Technology Transitions in the Presence of Uncertain Learning Curves: The Case of Green Tech

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The case of green technologies

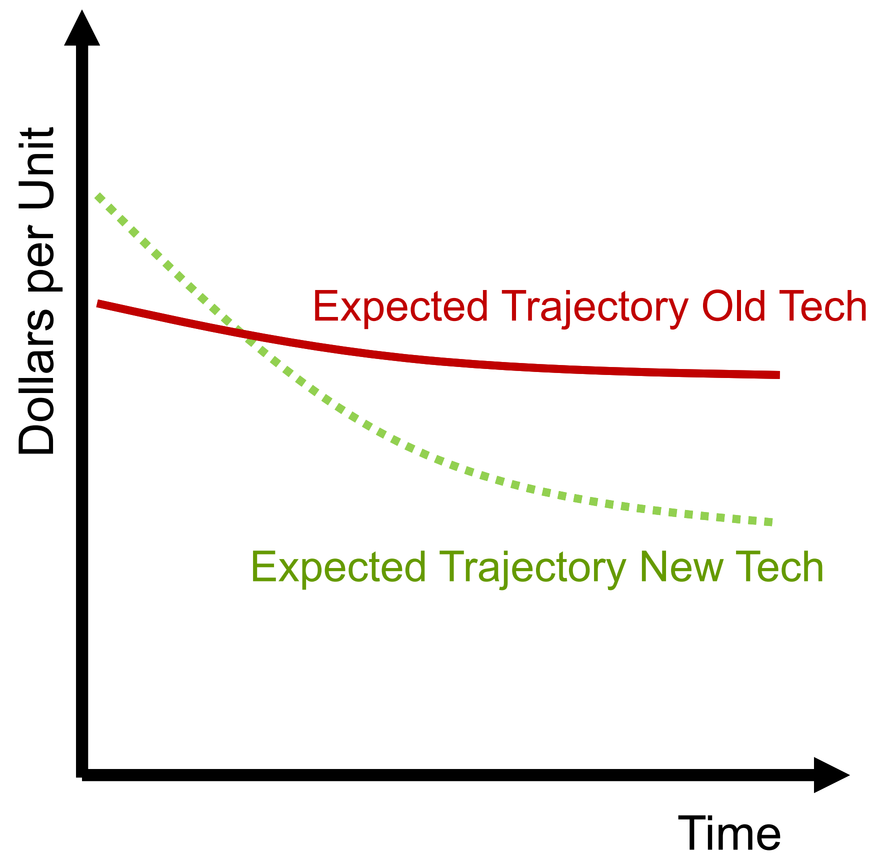
- Efforts to decarbonize the economy imply the need to transition from established to socially desirable technologies.
- Existing research often links the timing of these transitions to path dependency and lock-in effects based on deterministic assessments of the future.
- This project aims to explore the implications of two forms of uncertainty on transitions from an old to a new (green) technology.

A few caveats …

- Our goal is to examine how uncertainty affects resource allocation.
  - This presentation may be less analytical than others at this conference.
- This presentation offers limited insight that is specific to ‘green” technologies
  - Our current model shows that uncertainty matters.
  - We are examining two firm models and models with various policy choices to show how they affect investment decisions under uncertainty.

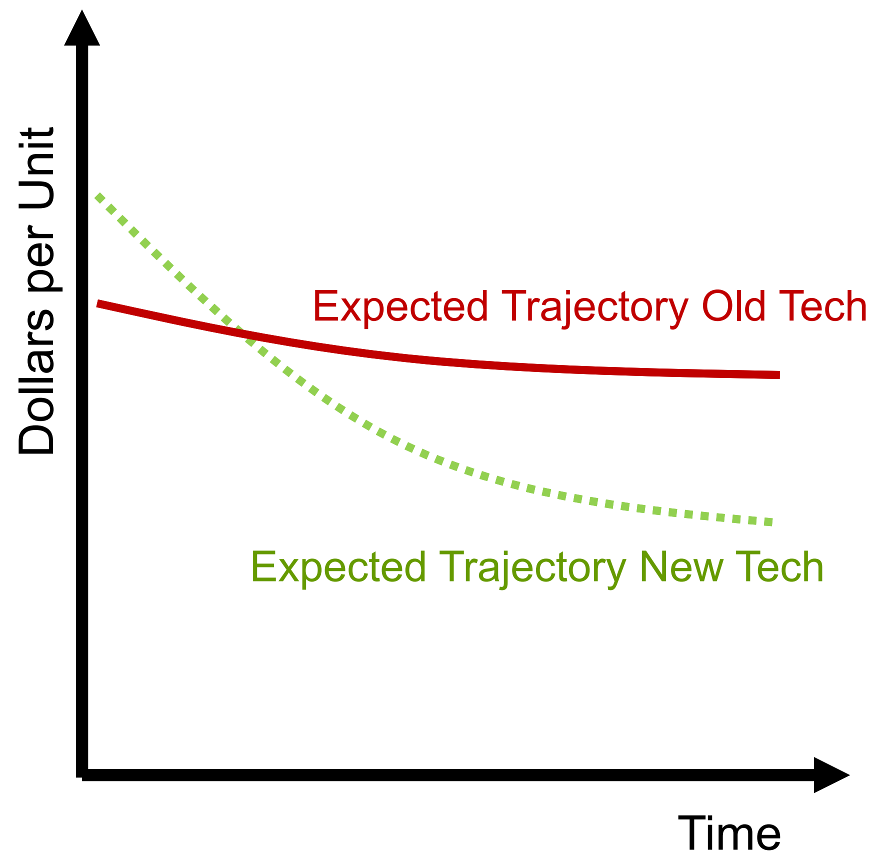
Classic approaches to understanding investment assume away uncertainty

- A single firm chooses between two technologies
- We simplify by focusing on cost improvements (c.f., S-curves)
- Standard formulation
  - $K_t^j = K_{t-1}^j e^{-q_{t-1}\gamma^j}$
    - K_t^j is the cost of technology j,
    - γ^j is the progress rate for technology j,
    - q_t is the known quantity in period t.



