Directed Technical Change and the Energy Transition: The Role of Storage Technology

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Innovation in clean technologies

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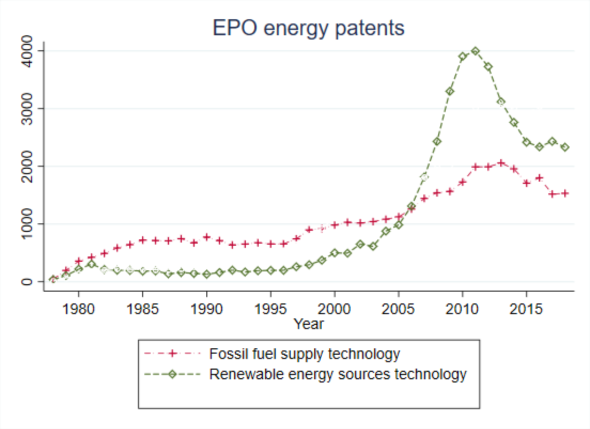

Data sources

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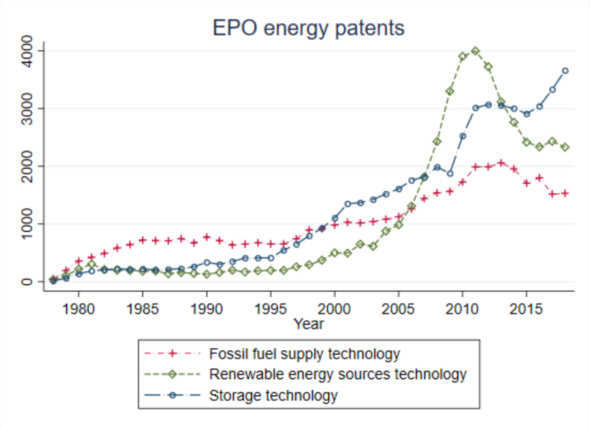

Other PO's Renewables Storage batteries Not EV-driven Biased public funding Data sources

Innovation in clean technologies

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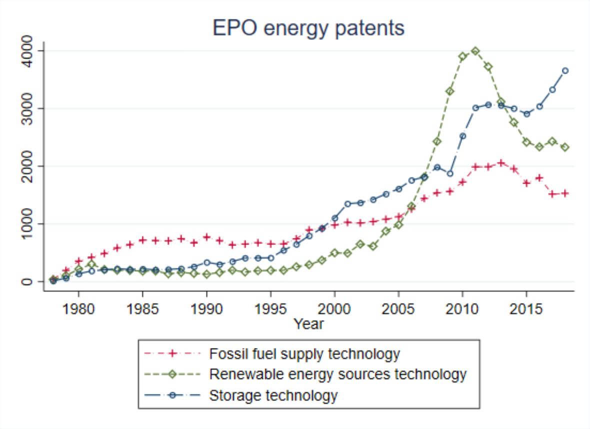
- The challenge of intermittency → storage technologies
- Storage patenting rise not explained by public support



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- ... calibrate it for the US economy, and use it to:
  - Evaluate effectiveness of US energy policy (pre- and post- IRA) to achieve
    - Energy transition and climate goals (COP28)
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  - Evaluate effectiveness of US energy policy (pre- and post- IRA) to achieve
    - Energy transition and climate goals (COP28)
    - Explore substitutability between sources of energy
- Main findings
  - Technological gap between renewables and storage is a relevant driver of private incentives to innovate in energy sectors.
    - Comparable to the effect of shale gas boom in deterring green innovation
  - Both pre- and post-IRA policy measures are unable to reach COP28
    - In the absence of a carbon tax, high efforts in production subsidies would be necessary
  - Due to low productivity of storage, fossil fuels and renewables are currently complements

Introduction

Literature

Theoretical framework
  - Model setup
  - Equilibrium and path dependence

Calibration

Main results

Conclusion

Literature

- Micro-oriented and literature on electricity markets:
  - Finds only limited importance of battery capacity due to high costs
  - Ambec and Crampes, 2019; Stöckl and Zerrahn, 2020; Pommeret and Schubert, 2022; Helm and Mire, 2018
- Endogenous growth literature:
  - Cost of transition is determined by the substitutability between fossil fuels and renewables
  - Acemoglu et al. 2012; Fried, 2018; Jo and Miftakhova, 2022; Gentile, 2024
  - Recent collapse in green innovation caused by fracking boom
  - Popp et al. 2022; Acemoglu et al. 2023
- Our approach: Incorporate energy storage in standard models of directed technical change to evaluate and explore energy policy and the collapse in green innovation

