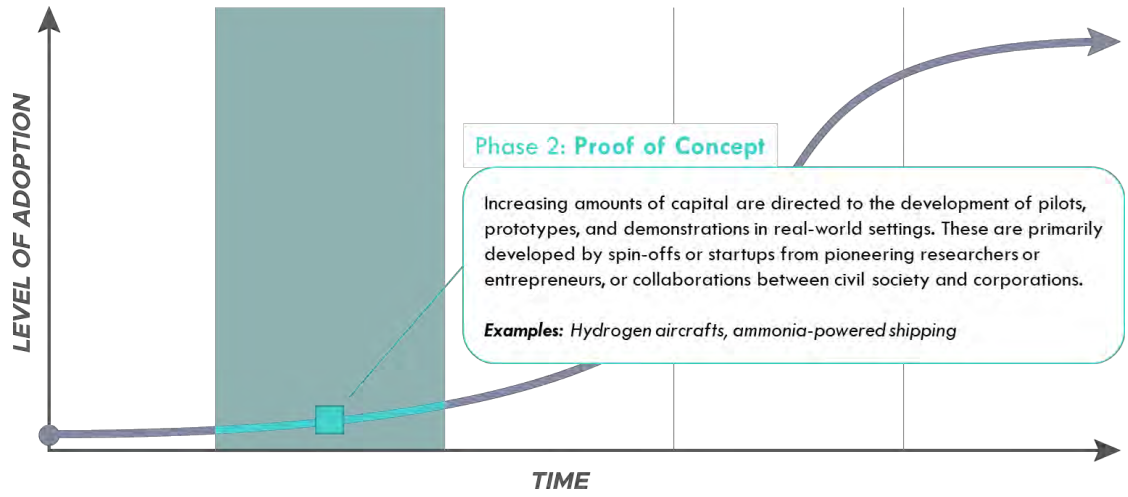
When developing transition strategies, it is crucial to understand which phase an innovation is in. Because system dynamics are specific to each phase, an intervention or strategy that works well in one phase may not be as effective in another.