Classic approaches provide 2 rationales for slow transitions to the "new"

- ↑ the discount rate pushes the adoption of the new into the future
- The threat of cannibalization defers investment in the new
  - Adjustment costs.
  - Patent race literature.
- Both rationales imply that new entrants have a larger incentive to pursue new technology.



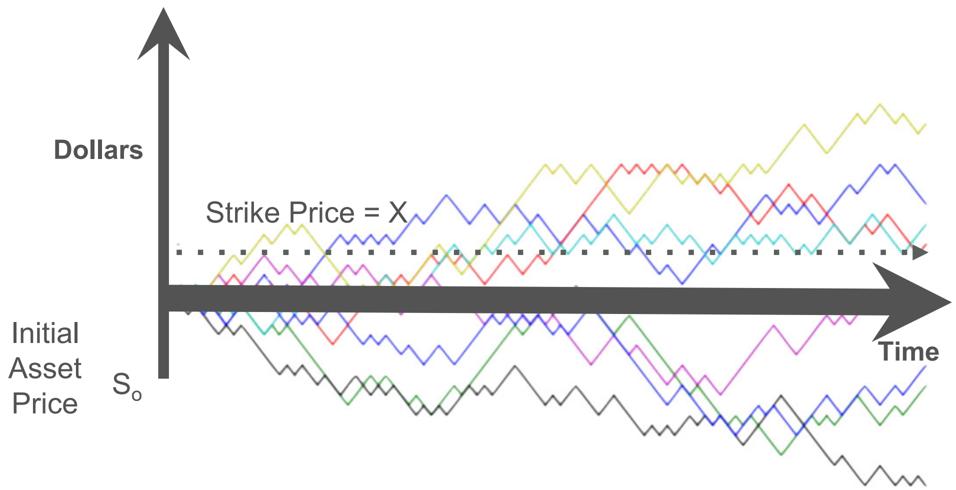
(How) Does uncertainty in technological trajectories affect "green" investment?

- If uncertainty varies across the technologies an alternative explanation is plausible

- Uncertainty regarding the development of old and new technology may affect investment.
  - As well as perceptions of uncertainty or the ability to separate signal from noise.

- This explanation is independent of the expected cross-over point, cannibalization concerns, or even potential externalities.

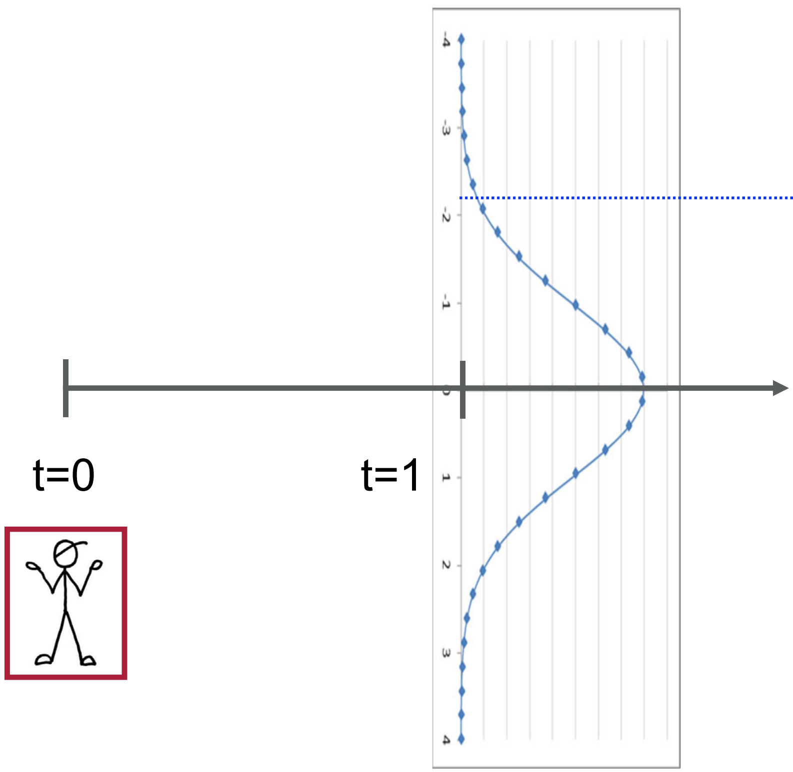
Two prominent theories of sequential decision-making