Analytic model

- Endogenous growth model (Acemoglu, 2002) with different sources of energy (Acemoglu et al. 2012)
  - Endogenous innovation to improve energy sources' technology
- Extended energy sector:
  - Storage capacity
  - Technology spillovers
- Extended policy tools:
  - Carbon tax
  - Research subsidies
  - Energy production subsidies
- Useful to
  - Understand the role of storage innovation in the energy transition
  - Evaluate the effect of climate policies, e.g., IRA
  - Design policy mixes to reach decarbonization targets

Final good production

- Discrete time economy
- Final good produced using two energy inputs (clean Y_c and dirty Y_d), according to

$$Y_t = \left(Y_{dt}^{\frac{\epsilon-1}{\epsilon}} + Y_{ct}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}. \tag{1}$$

- Perfectly competitive firms (pcf)

$$\max_{\{Y_{dt}, Y_{ct}\}} P_t Y_t - p_{dt}(1 - z_{dt}) Y_{dt} - p_{ct}(1 - z_{ct}) Y_{ct}, \tag{2}$$

- where z_j represent taxes or subsidies to the use of inputs

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- $Y_c \sim$ composite of renewable Y_r and storage Y_s capacity, produced by pcf

$$Y_{ct} = \left(\delta Y_{rt}^{\frac{\rho-1}{\rho}} + (1-\delta) Y_{st}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} . \tag{3}$$

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Assumption 1

Y_d and Y_c are substitutes, $\epsilon > 1$, while Y_r and Y_s are complements, $\rho \in (0, 1)$.

Intermediates and machines production

- Production of intermediates $j \in \{d, r, s\}$ is given by

$$Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{ijt}^{1-\alpha} x_{ijt}^{\alpha} di. \tag{4}$$

- Produced by pcf, under a fixed supply of workers

$$L_{dt} + L_{dt} + L_{dt} \leq L \equiv 1.$$

- The use of the dirty input releases CO2 emissions and affect temperature

$$E_t = \xi_t Y_{dt}$$

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$$E_t = \xi_t Y_{dt}$$

- Machines: x_{jit}
  - Unit continuum in each sector j
  - Cost: ψ units of final good
  - Produced by single monopolist

$$\max_{\{p_{ijt},\ x_{ijt}\}} (p_{ijt} - \psi) x_{ijt}. \tag{5}$$

$$p_{ijt}^{x} = \frac{\psi}{\alpha}. \tag{6}$$

Innovation

- A fixed mass of scientists that decide on which sector to innovate

$$s_{rt} + s_{st} + s_{dt} \leq 1. \tag{7}$$

- If successful (with prob. $\eta_j s_{jt}^{\sigma}$, congestion), the scientist becomes the monopolist producer of that machine in the next period

$$A_{jit+1} = (1 + \gamma) A_{jit}. \tag{8}$$

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- Without spillovers: $A_{jt} = (1 + \gamma\eta_j s_{jt}^{\omega})A_{jt-1}$
- With spillovers: $A_{jt} = A_{jt-1}\left[1 + \gamma\eta_j s_{jt}^{\omega}\left(\frac{A_{t-1}}{A_{jt-1}}\right)^{\nu}\right]$, where $A_t = \frac{A_{dt}+A_{rt}+A_{st}}{3}$.

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- Allocation of scientists
  - In **equilibrium**, expected profits must equalize

$$\Pi_{dt} = \Pi_{rt} = \Pi_{st}. \tag{9}$$

Allocation of scientists I (without spillovers)

- Expected profit of research in sector j relative to sector k

$$\frac{\Pi_{jt}}{\Pi_{kt}} = \frac{1+q_{jt}}{1+q_{kt}} \times \frac{\eta_j}{\eta_k} \left(\frac{s_{jt}}{s_{kt}}\right)^{\omega-1} \underbrace{\left(\frac{p_{jt}}{p_{kt}}\right)^{\frac{1}{1-\alpha}}}_{\text{Price ef.}} \times \underbrace{\frac{L_{jt}}{L_{kt}}}_{\text{Market size ef.}} \times \underbrace{\frac{A_{jt-1}}{A_{kt-1}}}_{\text{Direct productivity ef.}} \quad (10)$$

- Path dependence (ambiguous):
  - Price effect (-):

$$\frac{p_{jt}}{p_{kt}} = \left(\frac{A_{jt}}{A_{kt}}\right)^{-(1-\alpha)}$$

  - Market size effects: complements (-) vs substitutes (+)

$$\frac{L_{rt}}{L_{st}} = \left(\frac{\delta}{1-\delta}\right)^{\rho} \left(\frac{A_{rt}}{A_{st}}\right)^{-\sigma}$$

$$\frac{L_{ct}}{L_{dt}} = \left(\frac{A_{dt}}{A_{rt}A_{st}}\right)^{\phi} ((1-\delta)^{\rho} A_{rt}^{\sigma} + \delta^{\rho} A_{st}^{\sigma})^{\frac{1-\epsilon}{1-\rho}} \left(\frac{1-z_{ct}}{1-z_{dt}}\right)^{-\epsilon}$$