Exhibit 5. The five phases of the S-curve

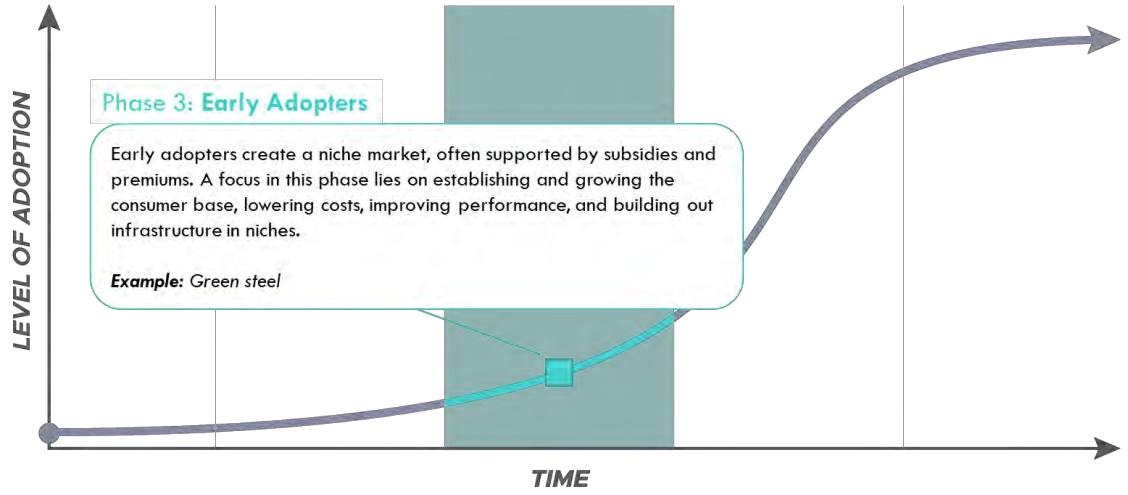
Phase 1: Solution Search



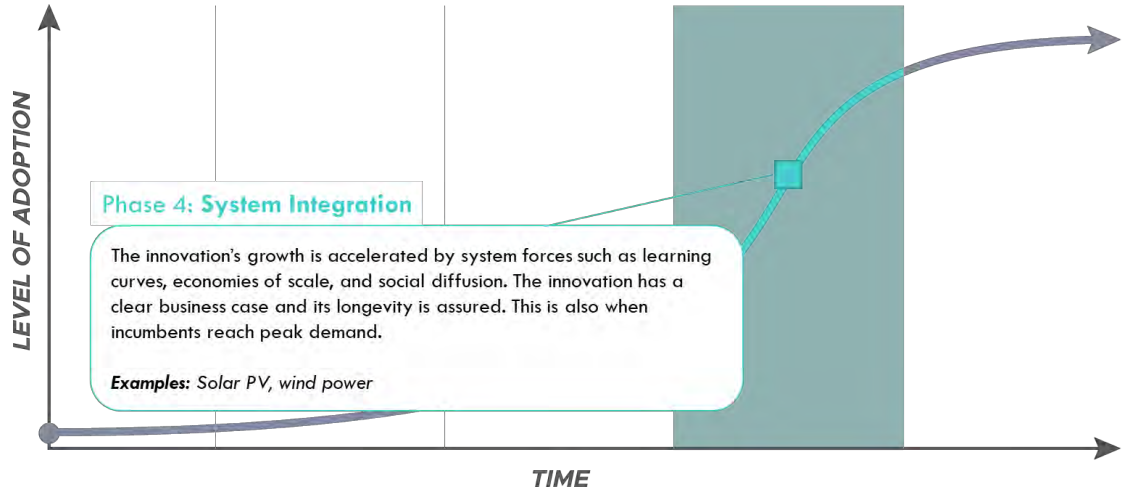
Phase 2: Proof of Concept



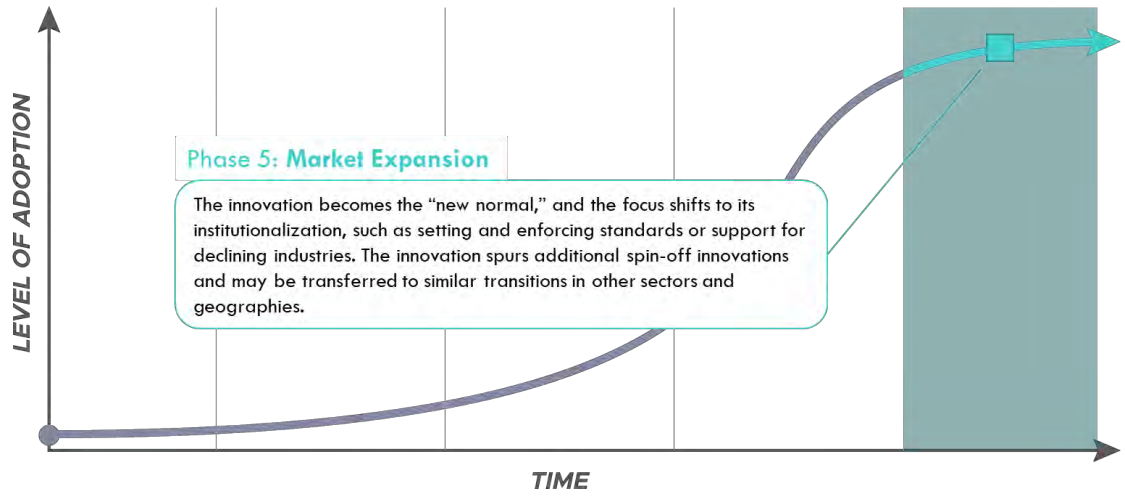
Phase 3: Early Adopters



Phase 4: System Integration



Phase 5: Market Expansion



6. A Guide to Accelerate Transitions

Transitions can be accelerated with interventions and strategies aimed at resolving barriers and advancing innovations into subsequent phases. Below is a brief snapshot of the main objectives and key activities of each phase.