These theories point to distinct forms of uncertainty

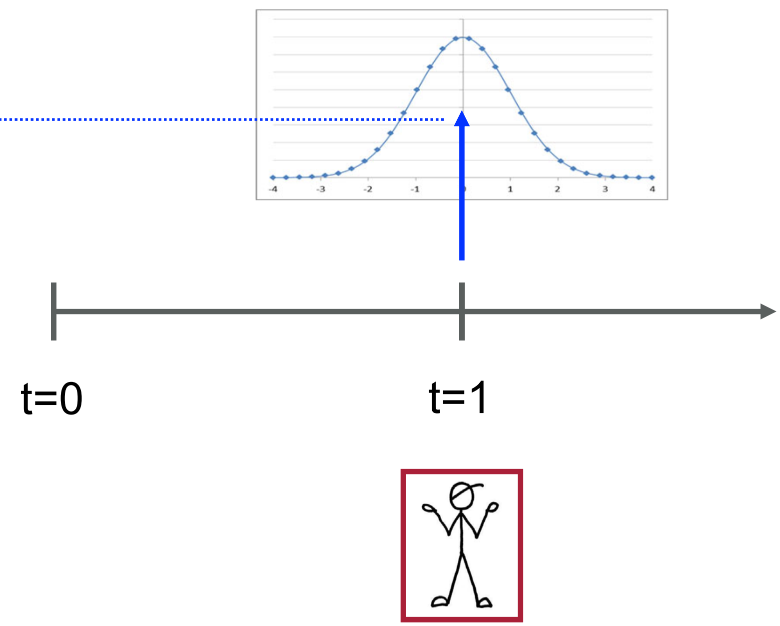
'Prospective' Uncertainty

Uncertainty about the future value of a project
(e.g., Two expert meteorologists have opposing forecasts for tomorrow's weather)



'Contemporaneous' Uncertainty

Uncertainty about the current value of a project
(e.g., Two expert oncologists have opposing recommendations on how to treat a tumor)

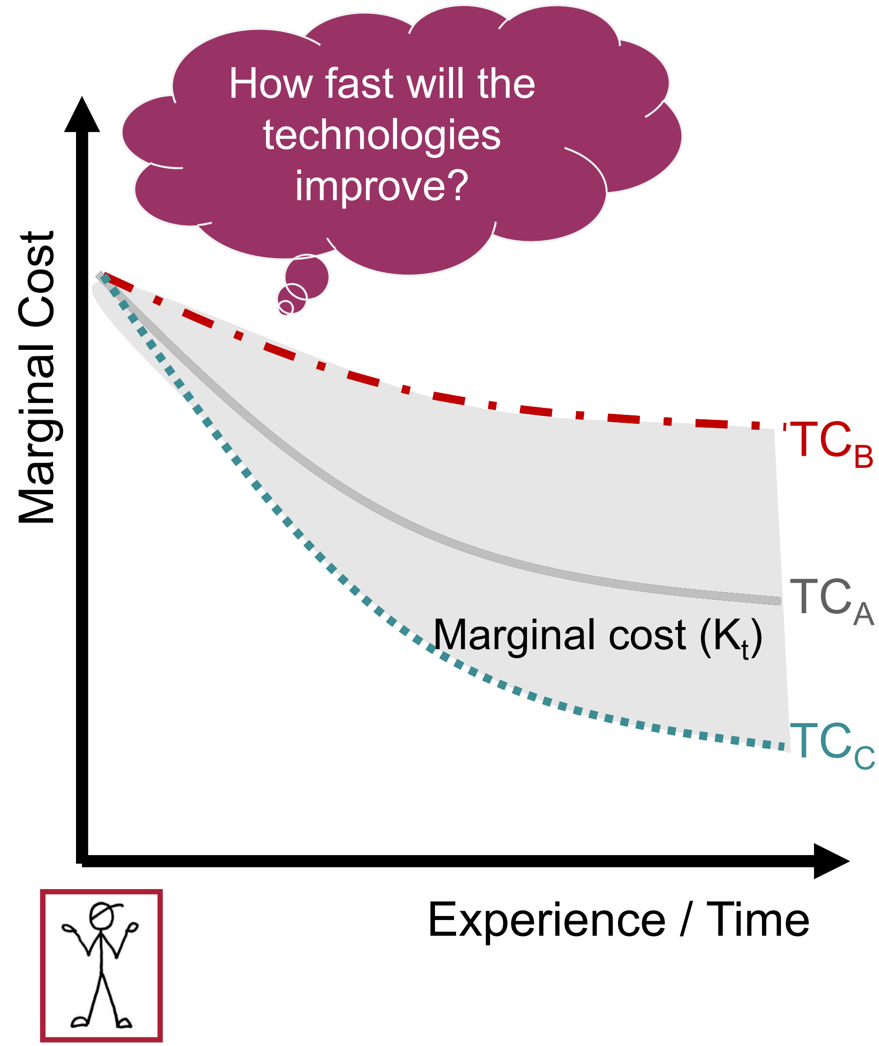


See Leiblein, Chen, & Posen (2017); Posen, Leiblein, & Chen (2018). Related ideas in van den Steen (2018). Other conceptions include ambiguity (e.g., Cont, 2006) and distinctions between risk and Knightian uncertainty (Knight, 1921; Koopmans, 1967).