Allocation of scientists II (without spillovers)

- Profitability of renewable research relative to storage research

$$\frac{\Pi_{rt}}{\Pi_{st}} = \frac{1+q_{rt}}{1+q_{st}} \frac{\eta_r}{\eta_s} \left(\frac{s_{rt}}{s_{st}}\right)^{\omega-1} \left(\frac{\delta}{1-\delta}\right)^{\rho} \underbrace{\left(\frac{1+\gamma\eta_r s_{rt}^{\omega}}{1+\gamma\eta_s s_{st}^{\omega}}\right)^{-(1+\sigma)} \left(\frac{A_{rt-1}}{A_{st-1}}\right)^{-\sigma}}_{\text{Direct path dependency effect (-)}}, \tag{11}$$

- where $\sigma \equiv (1-\alpha)(1-\rho)$ and q_j is the rate of a proportional profit subsidy financed through a lump-sum tax on the rep. hh.

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Lemma 1

Under Assumption 1, the evolutions of renewable and storage technologies experience a negative path dependence.

Proof The $\frac{\Pi_{rt}}{\Pi_{st}}$ is decreasing in A_{rt} and increasing in A_{st}

Allocation of scientists III (without spillovers)

- Profitability of renewable research relative to dirty research

$$\frac{\Pi_{rt}}{\Pi_{dt}} = \frac{1+q_{rt}}{1+q_{dt}}\frac{\eta_r}{\eta_d}\left(\frac{s_{rt}}{s_{dt}}\right)^{\omega-1}\left(\frac{1-z_d}{1-z_c}\right)^{\epsilon}\underbrace{\left(\frac{1+\gamma\eta_r s_{rt}^{\omega}}{1+\gamma\eta_d s_{dt}^{\omega}}\right)^{-1-\phi}\left(\frac{A_{rt-1}}{A_{dt-1}}\right)^{-\phi}}_{\text{Direct path dependency effect (+)}}$$

$$\times\underbrace{\delta^{\rho}\left[\delta^{\rho}+(1-\delta)^{\rho}\left(\frac{1+\gamma\eta_r s_{rt}^{\omega}}{1+\gamma\eta_s s_{st}^{\omega}}\right)^{\sigma}\left(\frac{A_{rt-1}}{A_{st-1}}\right)^{\sigma}\right]^{\frac{\rho-\epsilon}{1-\rho}}}_{\text{Indirect path dependency effect(-)}}. \quad (12)$$

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Lemma 2

Analytically ambiguous effect of an increase in A_{rt} on $\frac{\Pi_{rt}}{\Pi_{dt}}$.

Proof Direct path dependency effect (+); Indirect path dependency effect (-)

Allocation of scientists IV (without spillovers)

- Profitability of renewable research relative to dirty research

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Proposition 1

All else equal and under Assumption 1, an increase in the technology ratio between renewables and storage, $\frac{A_{rt-1}}{A_{st-1}}$*, or a decrease in the input share of renewables,* δ*, increase the strength of the indirect path dependency effect.*

Proposition 2

All else equal and under Assumption 1, higher levels of historical storage technology increase the profitability of renewables relative to dirty research.

Proofs

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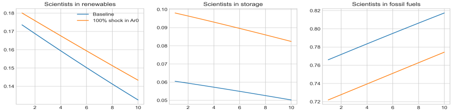
Calibration: US economy (2015-2090)

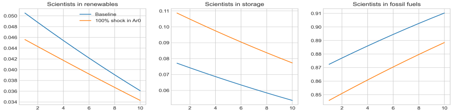
Table 1: Parameter values

Parameter	Value	Source
Time periods	5 years	-
Final good production and consumption		
Electricity elasticity of substitution, ϵ	1.5	Fried (2018)
Clean energy elasticity of substitution, ρ	0.5	Informative calibration
Distribution parameter in clean energy, δ	0.85	
Coefficient of relative risk aversion: ν	2	Standard
Per annum discount rate, ρ	0.015	Standard
Intermediate production		
Share of machines in production, α	1/3	Standard
Cost of machines, ψ	α	Normalization
Initial productivity of renewables, A_{r0}	704.7	Calibration
Initial productivity of energy storage, A_{s0}	62.4	Calibration
Initial productivity of fossil fuels, A_{d0}	1332.6	Calibration
Research sector		
Size of innovations, γ	1	Normalization
Probability of innovation in renewables, η_r	0.2	Acemoglu et al. (2012)
Probability of innovation in energy storage, η_s	0.2	Acemoglu et al. (2012)
Probability of innovation in fossil fuels, η_d	0.2	Acemoglu et al. (2012)
Decreasing returns to scientists, ω	0.5	Acemoglu et al. (2016)
Spillover parameter, ν	0.3	-
Policy tools		
Production subsidies q_j	Values q_j's	Calibration
R&D subsidies z_j	Values z_j's	Calibration