Phase 1: Solution Search

- **Main Objectives:** Identify innovations with high potential (e.g., using hydrogen, electricity, or sustainable aviation fuels as alternatives for fossil aviation fuels)
- **Key Activities:** R&D, roadmaps, commitment setting, awareness raising

Phase 2: Proof of Concept

- **Main Objectives:** Prove the technical feasibility of using the innovation for the opportunity/goals clarified in phase 1
- **Key Activities:** Demonstrations and pilots, impact validation, building initial business case

Phase 3: Early Adopters

- **Main Objectives:** Establish and grow a niche market and develop a business case for mass market
- **Key Activities:** Demand creation (e.g., subsidies, public procurement, offtake agreements), market targeting, certification schemes, value chain projects

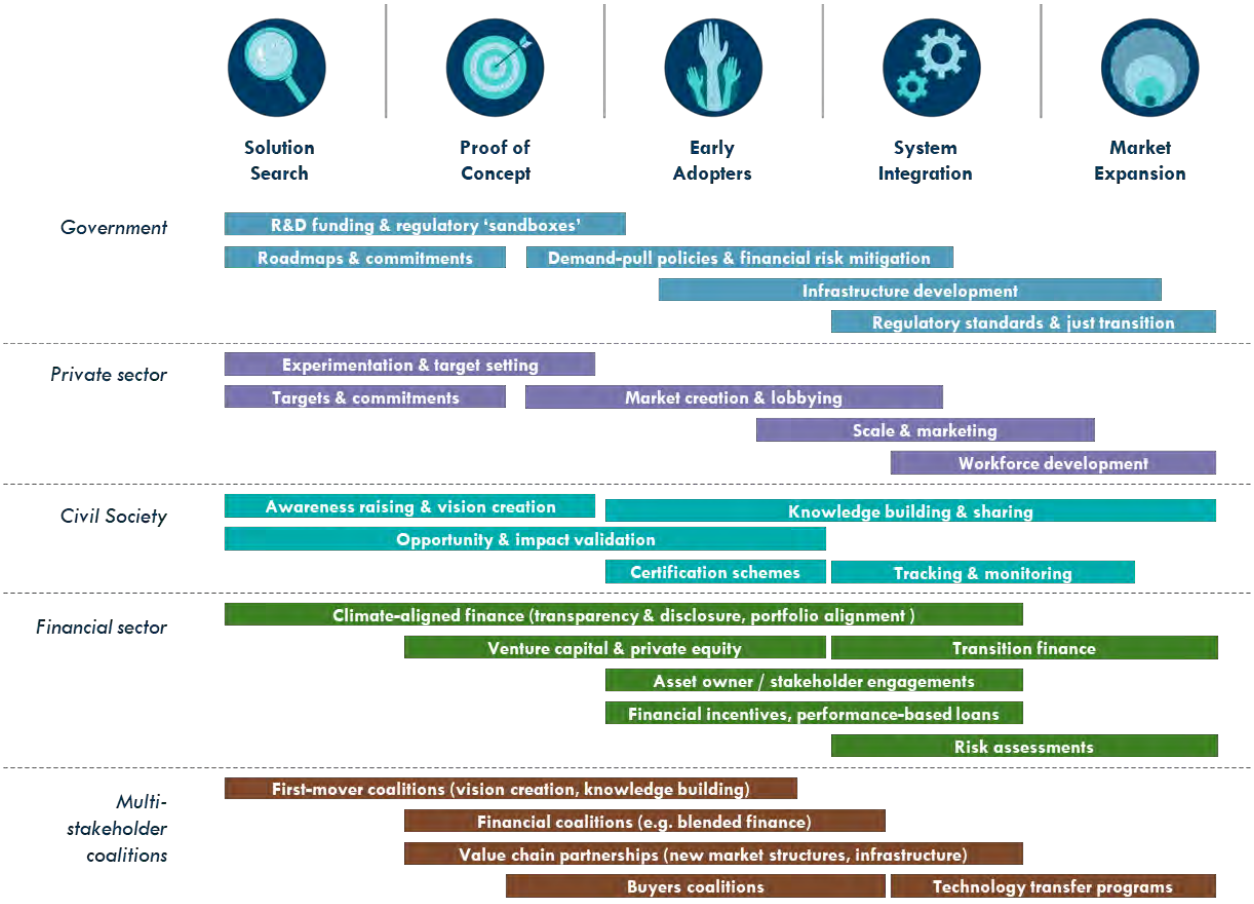
Phase 4: System Integration

- **Main Objectives:** The innovation becomes affordable and accessible for the majority of players
- **Key Activities:** Value chain and infrastructure projects, workforce development, regulatory standards, initiate phase-out of the old

