UCL Institute for Sustainable Resources

Induced innovation in energy technologies and systems: a systematic review of evidence

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Paris Energy Economics Seminar
2nd June 2021

Grubb M., P.Drummond, A.Poncia *et al*, A. Dechezlepraitre (2021). Induced innovation in energy technologies and systems a review of evidence and potential implications for CO2 mitigation, Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abde07

Motivation & Objective

- Innovation is crucial to tackling climate change. But *how* innovation occurs is just as important, to:
  - The long-run economics
  - Choice of policy instruments / mixes
  - Initial strength of response, "waiting for innovation inc R&D, *vs* inducing innovation through deployment"

- Innovation is often assumed to be due to R&D / technology-push, but the idea that the *direction* of innovation could respond to market conditions – incentives and expectations – was already argued by Hicks (1932), with learning-by-doing modeling by Arrow (1962), etc.

- However most (not all) dominant models, including majority of Global Integrated Assessment Models, assume innovation occurs *exogenously* to the model, or is a result of R&D (explicit knowledge investment) – and can reinforce the argument to 'wait for better technologies' or focus on R&D

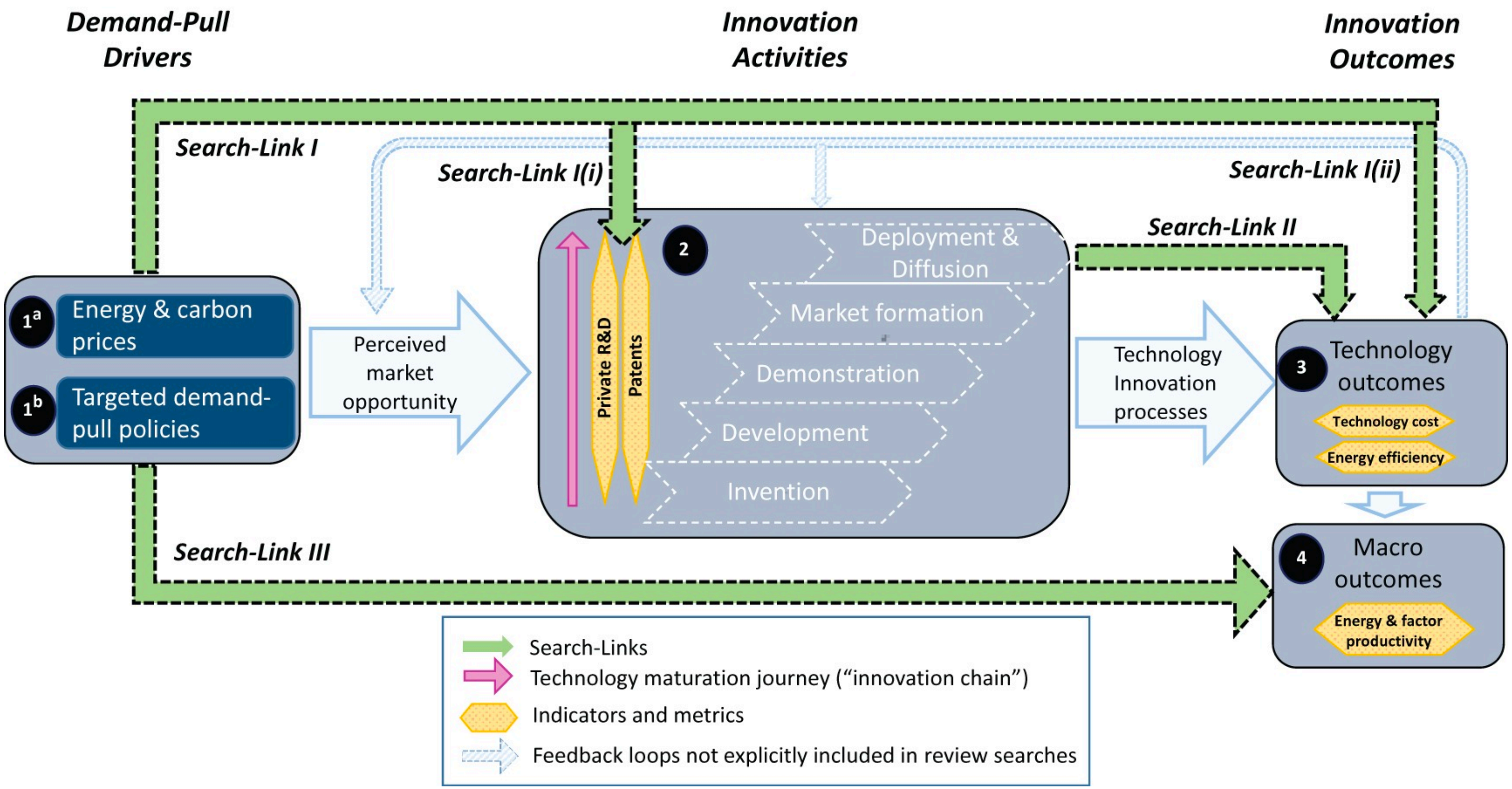
- An extensive phase of theoretical and exploratory modeling developments opened many avenues in the 2000s, but two major reviews confronted same problem: "our ability to conceptually model technical change has outstripped our ability to validate models empirically."