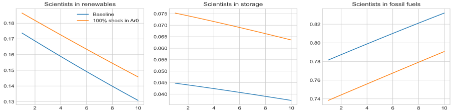
Numerical illustration of Proposition 1: Effect of a shock to A_{r0} (x2) on the allocation of scientists (no policy)



(a) $A_{r0} = A_{d0} = A_{s0} = 100, \delta = 0.75$



(b) $A_{r0} = A_{d0} = 100, A_{s0} = 10, \delta = 0.75$



(c) $A_{r0} = A_{d0} = 100, A_{s0} = 10, \delta = 0.95$

- A shock in A_{r0}: a) increases s_r when $A_{s0} = A_{r0}$; b) decreases s_r when $A_{s0} < A_{r0}$; c) increases s_r when $A_{s0} < A_{r0}$ but δ is high

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Main Results

1. US energy policy evaluation
2. Exploration of the recent collapse in renewable innovation (shale gas boom, storage technology level)
3. Estimation of the elasticity of substitution between fossil fuels (Y_d) and renewables (Y_r)

1. US energy policy evaluation

- 1. No policy
- 2. Pre−IRA energy policy

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  - 1/3 IRA's costs on production and investment tax credits for clean electricity and storage (Bistline, Mehrotra and Wolfram, 2023)

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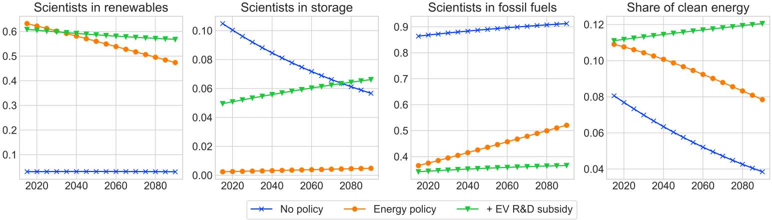
Table 2: Policy rates under each policy scenarios

	z_d	z_c	$\frac{(1+q_r)}{(1+q_d)}$	$\frac{(1+q_r)}{(1+q_s)}$
1. No policy	0	0	1	1
2. Energy policy	0.005	0.152	5.6	33.8
3. + EV R&D subsidy	0.005	0.152	5.6	7.1
4. + IRA subsidy	0.005	0.2	5.6	7.1

Pre- vs post-IRA

- Current energy policy is not sufficient to decarbonize energy production



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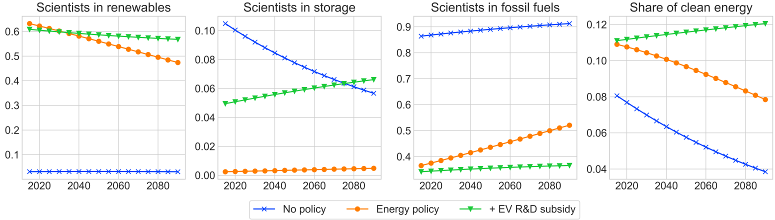
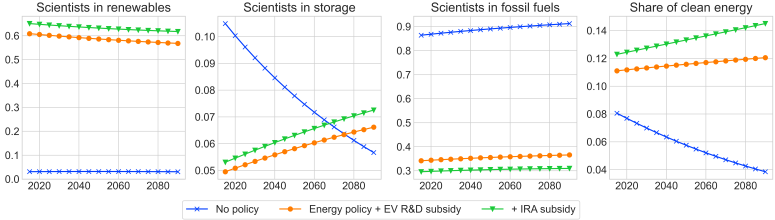


- ...and neither is the IRA production subsidy



Decarbonization targets

- COP28 Agreement: triple global renewable power capacity by 2030, Y_{r30} (rel. 2022)

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Table 3: Decarbonization targets by 2030

	COP28	$\%\Delta Y_r$	z_c	s_{r30}	s_{s30}	s_{d30}	A_{s0}
IRA subsidy	✗	77.6	0.2	0.64	0.06	0.30	111.3

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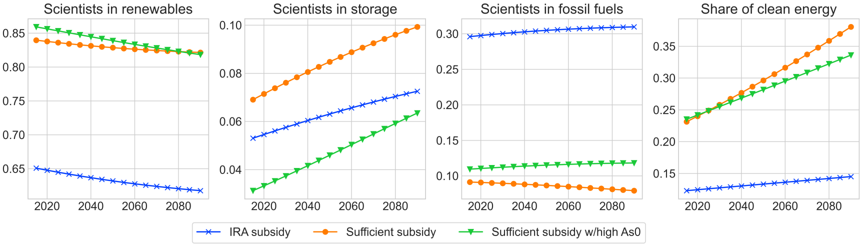
Table 3: Decarbonization targets by 2030