Phase 5: Market Expansion

- **Main Objectives:** Mitigate transition losses and resistance, adapt innovation to new markets
- **Key Activities:** Capacity building, knowledge and technology transfer programs, invest in and supplement new innovations

Exhibit 6. A snapshot of key stakeholder activities in each phase



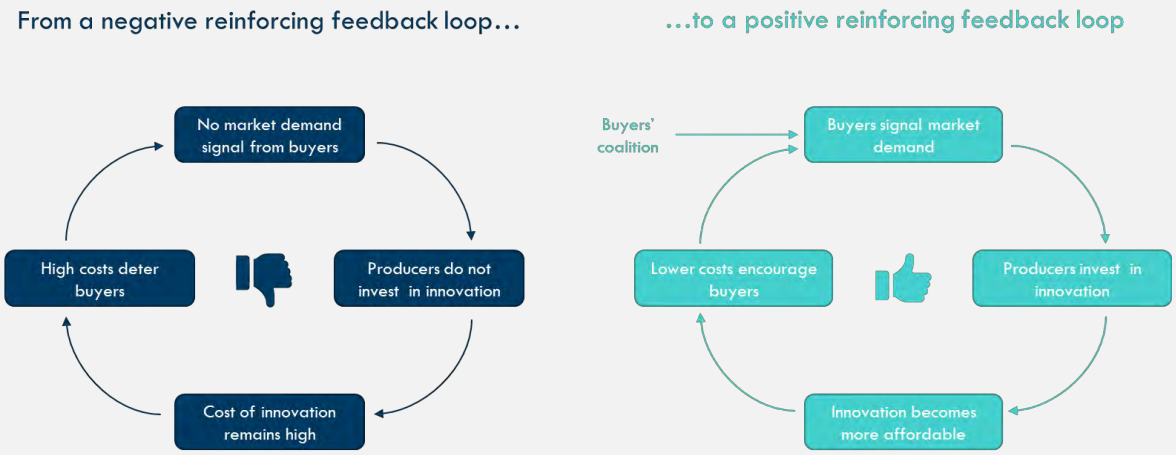
The table at the end of this article provides a more detailed description of common barriers, the listed activities, and opportunities for coalition building in each phase.

You can find examples of successful interventions here.

How Interventions Can Create Positive Reinforcing Feedback Loops: An Example

In the Early Adopters phase, potential users are often deterred by high costs and limited availability. Producers interpret this as a lack of market demand, and do not make the investments needed to bring down the costs of the innovation. This a negative reinforcing feedback loop.

To solve this problem, first-movers can come together to aggregate their demand in a buyers' coalition. Together, the buyers send a clear demand market signal to the producers. This gives producers the market confidence they need to invest in the innovation and bring down costs. This arrangement can be further solidified through offtake agreements, where buyers commit to buying a certain amount, and producers commit to selling at a certain price.



8. One Innovation Is Not Like the Other

Innovations rarely proceed neatly through the phases. Often, they become stuck or fail due to systemic barriers. Many factors influence these barriers, including characteristics of the innovation itself.

- Technologies that are small and modular can go through rapid experimentation. This enables steep cost reduction and rapid scale once it's market ready (e.g., solar photovoltaics). The "valley of death," the conversion from academics and research to working prototypes (phase 2–3), is likely to cause failure or delay. Competition is strong in these markets, and many businesses will fail in the process.
- Technologies that require big investments and involve large risks (e.g., nuclear power) are less likely to advance rapidly on a learning curve and reach mass market (phase 3–4) because of the inability for rapid experimentation.

