From fossil fuels to renewables: The role of electricity storage

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Directed technical change in electricity

- Climate change concerns have led society to seek alternatives to reduce GHG emissions
- Electricity production is a main GHG source
  - 32% of GHG emissions in the US in 2012 (transportation sector responsible for 28%)
  - Up 11% from 1990

⇒ Highlights importance of shift from fossil fuels to renewable sources

Electricity storage plays important role

- A major obstacle for increasing the share of renewable sources in the grid mix is the intermittency of renewable energy sources – ex: wind, solar
- Large scale electricity storage represents a potential solution
  - Increases the flexibility in meeting demand – produce then dispatch when needed
  - Enables the utilization of more of the potential energy available from intermittent sources

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- Electricity storage – a double-edged sword?
  - Creates more arbitrage possibilities for existing power producers, including nonrenewable producers

Research question

- RQ: Does electricity storage shift the direction of innovation toward renewable energy sources?
- What this study does:
  - Model: Electricity storage endogenously improves the substitutability between renewable and fossil fuel technologies
  - Empirical analysis to test how and to what extent innovation in electricity storage affects innovation in renewable and fossil fuel generating technologies

Storage initiatives

- Public and private initiatives to increase electricity storage capacity
- Innovation is key: The cost of energy storage currently a big roadblock
- IHS CERA: 40 GW of storage capacity will be connected to the grid globally by 2022
- Storage technologies: Compressed air storage, liquid air storage, large batteries, power-to-gas, *pumped hydro*

Theory model

- Directed technological change framework
- An application to the electricity sector
- Electricity storage changes substitutability between renewable and nonrenewable electricity

Model assumptions

- One-period model:
  1. Innovation at beginning of period
  2. Production with improved technologies at end of period
- Individuals: Consume electricity and aggregate outside good
- Firms: Electricity retailers and generators, innovators
  - Take all prices and initial technologies as given

Endogenous elasticity of substitution

- The more efficient the storage technology, the higher the elasticity of substitution between renewable and nonrenewable electricity:

$$Y = \left(Y_c^{\frac{\epsilon(A_s)-1}{\epsilon(A_s)}} + Y_d^{\frac{\epsilon(A_s)-1}{\epsilon(A_s)}} \right)^{\frac{\epsilon(A_s)}{\epsilon(A_s)-1}}$$

  where A_s is the current efficiency of the storage technology
- Innovation improves the storage technology

Innovation

- Innovation in three technologies: renewable and nonrenewable electricity generation, and storage
- Innovation x_j costs $\frac{1}{2}\psi_j x_j^2$ and yields technical progress:

$$A_j = (1 + x_j)\, A_{j0},\ j = c, d, s$$

- Renewable and nonrenewable generation (c, d):
  - Innovation yields more efficient production technologies

  $\Rightarrow$ Lowers cost of electricity generation
- Storage technologies (s)
  - Innovation increases substitutability between renewable and nonrenewable electricity:

$$\epsilon(A_s) = \epsilon_0\, (1 + x_s)\, A_{s0}$$

Equilibrium

1. End-of-period production problem: Production levels of renewable and nonrenewable electricity for given technologies
2. Beginning-of-period innovation problem: Innovation effort in renewable generation, nonrenewable generation, and storage technologies

Innovation in equilibrium

- Innovation in renewable and nonrenewable generation:

$$\psi_j x_j P^{\beta-\epsilon} = \left(\epsilon P F^{\frac{1}{\epsilon-1}} + 1 - \epsilon\right) F_j^{1-\epsilon} \left(\frac{A_{j0}}{A_j}\right), \; j = c, d$$

- Innovation in storage:

$$\frac{\psi_s x_s P^{\beta-\epsilon}}{\epsilon_0 A_{s0}} = \ln P \left(P F^{\frac{\epsilon}{\epsilon-1}} - F\right) + F_c^{1-\epsilon} \ln F_c + F_d^{1-\epsilon} \ln F_d$$
$$+ P F^{\frac{\epsilon}{\epsilon-1}} \left\{ \left(\frac{\epsilon}{\epsilon-1}\right) \frac{F_c F_d^{\epsilon} \ln F_c + F_c^{\epsilon} F_d \ln F_d}{F_c^{\epsilon} F_d + F_c F_d^{\epsilon}} + \frac{\ln F}{(\epsilon-1)^2} \right\}$$

- Highly nonlinear equation system that characterizes innovation equilibrium: x_c^*, x_d^* and x_s^*

→ Note that ϵ, A_j, F, F_j are all functions of innovation (x_j)

From theory to empirical analysis

According to the theory model, innovation mainly depends on the following factors:

- The initial state of technologies (knowledge stocks), A_{j0} for $j = c, d, s$
- Electricity prices, P
- Fossil fuel prices, f

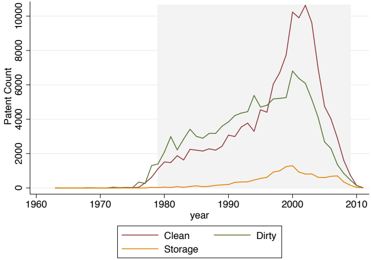
Unique dataset
What data do we need?