	COP28	$\%\Delta Y_r$	z_c	s_{r30}	s_{s30}	s_{d30}	A_{s0}
IRA subsidy	✗	77.6	0.2	0.64	0.06	0.30	111.3
Sufficient subsidy	✓	200	0.46	0.83	0.08	0.09	111.3
Sufficient subsidy+higher A_{s0}	✓	200	0.345	0.85	0.037	0.11	222.6

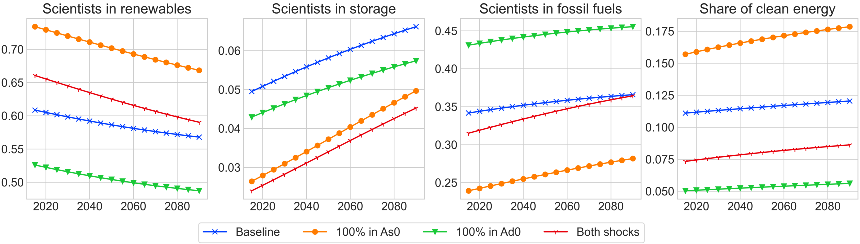
Decarbonization goal

- COP28 goal attainment ensures green path



2. Collapse in renewable innovation

- Shale gas boom (100% ↑ A_{d0}) vs. storage-renewables technological gap



- The large technological gap between renewables and storage can have reduced the level of innovation in renewables by a magnitude similar to that of the shale gas boom

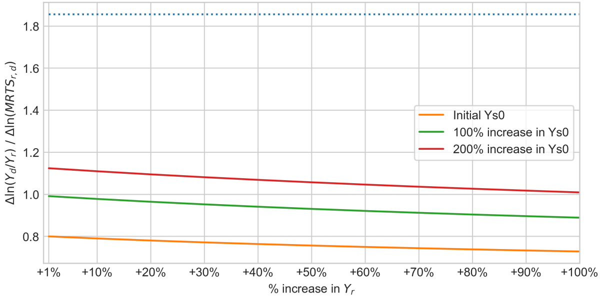
3. Variable elasticity of substitution btw renewables and fossil fuels

- Elasticity calculation

$$el_{r,d} \equiv \frac{\Delta \ln\left(\frac{Y_{dt}}{Y_{rt}}\right)}{\Delta \ln(MRTS_{r,d})}, \tag{14}$$

where

$$MRTS_{r,d} = \frac{\frac{\partial Y_t}{\partial Y_{rt}}}{\frac{\partial Y_t}{\partial Y_{dt}}} = Y_{dt}^{\frac{1}{\epsilon}} \delta Y_{rt}^{-\frac{1}{\rho}} \left(\delta Y_{rt}^{\frac{\rho-1}{\rho}} + (1-\delta) Y_{st}^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho+\epsilon}{\epsilon(\rho-1)}} .$$



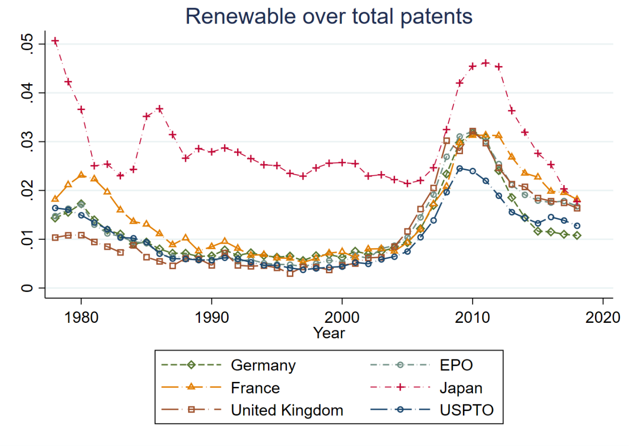
Conclusion

- Accounting for the complementarity between renewables and storage results in insightful path dependencies
- Technological gap between renewables and storage is a relevant driver of private incentives to innovate in energy sectors.
  - Comparable to the effect of shale gas boom in deterring green innovation
- IRA falls short in achieving near term climate goals
- Staying within the IRA framework (production subsidies) would require much higher subsidies...
- ... even if past policy choices had partially addressed the big gap between renewables and storage technologies
- Due to low productivity of storage, fossil fuels and renewables are currently complements

Appendix

Stylized facts

- Similar patterns in renewable innovation across countries



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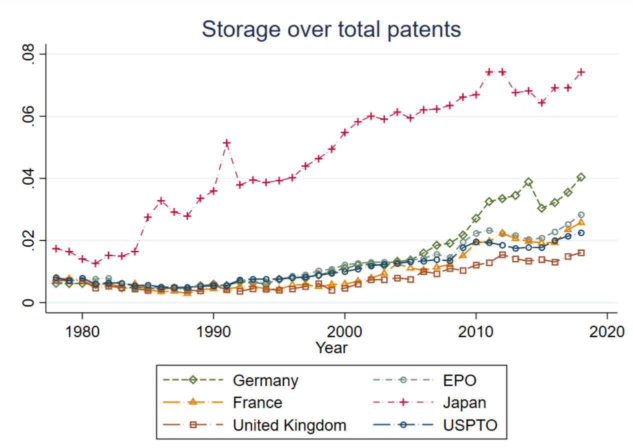
Stylized facts