- Complex innovations that require multiple technologies to be rolled out at once (e.g., electric vehicles and charging stations) rely on prototypes of multiple innovations and on value chain projects (phase 2–3) to help with phased infrastructure build-out and niche market creation.
- Innovations that fail to outperform existing markets in costs are more likely to remain stuck in phase 3 as a "niche market." They often remain dependent on premiums and certification (e.g., certified organic products) and will require additional interventions such as behavioral nudging, government policies, and multi-stakeholder convening to progress.
- Changing norms or preferences primarily progress through social contagion (e.g., smoking rates in the United States). These changes can go very fast in social networks but will not scale through an adoption S-curve across networks and geographies.

9. What's Next

Our upcoming reports will:

- Further elaborate on the frameworks and strategies we introduce here
- Describe examples of corporations, coalitions, and other organizations that have developed and implemented strategies for success in a rapidly changing world
- Present analysis on why corporate commitments and action matter for non-linear change
- Showcase modeling of rapid non-linear change

To learn more about S-curves and how transitions work in the meantime, we invite you to visit our Transition Toolkit hosted on the 1.5°C Wayfinder website.

Note: Our framework derives from multiple studies in the innovation systems and technological transitions literature, including the Multi-Level Perspective framework by Frank Geels, Diffusion of Innovations by Everett Rogers, Mission-Oriented Innovation Systems by Marianna Mazzucato and Marko Hekkert et al., Changing the Game by Lucas Simons and Andre Nijhof, Think-Do-Scale by RMI, and others. The Paris Effect (Systemiq), The State of Climate Action (WRI), Accelerating the Low Carbon Transition (ETC and Brookings), and the 2022 IPCC AR6 Working Group II report have in recent years applied similar transition frameworks.

Appendix: Phase Details and Roles by Sector

Phase	1 – Solution Search	2 – Proof of Concept	3 – Early Adopters	4 – System Integration	5 – Market Expansion
Who's involved?	Visionaries	Innovators	Early Adopters	Early & Late Majority	Laggards
Phase complete when…	- There is alignment and/or motivation around a common problem - A set of solutions are identified that have significant potential to address (part of) the problem - One or more actors (funds, governments, corporations) are ready to invest in pilots of specific solutions	- Demonstration of technical feasibility (e.g., successful completion of pilot projects) - Emerging consensus on "winning" solution(s) - Niche markets are identified and start to emerge	- Niche market is established - Business case for mass market is clear - Market consensus on "winning" solution(s) - Initial value chain build-out (e.g., infrastructure, complementary technologies)	- Enabling environment (e.g., infrastructure, regulation) is established - The innovation reaches critical mass and becomes affordable and accessible for the majority of players	- The innovation reaches market saturation and/or is ready to be transferred to new markets - New supplement innovations are developed - Transition losses and resistance are fully addressed
Common barriers	- Limited understanding of the problem - Lack of leadership or coordination to address the problem - Limited options in innovation landscape, often due to lacking resources for early research	- The "valley of death" – limited resources to make the bridge from public-funded early research to private-funded commercialization research - Lack of regulatory support and flexibility for experimentation - Low technological or commercial viability	- Business case does not materialize beyond niche markets - Lack of market confidence, risk aversion - High costs and limited availability of the innovation - Knowledge gaps related to the use of the innovation - Resistance from incumbents	- Challenges adapting the innovation to a mainstream audience - Limited resources for establishing a wider enabling environment (e.g., infrastructure, regulation, human capital) - Lack of standardization, higher risk of misinformation	- Challenges adapting the innovation to new markets - Limited resources for capacity building in new markets