Accounting for prospective uncertainty in a technological trajectory

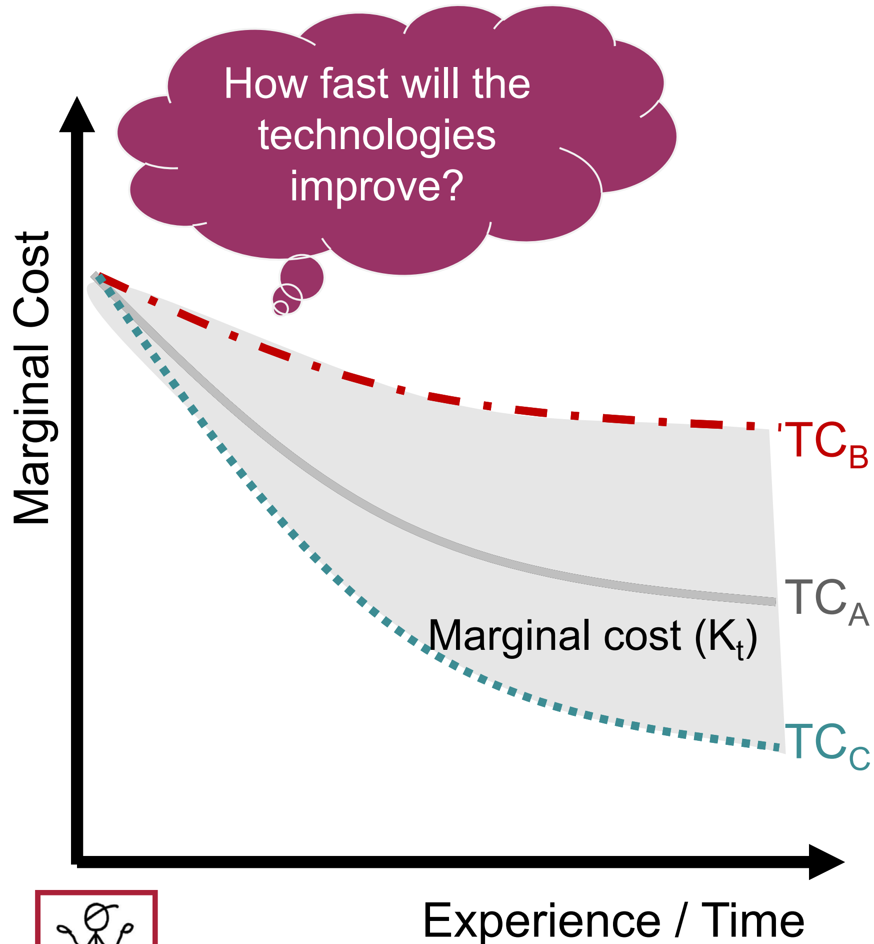
- Predicting the future is easy … getting it right is the hard part

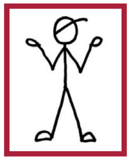
"In the standard formulation of organizational learning, cost reductions are obtained as a predictable by-product of accumulated production volume...(yet) not only are variations in the rate of learning difficult to predict, they are difficult to understand after the fact." (Thompson, 2012: 221)



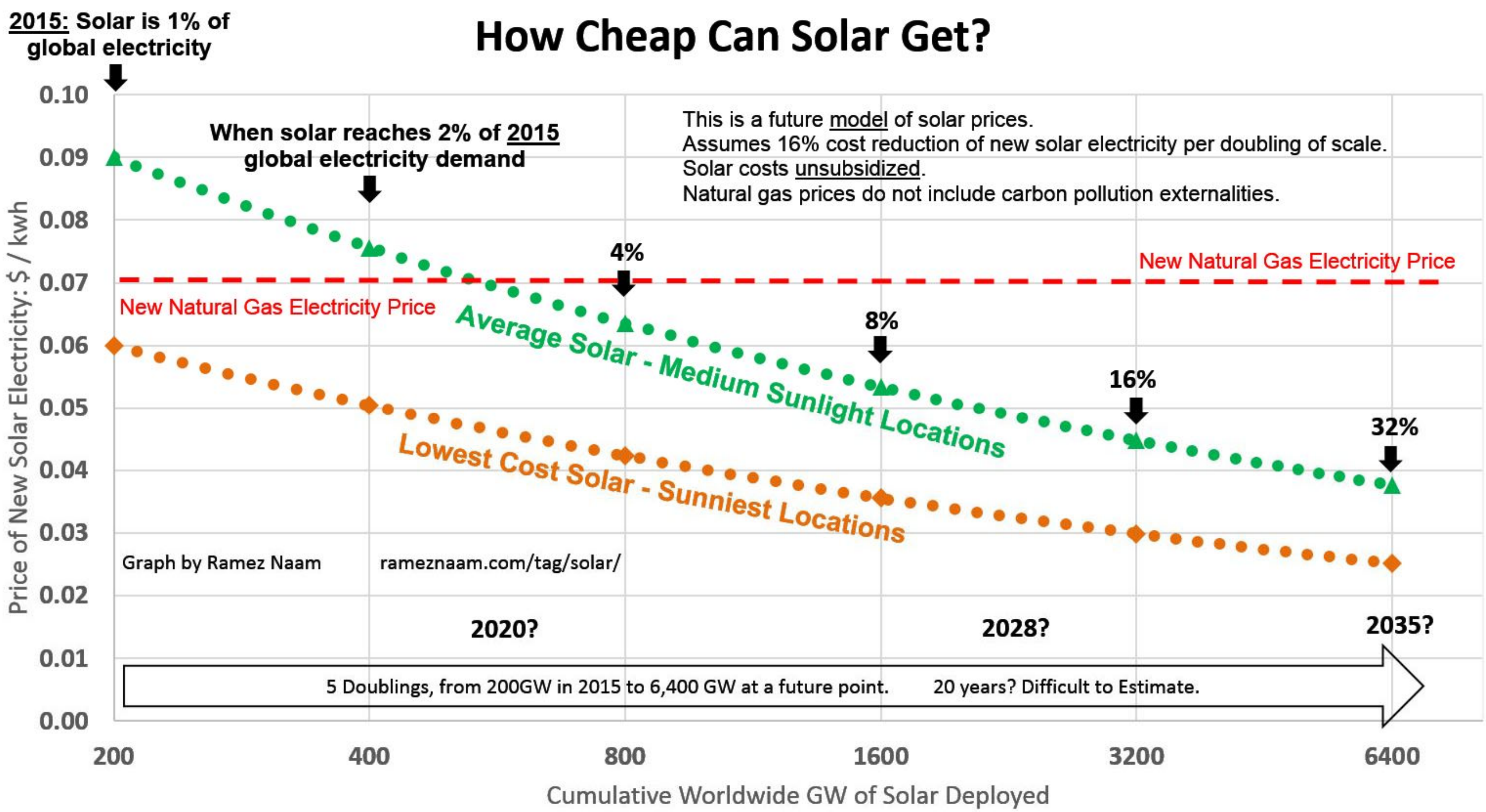
Accounting for prospective uncertainty in a technological trajectory

- (How) Does prospective uncertainty change our understanding of investment?
- If learning provides a claim on future adoption, prospective uncertainty may generate "option value."
- Prospective uncertainty may also alter the comparative importance of incentives between incumbents and entrants.