Research Question & Systematic Review Objective

*Do **'demand-pull'** factors (specifically energy prices, carbon prices and targeted policy interventions - beyond public R&D programmes) drive **innovation** in energy supply and energy using technologies and related systems?*

- A Systematic Review (SR) aims to provide **a complete summary of the current state of evidence** regarding a stated research question, by reviewing and synthesising all literature directly related to it (or components of it).
- Submitted as a proposal (and accepted) for a Special Issue of ***Environmental Research Letters***, on systematic reviews for IPCC AR6. Published in March 2021.
- This SR brings together a wide literature - **econometric** studies, **experience curve** studies, **qualitative and mixed-methods** studies, and **macro-economic** studies
- We focus on ***technology innovation***, acknowledging the wider socio-technical literature also underlines the importance of social / institutional innovation along with this

Sub-division of review into 3 *'Search-Links'*



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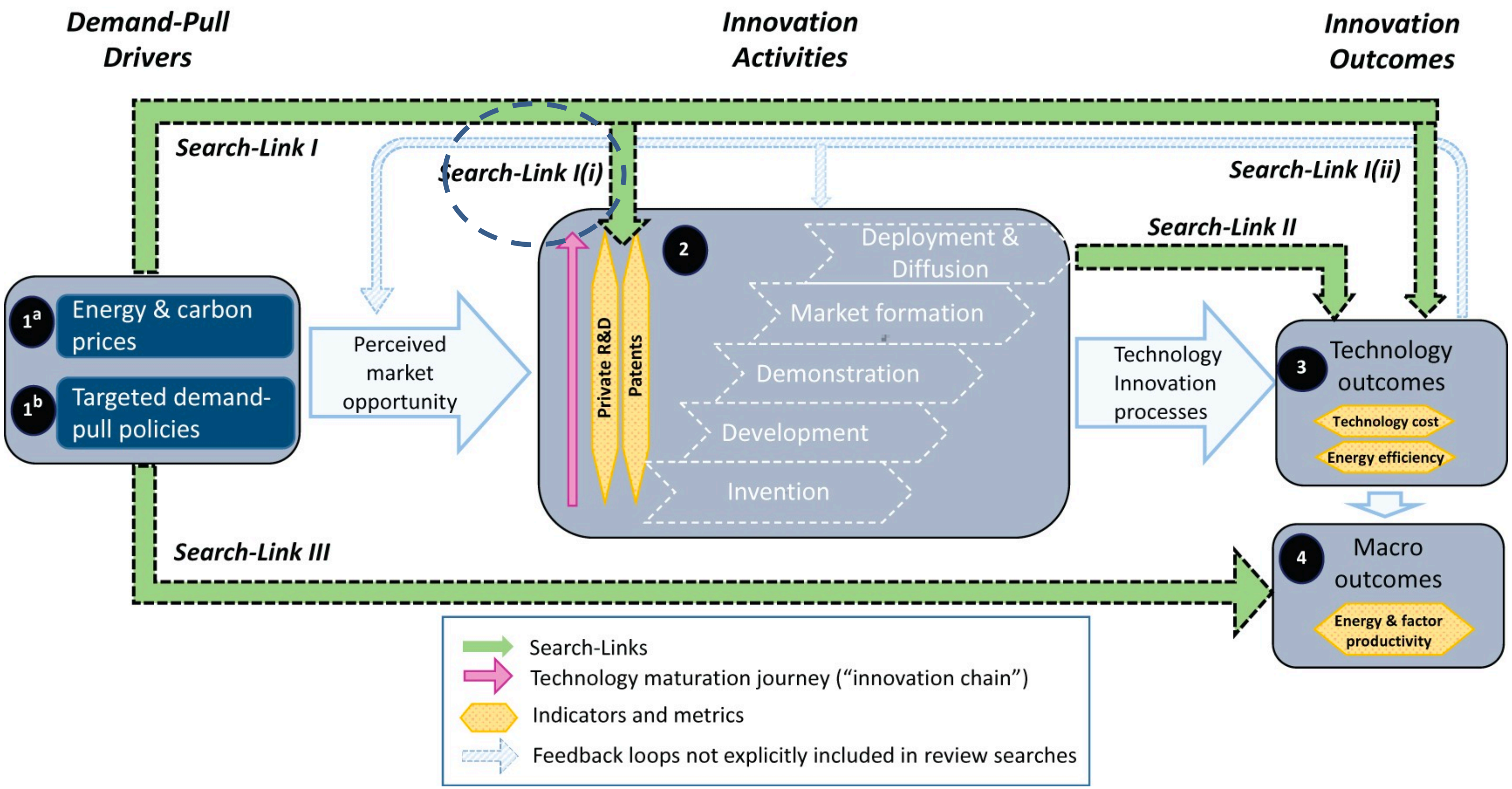