- Similar patterns in storage innovation across countries



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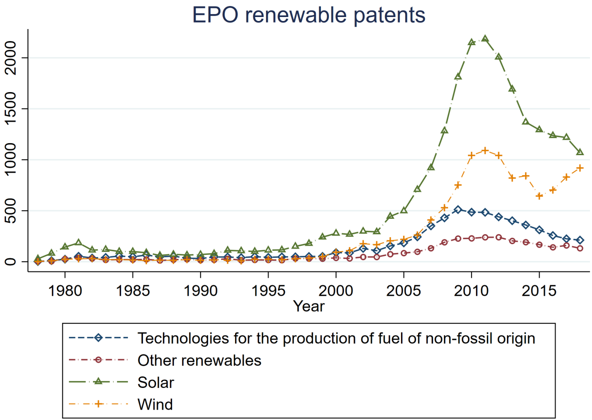
Stylized facts

- Solar and wind drive the renewable collapse



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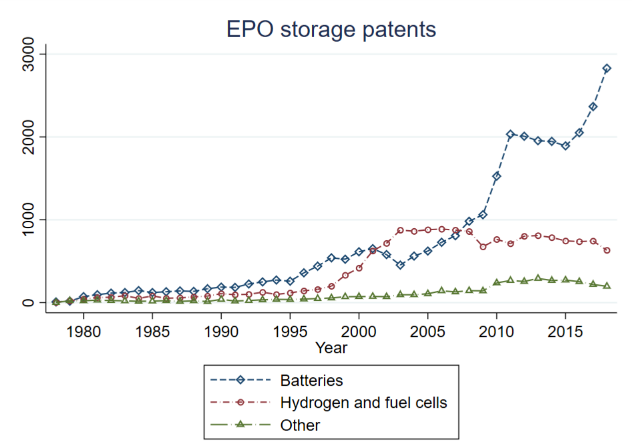
Stylized facts

- Batteries drive the storage rise



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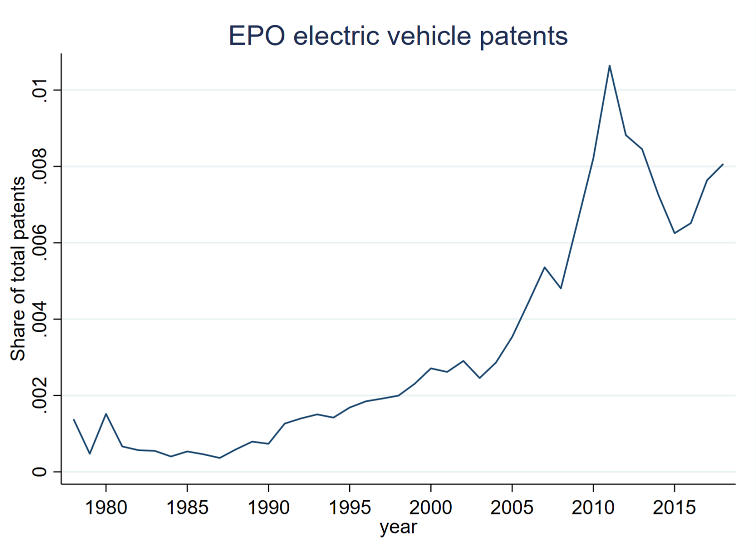
Stylized facts

- Sharp increase in electric vehicles patent since mid-2000s (1% in 2010)
- Rise in storage not driven by advances in electric vehicle technologies



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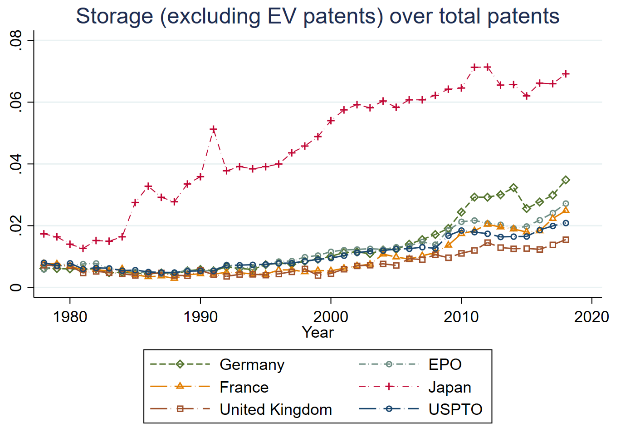