Prospective uncertainty example: *We don't know how cheap solar will get in the future*

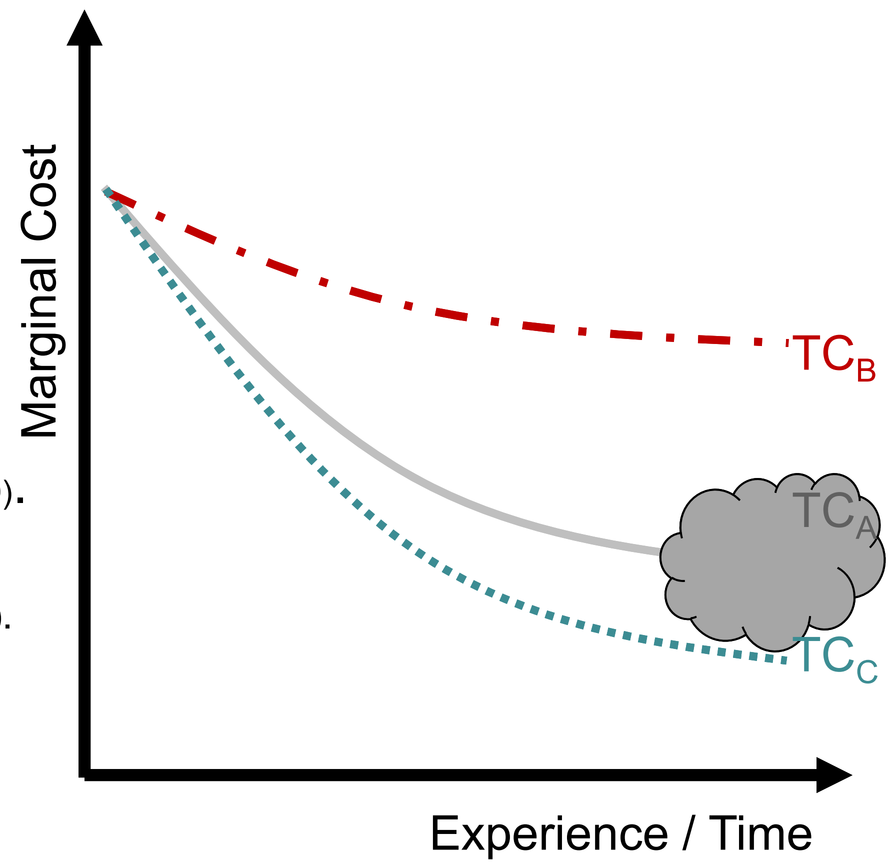


Source: https://rameznaam.com/2015/08/10/how-cheap-can-solar-get-very-cheap-indeed/. Accessed 3/7/2023.

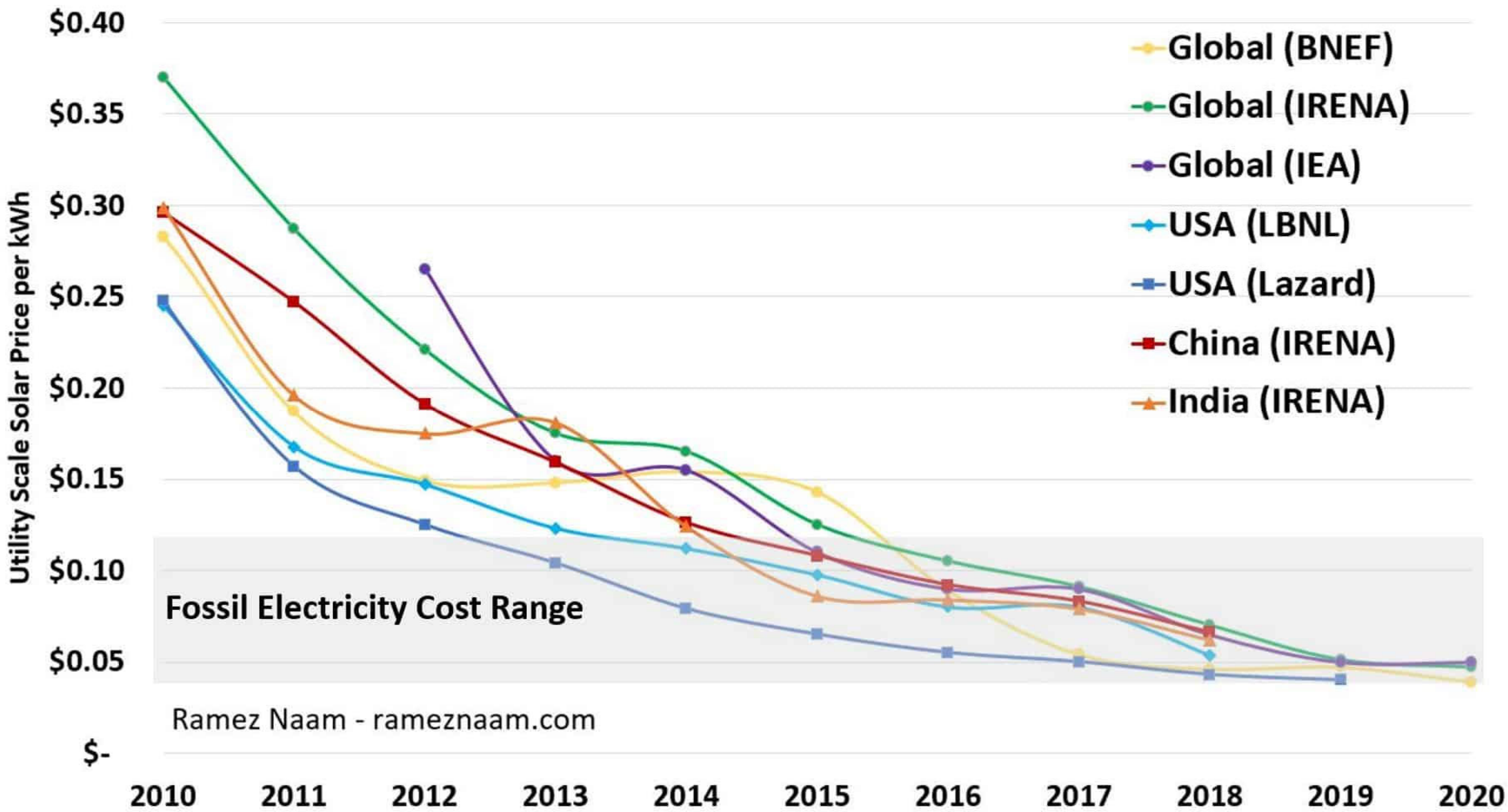
Accounting for contemporaneous uncertainty in technological trajectories