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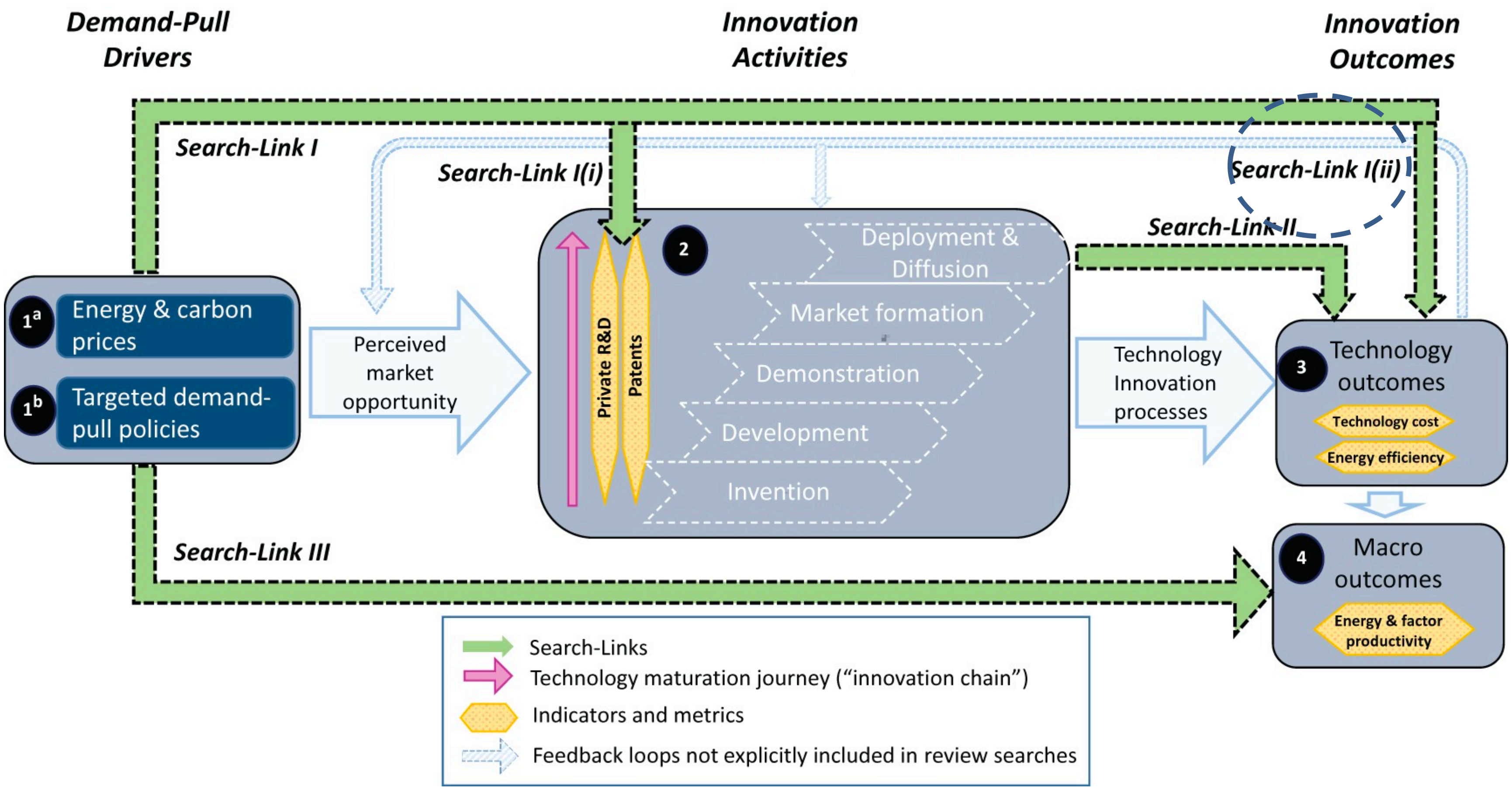

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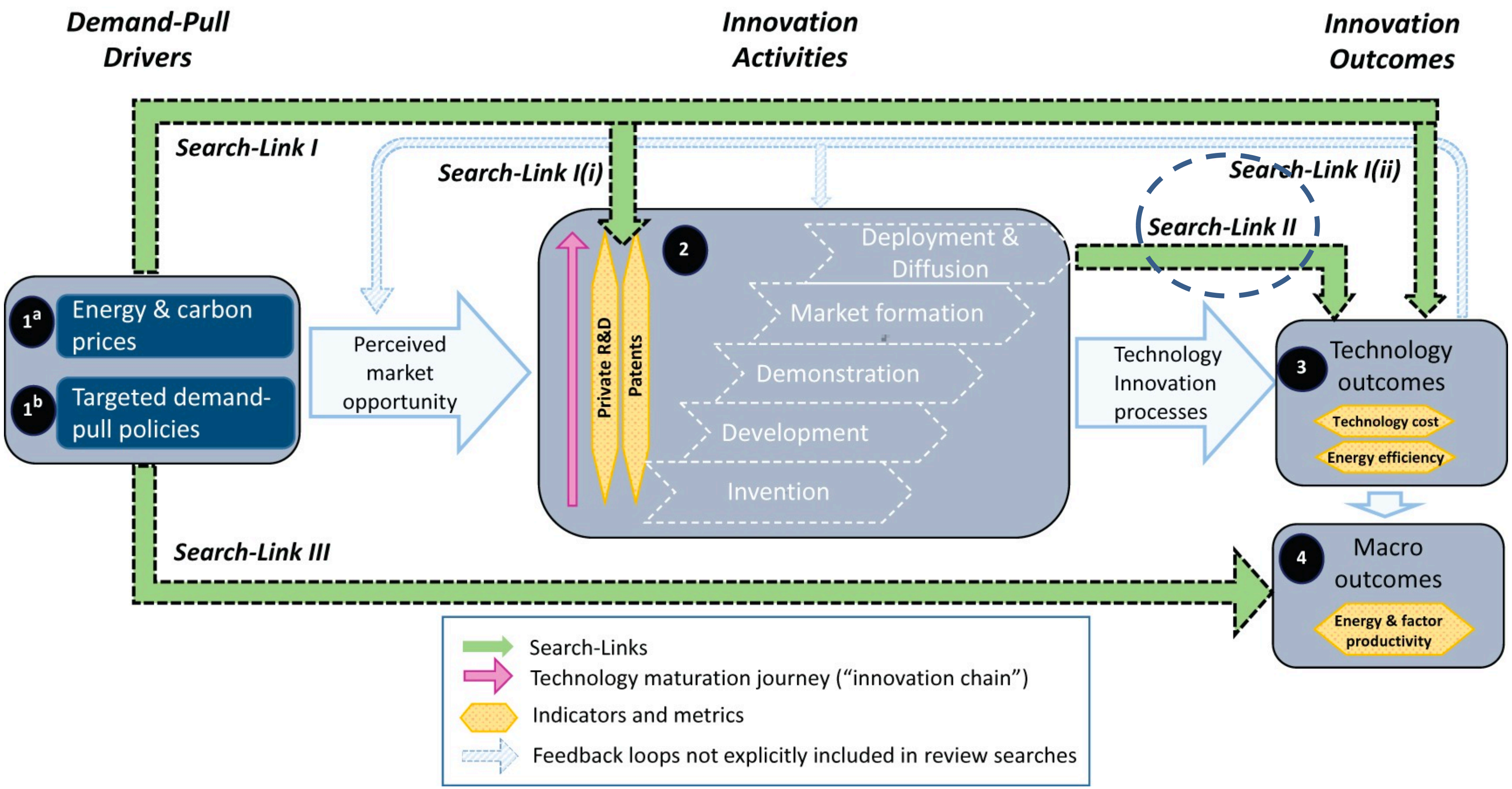