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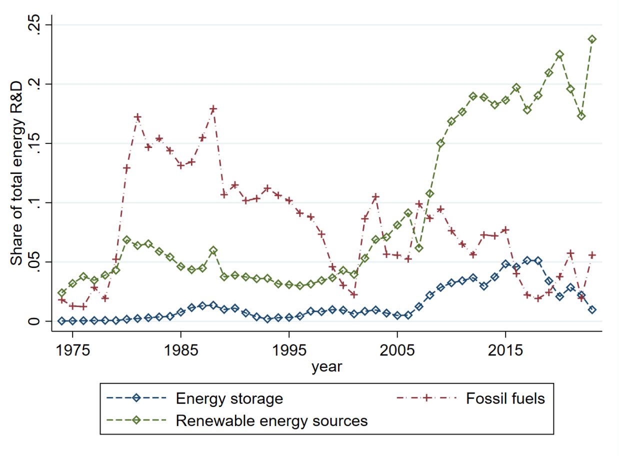
Stylized facts

- IEA members: Public support for storage cannot explain innovation increase
- 2019-2023: Only 2% energy storage (21% renewables and 4% fossil fuels)
- 2015 US: Relative to the total installed costs of renewables and storage, renewables are subsidized 30 times more than storage



Data sources

- Innovation trends are measured by patent applications:
    - Universe of patent applications filed at the European Patent Office (EPO) from PATSTAT
    - Identify patent applications in fossil fuels, renewables and energy storage with new methodology from the IEA (2021)
    - Classification is based on the assigned CPC codes codes
- Innovation policy is measured by public expenditure on energy R&D:
    - Data on public budgets on research, development and demonstration in energy technologies from the IEA (2023)
    - Budgets are reported by all IEA member countries
    - Extract total expenditures on fossil fuels, renewables and energy storage

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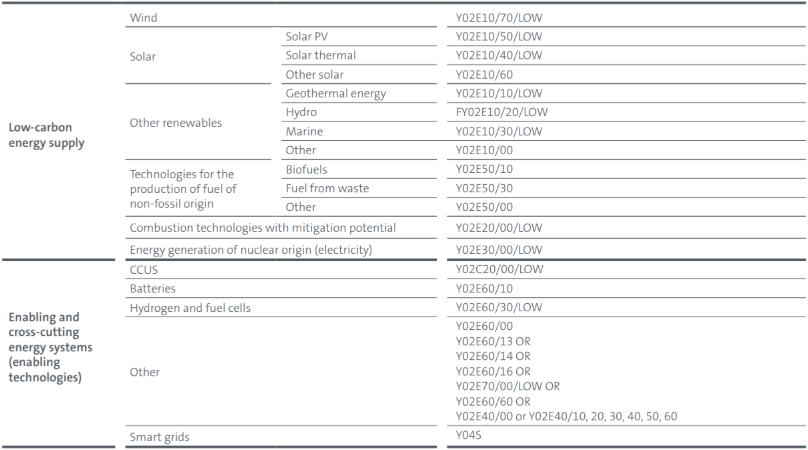
Cartography of LCE technologies from the IEA

- Renewable energy = Low-carbon energy supply (excl. nuclear and combustion)
- Energy storage = Batteries + Hydrogen and fuel cells + Other (Y02E 60/13, Y02E 60/14, Y02E 60/16)



Low-carbon energy supply	Wind		Y02E10/70/LOW
	Solar	Solar PV	Y02E10/50/LOW
		Solar thermal	Y02E10/40/LOW
		Other solar	Y02E10/60
	Other renewables	Geothermal energy	Y02E10/10/LOW
		Hydro	FY02E10/20/LOW
		Marine	Y02E10/30/LOW
		Other	Y02E10/00
	Technologies for the production of fuel of non-fossil origin	Biofuels	Y02E50/10
		Fuel from waste	Y02E50/30
		Other	Y02E50/00
	Combustion technologies with mitigation potential		Y02E20/00/LOW
	Energy generation of nuclear origin (electricity)		Y02E30/00/LOW
Enabling and cross-cutting energy systems (enabling technologies)	CCUS		Y02C20/00/LOW
	Batteries		Y02E60/10
	Hydrogen and fuel cells		Y02E60/30/LOW
	Other		Y02E60/00 Y02E60/13 OR Y02E60/14 OR Y02E60/16 OR Y02E70/00/LOW OR Y02E60/60 OR Y02E40/00 or Y02E40/10, 20, 30, 40, 50, 60
	Smart grids		Y04S