- "CU" reflects incertitude regarding current production costs (e.g., noise).

- Sources
  - Measurement costs (Barzel, 1981).
  - Influence costs (Milgrom & Roberts, 1990).
  - Idiosyncratic factors (i.e., limits in accounting systems, lumpy experimentation).



Imperfect CU example: *Range in actual costs for solar projects at a point in time*

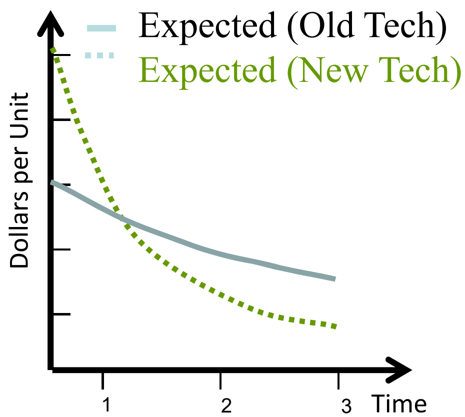


Average (unsubsidized) cost of projects actually built from multiple independent sources.

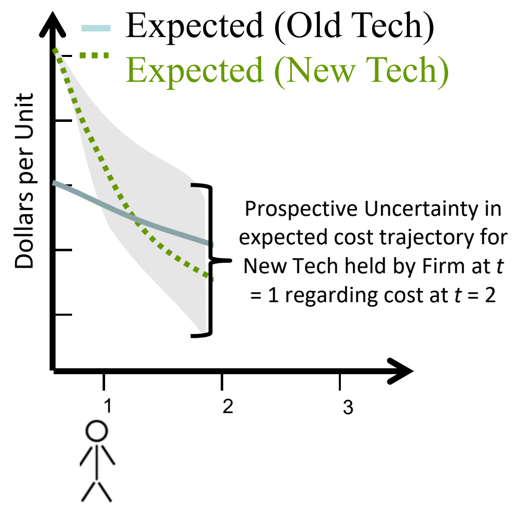
Source: https://rameznaam.com/blog/ Accessed 3/7/23.

This project examines three scenarios w/ two technologies & an uncertain trajectory

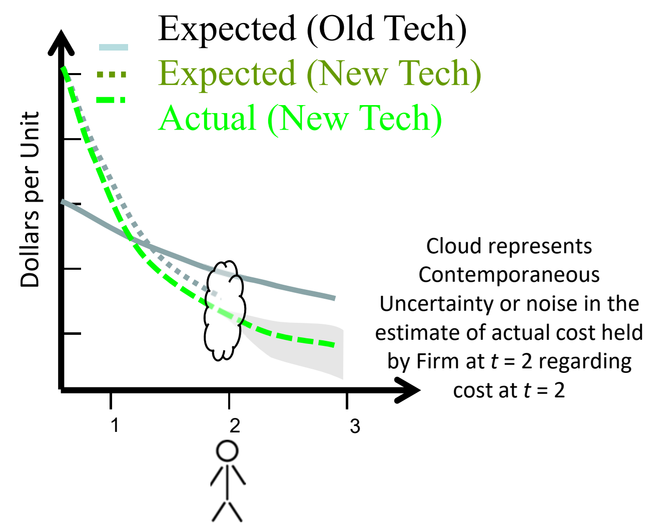
No Uncertainty



Prospective



Prospective & Contemporaneous



My prior papers link the Black-Scholes option model & the Bandit learning model

Black-Scholes model

$$\boxed{s(1,1) = s(0,0) + r_f - \sigma_p^2/2 + \sigma_p \nu_p,}$$

Bandit model

$$\boxed{\hat{s}(1,1) = s(0,0) + \sigma_c \nu_c,}$$

Two models of decision-making and learning under uncertainty.