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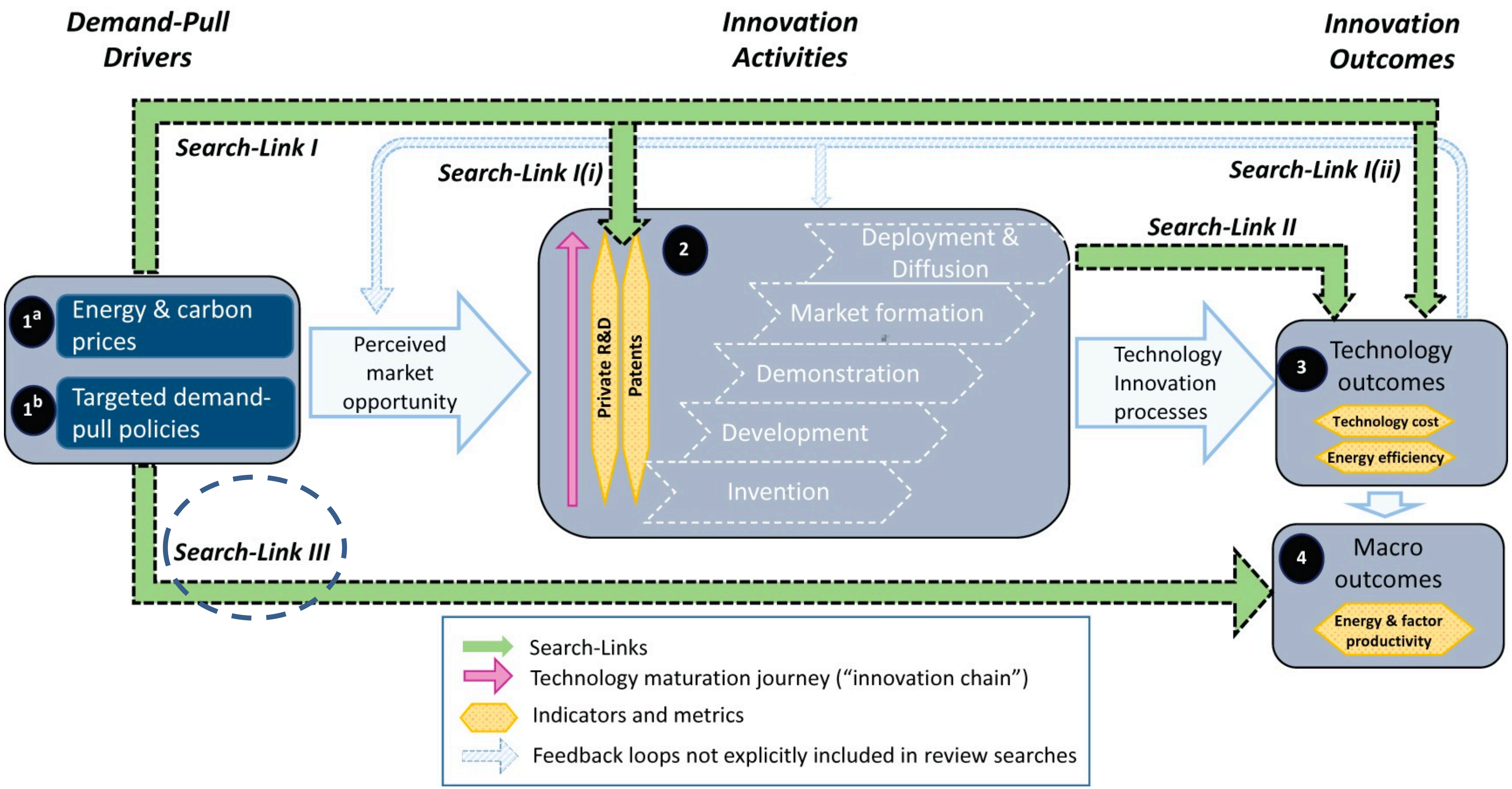
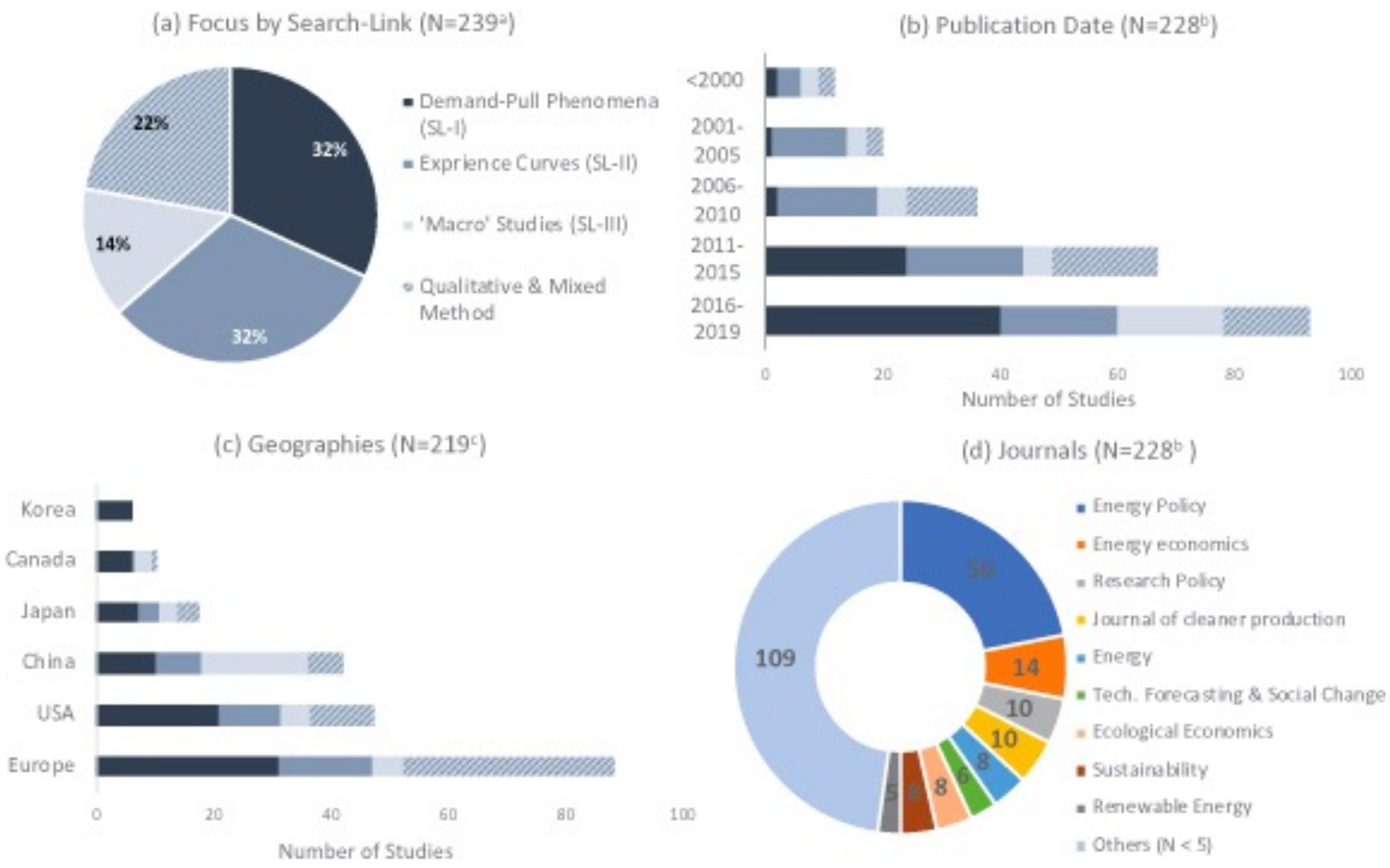