		- Highly decentralized group of stakeholders	- Avoiding responsibilities between actors (pointing fingers)	- Continued resistance from incumbents	
Government roles	- Provide **public R&D funding** - Define research agendas and publish technology **roadmaps / strategies** that break down the transition in manageable pieces - Set (binding) **targets and commitments** -	- Provide **grant funding** for demos and pilots - Create **regulatory "sandboxes"** that allow flexibility and support around strict standards, market access, and infrastructure	- Implement **demand pull policies** (e.g. subsidies, public procurement) - Alter the economic playing field through taxes and regulation - **Mitigate risk** for financial and private sectors (e.g. **blended finance**) - Fund **infrastructure projects** serving niche markets - Run **public awareness campaigns** on innovation benefits	- Alter the economic playing field through taxes and regulation - Fund large-scale **infrastructure projects** - Develop **regulatory standards** targeting phase-out of "the old" - Implement **just transition policies** - Run **public awareness campaigns** on innovation benefits	- Implement **just transition policies**; mitigate transition losses and resistance - **Update and create new regulations**, standards, and institutions as needed - Enforce phase-out of "the old"
Private sector roles	- Set voluntary **targets and commitments** - Conduct **corporate R&D**	- Conduct **demos and pilots**, stimulate experimentation - Develop vision including root cause analysis and value chain perspectives - **Showcase what is possible** through marketing -	- Establish niche markets supported by **offtake agreements** and **buyers coalitions** - Pursue **cost reduction and quality improvement** in niche markets - **Refine business model** and go-to-market strategy	- Expand to **mass market** - Conduct **value chain projects** - Invest in physical assets and **workforce development** - **Lobby** for better regulations, counter incumbent narratives - Shape consumer preferences	- Develop **new markets** - Engage in **transition risk management** practices

			- Shape consumer preferences through behavioral nudges and **marketing** - **Lobby** for better regulations and subsidies, counter incumbent narratives	through behavioral nudges and **marketing**	
Civil society roles (e.g. NGOs, media, advocacy groups)	- **Validate innovation opportunities** - **Raise public awareness** (on need for innovation and/or urgency of problem) through advocacy and movement building - Provide platforms for commitment setting -	- **Validate innovation impacts** - **Raise public awareness** (on innovation benefits, urgency) - Facilitate and participate in coalition building	- **Information campaigns** to support buyer understanding of the innovation and its benefits - Support niche market creation (e.g. **certification schemes**) - Place **public pressure** on key government and private sector actors (in this phase, emphasize rewarding frontrunners e.g. certification schemes, scorecards) - Facilitate and participate in **coalition building**	- **Information campaigns** to support buyer understanding of the innovation and its benefits - Place **public pressure** on key government and private sector actors (in this phase, emphasize calling out laggards, e.g. through **tracking & monitoring**) - Push for just transition policies - Facilitate and participate in **coalition building**	- **Knowledge and technology transfer** to new markets - Facilitate and participate in **coalition building**
Philanthropic sector roles	- Fund, support, and amplify phase-appropriate civil society and multistakeholder coalition activities				

Financial sector roles	- Set voluntary targets and commitments - Launch & participate in **climate-aligned finance** agreements, committing to transparency & disclosure, portfolio alignment	- Provide **venture capital and private equity funding** to early start-ups or promising companies - Participate in **climate-aligned finance** agreements	- Provide **venture capital and private equity funding** to emerging companies - Participate in **climate-aligned finance** agreements - Implement **financial incentives** (e.g., sustainability-linked loans) - **Engage and consult** with asset owners & shareholders	- Provide **transition finance** - Participate in **climate-aligned finance** agreements - Implement **financial incentives** (e.g., sustainability-linked loans) - Conduct **risk assessments** on stranded assets - **Engage and consult** with asset owners & shareholders -	- Provide **transition finance**
Examples of possible multi-stakeholder / cross-sector coalitions	- Develop a shared problem statement and vision for the future *(multi-stakeholder)*	- Design and test new market structures *(value chain partners)* - Align messaging & amplify public awareness / marketing campaigns *(private sector + NGOs, advocacy groups)* - Build and share knowledge *(private sector + research orgs)*	- Build out niche market infrastructure *(value chain partners, public + private)* - Leverage demand to motivate sellers and accelerate niche market development *(buyers + NGOs)* - Build and share knowledge *(private sector + NGOs / research orgs)* - Share financial risk e.g. blended finance *(public + private sector)*	- Coordinate phased rollout of new infrastructure, regulations *(multi-stakeholder)* - Align messaging & amplify public awareness / marketing campaigns *(multi-stakeholder)* - Align lobbying strategies *(private sector + NGOs)*	- Jointly develop technology and knowledge transfer programs *(private sector + NGOs, IGOs)*

			- Align messaging & amplify public awareness / marketing campaigns *(multi-stakeholder)* - Align lobbying strategies *(private sector + NGOs)*		