They consider different types of uncertainty — there are parameter settings that reduce the general equation below to either a Black-Scholes or Bandit model.

$$\hat{s}(1,1) = \underbrace{\boxed{s(0,0)}}_{\text{DCF}} + \underbrace{\boxed{r_f - \sigma_p^2/2 + \sigma_p \nu_p}}_{\text{B-S}} + \underbrace{\boxed{\sigma_c \nu_c,}}_{\text{Bandit}}$$

Our Approach Continues to Build on the Black-Scholes and Bandit Models

Trajectory via B-S

$$k_t^j = k_{t-1}^j - \gamma^j - \frac{\sigma_p^2}{2} + \sigma_p \upsilon_p$$

"Fractional" Updating

$$\widehat{k_t^j} = k_{t-1}^j + \sigma_c \varepsilon_c$$

Two models of decision-making and learning under uncertainty.

The model assumes that the production provides a claim (via learning) on future technical progress. Since contemporaneous uncertainty is a noisy representation of the process, it is not contingent on production.

$$\widehat{k_t^j} = \boxed{k_{t-1}^j} + \boxed{q_{t-1}} \boxed{\left(-\gamma^j - \frac{\sigma_p^2}{2} + \sigma_p \upsilon_p\right)} + \boxed{\sigma_c \varepsilon_c}$$

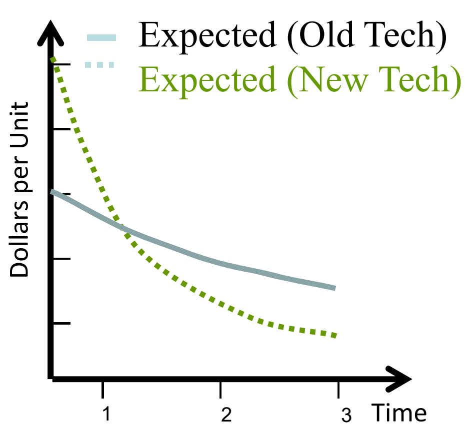
Prior Cost | Prod'n | Technical Progress | Prospective Uncertainty | Contemp. Uncertainty

The model now accounts for the evolution of multiple (j) technologies.

* The shift from "S" to "K" parameters reflects a change from asset value to cost.

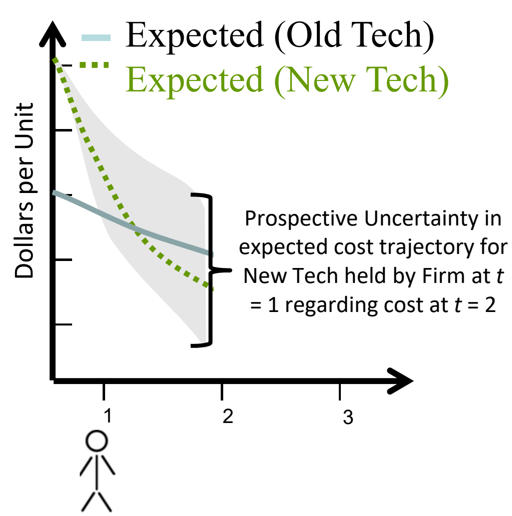
Summary of approach across three scenarios

No Uncertainty



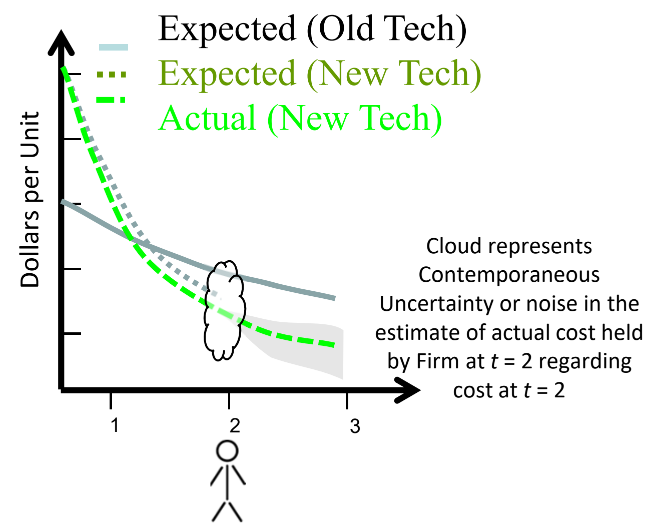
- The firm has full information on current costs *and* future cost reductions $(b^j_{t,t+n} = k^j_{t,t+n})$.
- The firm calculates an optimal decision (max π).

Prospective



- The firm has full information on current costs $(b^j_t = k^j_t)$ but is uncertain about future cost reductions.
- The firm calculates an optimal decision (max π) in expectations.