Overview of literature



Searched Web of Science Core Collection – **4,800** results

Key Inclusion Criteria:

(1) Relates to energy supply, energy efficient low-carbon technologies
(2) Focuses on demand-pull drivers of innovation *(excl. SL-II)* – ***not adoption***
(3) Conducts original empirical analysis
(4) Published in an English language, peer-reviewed academic journal

…applies to econometric/quantitative, qualitative & mix-methods studies

Included studies: **228** (239 results, with overlap between 'Search-Links')

(~80% of results excluded at 'title' stage as didn't comply with criterion (1))

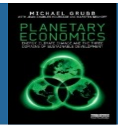
Key Results – *Search-Link I* *(energy prices -> innovation indicators/outcomes)*

- **Vast majority** of studies in SL-I examine link between 'demand-pull' drivers and ***indicators*** of innovation (i.e. patents) – **very few** directly examine the link between 'demand-pull' and innovation ***outcomes*** (i.e. technology cost-reduction)

Energy & Carbon Prices → Patents

- Econometric literature frequently derives ***price elasticities of patenting*** (i.e. % change in patent applications against % change in energy price), most often in *electricity, industry* and *transport* (very limited literature on buildings)

- Overall, **clear evidence of a positive** link between energy price increases and patenting across these sectors – although strongest effects are usually **lagged**, often by several years



Key Results – ***Search-Link I*** *(energy prices -> innovation indicators/outcomes)*

Study	Geography	Years	Independent Variable	Dependent Variable	Patent Elasticity
Multi-sector					
Kruse & Wetzel (2016)	26 (OECD) Countries	1998-2009	Average Energy Price	Ratio: Green Patents (11 technologies) : All Patents (A)	0.53*
Verdolini & Galeotti (2011)	17 (OECD) Countries	1979-1998	Industrial Energy Price	Patents (12 technologies) (G)	0.4
Popp (2002)	USA	1970-1994		Patents (11 technologies) (G)	0.35
Oil & Transport					
Aghion *et al* (2016)	80 Countries	1986-2005	Fuel Price	'Clean' Patents (G)	0.97
				'Grey' (Fuel Efficiency) Patents (G)	0.28
Kruse & Wetzel (2016)	26 (OECD) Countries	1998-2009	Average Energy Price	Ratio: Energy Efficiency in Transport Patents: All Patents (A)	0.77*
		1978-2009		Ratio: Biofuel Patents : All Patents (A)	-0.64*
Guillouzouic-Le Corff (2018)	22 (OECD) Countries	1985-2009	Household Oil Price	Biofuel Patents (A)	1.5
Fredriksson & Sauquet (2017)	French Civil Law Countries**	1986-2005	Fuel Price	'Clean' Patents (G)	2.32
	Common Law Countries***				1.2
Kessler & Sperling (2016)	USA	1976-2013	Oil Price	Biofuel (2nd Generation) Patents (A)	0.25
Jang & Du (2013)		1977-2010		Ethanol Patents (A)	0.04
Crabb & Johnson (2010)		1980-1999	Gasoline Retail Price Markup	Automotive Energy Efficiency Patents (A)	0.45
			Gasoline Price		0.36
			Domestic Wellhead Oil Cost		0.24
Electricity & Industry					
Kruse & Wetzel (2016)	26 (OECD) Countries	1978-2009	Average Energy Price	Ratio: Solar Patents: All Patents (A)	1.12*
				Ratio: Energy Storage Patents : All Patents (A)	1.08*
				Ratio: Ocean Energy Patents : All Patents (A)	0.61*
				Ratio: CCS Patents : All Patents (A)	0.56*
		1998-2009		Ratio: Geothermal Patents : All Patents (A)	0.37*
Ley *et al* (2016)	18 (OECD) Countries	1980-2009	Industrial Energy Price	Ratio: 'Green' Patents : All Patents (A)	0.48
				'Green' Patent (A)	0.34
Brolund & Lundmark (2014)	14 (OECD) Countries	1978-2009	Electricity Price	Bioenergy Patents (A)	0.87
			Ratio: Biomass : Light Fuel Oil Price		-0.33
Vincenzi & Ozabaci (2017)	11 (OECD) Countries	1990-2008	Electricity Price	Solar Patents (A)	0.12
Lin *et al* (2018)	China	2000-2012	Industrial Energy Price	'Clean' (Utility) Patents (A)	0.61
				Ratio 'Clean' Patents : All (Invention) Patents (A)	0.51
				'Clean' (invention) Patents (A)	0.38
Lin & Chen (2019)		2006-2016	Electricity Price	Renewable Patents (G)	0.78
He *et al* (2018)		2006-2013		Biomass Patents (A)	-0.41
				Renewable (Wind, Solar, Geothermal, Ocean, Biomass) Patents (A)	-0.72
				Wind Patents (A)	-0.72
				Solar Patents (A)	-0.8
Ye *et al* (2018)		2008-2014	Energy Price	Energy Conservation & Emission Reduction Patents (A)	0.14