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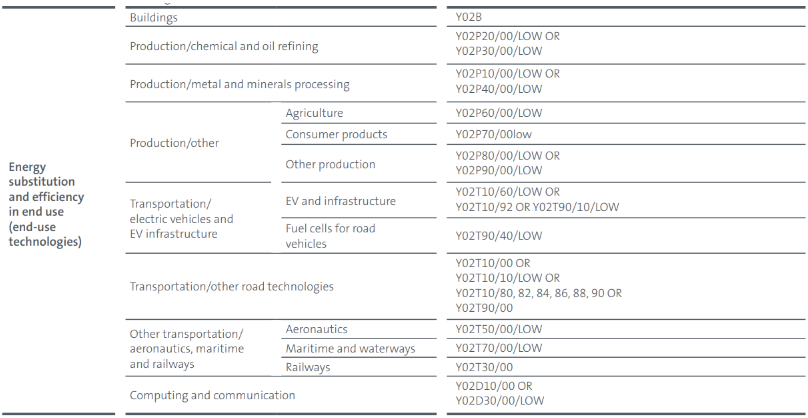
Cartography of LCE technologies from the IEA

- Electric vehicles = EV and infrastructure + Fuel cells for road vehicles



Energy substitution and efficiency in end use (end-use technologies)	Buildings		Y02B
	Production/chemical and oil refining		Y02P20/00/LOW OR Y02P30/00/LOW
	Production/metal and minerals processing		Y02P10/00/LOW OR Y02P40/00/LOW
	Production/other	Agriculture	Y02P60/00/LOW
		Consumer products	Y02P70/00low
		Other production	Y02P80/00/LOW OR Y02P90/00/LOW
	Transportation/ electric vehicles and EV infrastructure	EV and infrastructure	Y02T10/60/LOW OR Y02T10/92 OR Y02T90/10/LOW
		Fuel cells for road vehicles	Y02T90/40/LOW
	Transportation/other road technologies		Y02T10/00 OR Y02T10/10/LOW OR Y02T10/80, 82, 84, 86, 88, 90 OR Y02T90/00
	Other transportation/ aeronautics, maritime and railways	Aeronautics	Y02T50/00/LOW
		Maritime and waterways	Y02T70/00/LOW
		Railways	Y02T30/00
	Computing and communication		Y02D10/00 OR Y02D30/00/LOW

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Proofs

Proof of Lemma 1: Under Assumption 1 σ is positive, from which follows that $\frac{\partial \frac{\Pi_{rt}}{\Pi_{st}}}{\partial A_{rt-1}} < 0$ and $\frac{\partial \frac{\Pi_{rt}}{\Pi_{st}}}{\partial A_{st-1}} > 0$. ■ Back to Main

Proof of Lemma 2: Under Assumption 1, $\phi < 0$ and $\rho - \epsilon < 0$. ■

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Proof of Proposition 1: Under Assumption 1, $\frac{\partial(\text{Indirect path dependency effect})}{\partial \frac{A_{rt-1}}{A_{rt-1}}} < 0$. Furthermore, under lower values of δ, the negative component of $\frac{\partial(\text{Indirect path dependency effect})}{\partial \delta}$ is larger, making it more plausible to satisfy that $\frac{\partial(\text{Indirect path dependency effect})}{\partial \delta} < 0$. ■

Proof of Proposition 2: Under Assumption 1, σ is positive and $\epsilon > \rho$, from which follows that $\frac{\partial \frac{\Pi_{rt}}{\Pi_{dt}}}{\partial A_{st-1}} > 0$. ■

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Calibration ρ

- Elasticity of substitution between renewable and storage (ρ)
- Two approaches for curve fitting process
  - Bid information from solar-plus-storage markets in the US
    - $\rho = 0.34$
  - Aghahosseini et al. (2023)'s forecast on 2050 electricity generation by source (net-zero IEA scenario by 2050)
    - $\rho = 0.75$
- In progress
  - Method of moments

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Calibration z_j's

- Average annual production subsidy (%), 2010-2016:
    - Clean energy: 15.2%
    - Dirty energy: 0.5%
- Estimation
    - Average annual production subsidy , 2010-2016:
        - Clean energy: 11,756 million USD
        - Dirty energy: 1,204 million USD
    - Average annual LCOE, 2010-2016:
        - Clean energy: 148.5 USD per MWh
        - Dirty energy: 90.4 USD per MWh
    - Average annual generation, 2010-2016:
        - Clean energy: 521,375 GWh
        - Dirty energy: 2,761,098 GWh

$$\Rightarrow z_c = \frac{11{,}756{,}000{,}000USD}{521{,}375{,}000MWh \times 148.5USD/MWh} = 0.152$$

$$\Rightarrow z_d = \frac{1{,}204{,}000{,}000USD}{2{,}761{,}098{,}000MWh \times 90.4USD/MWh} = 0.005$$

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Calibration q_j's

- Average annual share of public expenditures on energy R&D, 2011-2015 (IEA, 2023):
  - Renewables: 13.5%
  - Fossil fuels: 2.4%
  - Energy storage: 0.4%
  - EV battery technology: 1.5%

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