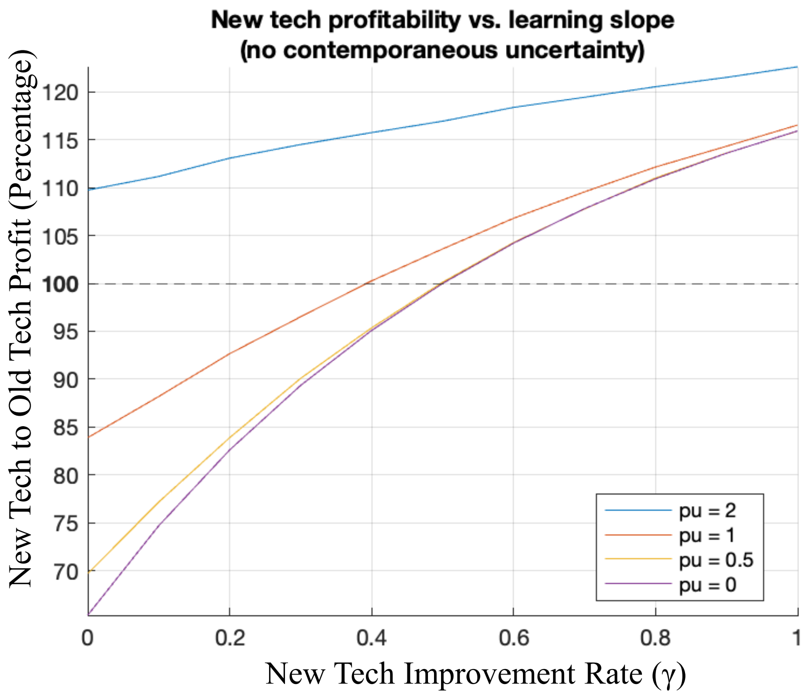
Prospective & Contemporaneous



- The firm is unsure of current costs and future cost reductions $(b^j_{t,t+n} \sim k^j_{t,t+n})$.
- Because the firm is acting on informative but noisy beliefs, all decisions involve some error.

Experiment 1a: Prospective Uncertainty & Technology Transitions

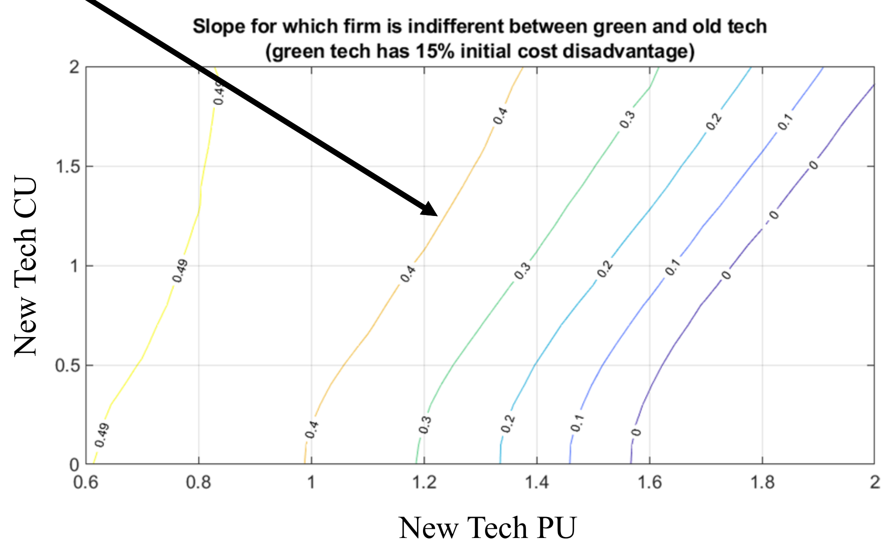
- Increasing γ in the new tech increases its viability
  - If PU = 0, 1 to 1 rate at an improvement slope of 0.5
- Prospective uncertainty affects the likelihood of transition
  - For a given γ, ↑ PU ↑ value and ↓ the required improvement rate.
- Implications
  - Upside potential is sufficient to motivate exploration and uncovering the true improvement rate is valuable.



Assumes no further improvement in "old" technology and an initial cost of the "new" technology is 15% > "old."

Experiment 1b: Prospective & contemporaneous uncertainty function in opposition

- Consider improvement rate in new tech, $\gamma, = 0.4$
  - As CU ↑, greater PU is required to maintain indifference or greater γ required to transition.
- Implications:
  - Form of uncertainty matters
    - PU ↑ and CU ↓ transitions.
  - Consider the costs of overestimating the improvement rate of a new technology.



The isobars illustrate the indifference curves between investing in the old and that new at varying technology improvement rates (adopt when improvement rate is steeper).

Assumes no further improvement in “old” technology, no PU or CU in “old” technology, and an initial cost of the “new” technology is 15% > “old.”

Summary Contributions to Date

- A systematic way of thinking through the implications of technical progress and uncertainty.
  - Consider the implications of “uncertainty regimes” (PU, CU sets) on choices to adopt a new technology.
  - Policy makers should consider rebates that expire early in the presence of PU.

- A refinement to existing reasoning
  - In addition to negative externalities and deterministic rates of improvement, uncertainty affects the evaluation of technologies.

- An application of behavioral real options theory

Additional Experiments

- How does competition affect the adoption of new (green) technologies under different uncertainty regimes?
  - A two-firm case with an incumbent invested in an “old” but certain technology and an entrant considering a “new” technology w/ PU & CU.
  - Initial cost reducing, learning rate increasing, and uncertainty-reducing spillovers.
  - Multiple demand segments of varying sizes and preferences.

- Are subsidies or taxes more efficient?
  - Consider whether PU/CU combinations or the shape of demand/technology curves influence the efficacy of (demand or production) subsidies vis a vis simple (carbon) taxes.
  - To address the “green” framing.

- How do complementary assets affect adoption?
  - Examine whether PU/CU in focal tech (solar) is super or sub-additive with uncertainty in complementary assets (batteries).

Regardless, we hope to pave the way for empirical work …

- How do organizational differences (behavioral and economic) affect decision-making in different uncertainty regimes.
  - (How) Does TMT membership and cognitive type (Gavetti, 2011) affect perceptions of the technical progress?
  - Does the market-specific experience of senior managers mitigate entry-timing errors (Diestre, et al., 2015).
  - (How) Do mental representations (Csaszar and Levinthal, 2016), theories (Felin and Zenger, 2017) or categorizations (Pontikes, 2018) affect perceptions of technical progress?

Thank you!

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