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- Overall, **clear evidence of a positive** link between energy price increases and patenting across these sectors – although strongest effects are usually **lagged**, often by several years

- Patenting is commonly **path-dependent** and based on previous knowledge stock – e.g. firms previously involved in 'clean' patenting (e.g. renewables, electric vehicles) vs. 'grey' patenting (e.g. vehicle efficiency), tend to continue on that path

- Carbon pricing studies focus on EU ETS – largely **induced *incremental* innovation** (e.g. more efficient processes), and mostly when prices were high, or increasing stringency (and thus price) was expected in future.

Key Results – *Search-Link I (targeted policy -> innovation indicators/outcomes)*

Targeted Demand-Pull Policy → Patents

- Majority of studies focus on **Feed-in Tariffs** (FiTs). Clear evidence of induced patenting for solar PV, but mixed evidence for many other renewable energy technologies depending on timeframe, geography, and particularly *study design* (e.g. whether FiT design features – e.g. support level and duration – are accounted for).

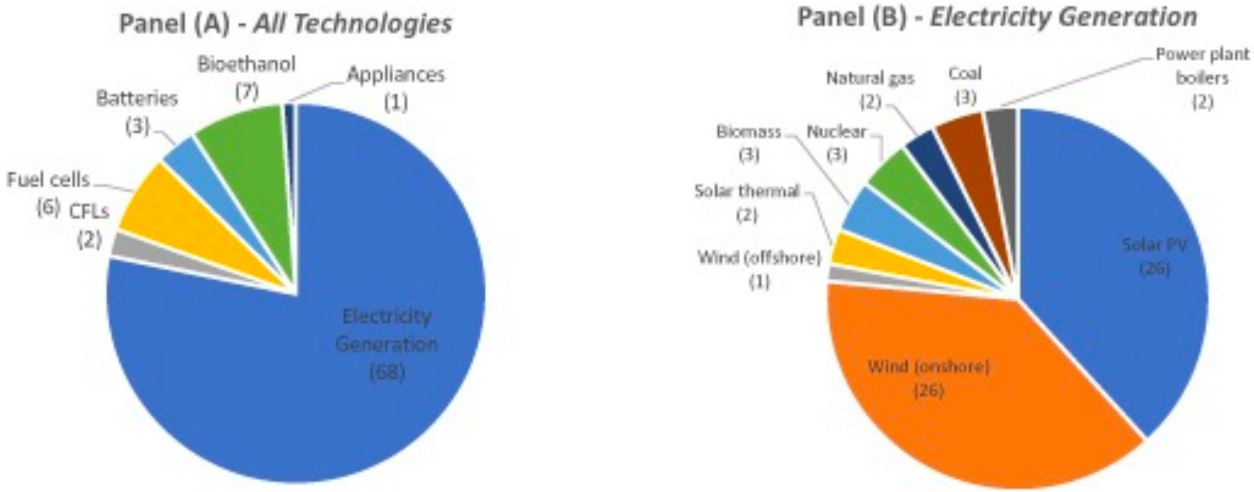
- **Renewable Portfolio Standards** found to be more successful in inducing patenting in more mature renewable technologies – e.g. onshore wind and first generation biofuels – than less mature, due to competition between technologies.

- **Regulatory (i.e. energy & CO_2) standards** are effective in increasing patenting in energy efficient & low-carbon technologies, but study results dependent on scope – e.g. CAFE vehicle fuel economy standards in U.S found to be ineffective in one study, but across a timeframe in which standards were static (~1984-2010).

- Few studies (econometrically) assess the role of overall **policy mixes**, but qualitative literature suggests characteristics of the overall policy mix (inc. design elements, implementation & enforcement, consistency, long-term reliability) **are crucial** in determining level and direction of innovative activity

Key Results – *Search-Link II* *(Experience Curves)*

- *Experience curves produce a* ***learning rate****: % reduction in cost per doubling in cumulative deployment (e.g. sales, capacity)*
- Limited scope to policy-deployed technologies (except in electricity generation)



- ***Overall conclusion*** - for almost all technologies, geographies and timeframes, learning rates are **positive**
- BUT:
  - (a) such studies measure correlation, not causation (with feedback also between cost and deployment)
  - *(b)* Most studies don't disentangle other factors (e.g. R&D funding, material input prices). Those that do, give reduced (but still positive) learning rates.

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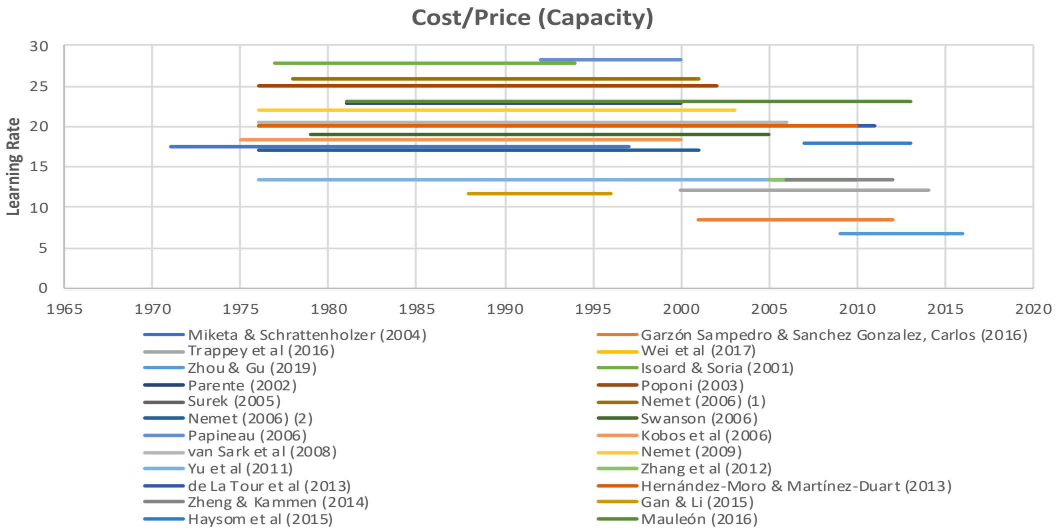
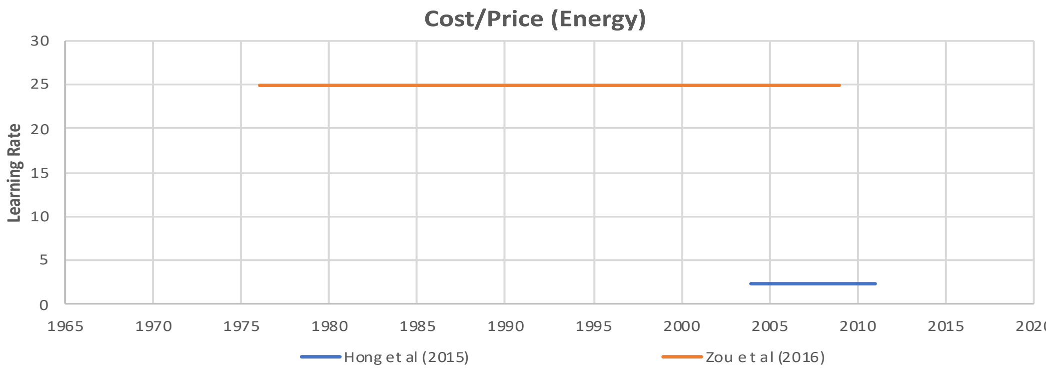
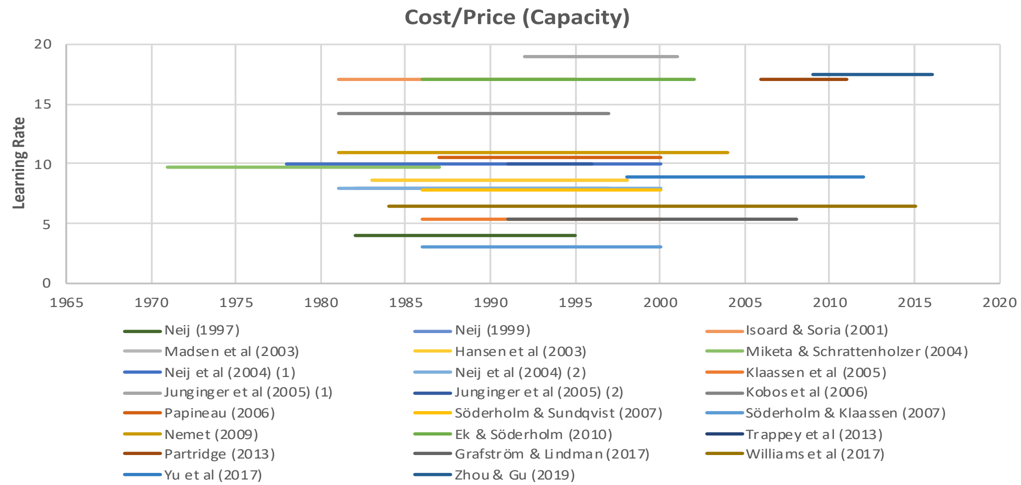
Key Results – ***Search-Link II*** *(Experience Curves)*

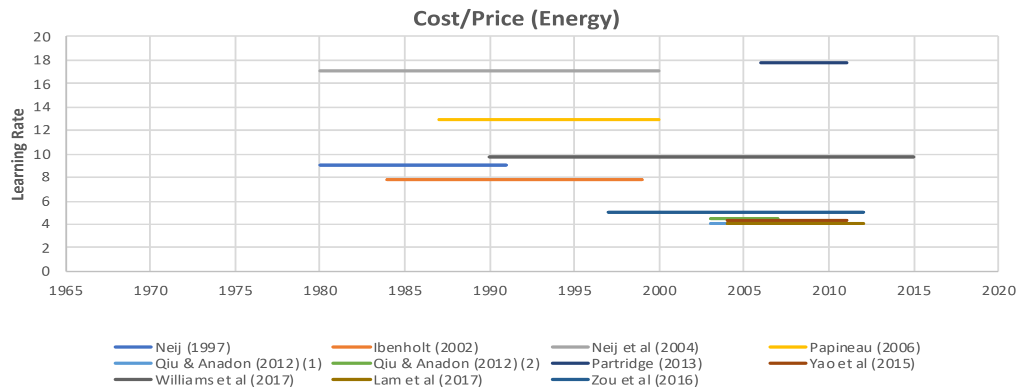
Solar PV





Onshore Wind





Key Results – ***Search-Link III*** *(Macro-outcomes) – the challenge*

- S-L III focusses on literature examining **the role of technical change**, induced by energy price changes or demand-pull policy, on **economy- or sector-wide** energy efficiency, energy intensity or total factor productivity (economic output/capital & labour input)

- At this macro level, the **combinations of other factors –** including exogenous and induced structural change (including trade effects), and exogenous technical change embodied in capital stock - makes it challenging to disentangle the impacts of actual induced technical innovation.

One broad category: Econometrically –evaluated determinants of economy-wide energy demand:

- ***Aggregate energy demand studies*** examine economy-wide energy demand or intensity as a function of production inputs and other determinants, eg. R&D, regulation, and energy price changes. "very few .. control for all three factors—R&D, price, and regulation … impact of specific regulatory policies on induced innovation remains largely untested."
- ***Aggregate production function studies*** *examine* energy-specific aggregate productivity levels with policy and price shocks; clear evidence (+ finally in publication, a Hassler paper in JPE finding initially low substitutability between energy and capital/labour but much greater substitutability over longer periods due to technical change).
- ***Stochastic-frontier analysis*** aims to estimate the technical frontier and explore what shifts this frontier. "use various frontier analysis methodologies and sometimes quite limited datasets, although collectively they tend to at least suggest that there are some gains from innovation induced by environmental regulation."

Key Results – *Search-Link III (Macro-outcomes) – additional lines of evidence*

- *Multi-sectoral decomposition studies* (to separate within-sector from cross-sector impacts and separate R&D from induced). Clear evidence that after the oil shocks of 1970s, technical change switched from energy-increasing to energy-saving. Probably most sophisticated study:
  - “by 2000, 40% of the reduction in aggregate energy intensity coming from technical change was attributed to induced technical change”

- *Asymmetric price elasticities* (‘what goes down doesn’t necessarily come back up …’). Early observations on response to oil shocks led to more complex analysis on role of embodied tech change, most extensive study on a modest (but long-standing) debate:
  - “almost all of the preferred models for OECD industrial energy demand incorporate both a stochastic underlying energy demand trend and asymmetric price responses”

ie. the macro-level evidence: energy-saving innovation is a combination of both exogenous and induced effects.

Overall, “the aggregate sectoral or macro level literature is surprisingly limited, likely a testament to the difficulty in extracting robust findings… . We do note that the findings tend to complement the findings from previous sections .. “

Summary – technical findings

*Do **'demand-pull'** factors (specifically energy prices, carbon prices and targeted policy interventions - beyond public R&D programmes) drive **innovation** in energy supply and energy using technologies and related systems?*

- Studies examining the influence of energy prices, carbon prices and other policies on innovation **very often use patent activity** as the dependent variable, rather than other outcomes (e.g. cost-reduction)

- Increasing energy and carbon prices, and introducing (or increasing the stringency/support of) targeted policy instruments, all have a clear, positive role in **enhancing innovation** (albeit with varied impacts across technologies, time and geographies, study design may sometimes account for opposing results)

- However, the **characteristics of the overarching policy landscape** are crucial in determining the **level of influence** they hold, and – along with the pre-existing knowledge stock - the **direction** of innovation

- Learning rates are **positive** in almost every instance examined, but studies measure **correlation between deployment and cost reduction** (not causation), and other influences on cost reduction often not accounted for

- **Economy- and sector-wide evidence** is slim, but **appears to concur** with the above – though focus & data to date on energy efficiency not decarbonisation *per se* - key area for future research

Overall implications

- "Hicks (1932) was right"
  - Demand-pull unambiguously influences innovation in energy efficiency & low-carbon technologies
- May be terminologically useful to distinguish
  - ***Deployment****: associated with stages of market development, encouraged with expectation of future benefits (e.g. cost reduction) with scale/experience*
  - …from ***diffusion****: a more autonomous, self-sustaining process (once e.g. cost-competitiveness is achieved)*
- Implies path dependency in emitting systems, and significant scope to reduce future abatement costs through enhanced (but diverse) early action
- Models which ignore this risk being misleading in their policy advice*
- Effective low carbon policy is complex because it needs to factor in a wide range of forces that can shape innovation

*eg. M.Grubb, C. Wieners and P. Yang (2021), Modeling Myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation, *Wiley Interdisciplinary Reviews: Climate Change.* DOI: 10.1002/WCC.698

Successful innovation must span a complex multi-domain journey

Technology journey	Basic R&D	Technology RD&D	Demonstration	Commercial-ization	Deployment	Wide Diffusion
Organisation & supply chain	A few individuals	Venture or new unit	First outsiders	Recruit specialists, Develop supply chain	Grow operational staff	Mature company or independent division
Customers and standards	No market defined	first targeting of possible markets	Choosing Market of commercial-ization	Early adopters and niches, basic standards	Expanding range of customers	Well defined Customer profile, trusted brand
Financing	Public or Internal funding	Internal funds or Project grants	Internal funds, project grants, angel or VC investors	First sales, internal or external funds still needed	First profits	Financing through private equity, banks, etc.
Market Regulation	Neutral or negative regulation	Neutral or negative regulation	Neutral regulation	Specific positive regulation	Positive general regulation	Fully adapted regulatory environment
Institutional	Research institutions	Bespoke technology institutions	First sector associations	Eg. first IPO, licence acquisitions	Lobbying, corporate expansion	Stable associations negotiating sector policy
Infrastructure	Research infrastructure	Test centres	Negative or neutral	'Piggybacking'/ First enabling infrastructure investments	Barriers from existing infrastructure	Adapted or dedicated infrastructure

Growing social scale and role of higher domains

1st

2nd

3rd

Source: Grubb, McDowell and Drummond (2017), On order and complexity in innovations systems, Energy Research & Social Science; derived from Fig.9.8 in Grubb et al (2014) *Planetary Economics*