We build a unique global, firm-level dataset of innovations in electricity storage, and clean and dirty generation, with information on:

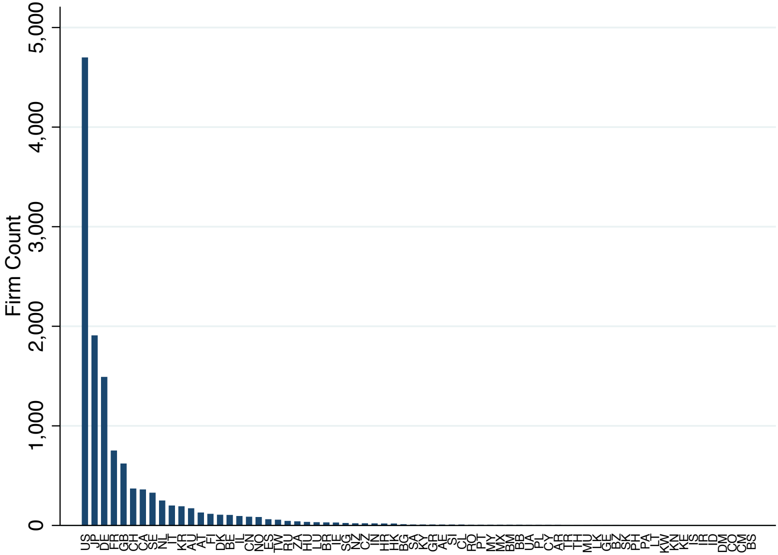
1. Innovations from the global patent database of the OECD
   - ⇒ Select electricity related patents using International Patent Classification (IPC) codes from the World Intellectual Property Organization (WIPO)
2. Energy prices from the International Energy Agency
3. Economic data from the Penn World Tables

Descriptive statistics

- 12,557 firms
- 70 countries
- Period: 1968-2011
- 260,252 patents:
  - Renewable: 129,753
  - Nonrenewable: 116,534
  - Storage: 13,965

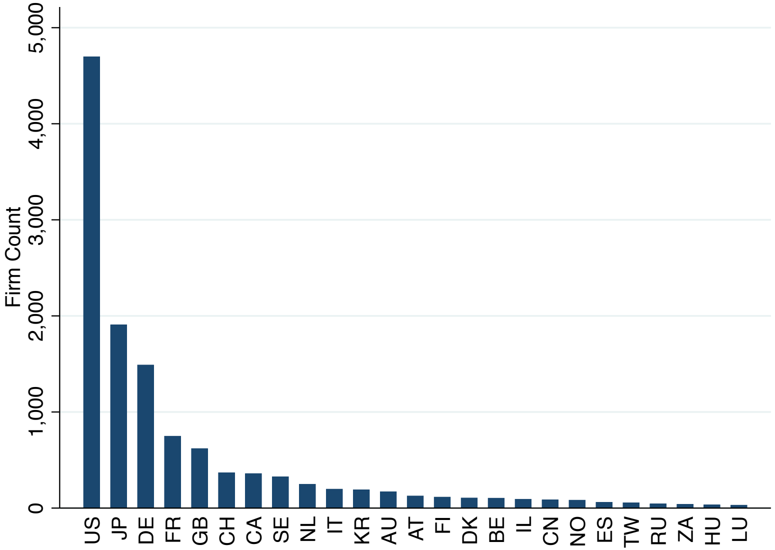


Innovating firms by country



Innovating firms by country

Zooming in on the top 25



Empirical strategy

Baseline specification (firm i; country n; technology $j = c, d, s$; in year t)

$$A_{jit} = \mathbf{E}_{njt-1}\boldsymbol{\beta_{1j}} + \mathbf{I}_{ijt-1}\boldsymbol{\beta_{2j}} + \mathbf{I}^2_{ijt-1}\boldsymbol{\beta_{3j}} + \mathbf{F}_{it-1}\boldsymbol{\alpha_j} + \mathbf{X}_{it-1}\boldsymbol{\gamma_j} + \delta_{tj} + \delta_{ij} + u_{ijt}$$

- A: number of patent applications filed by firm
- Relevant knowledge stock, K_{it}
  - Internal stock, $\mathbf{I}$: Firm's cumulative number of patents
  - External stock, $\mathbf{E}$: Cumulative number of patents by all other firms in the relevant region (spillover effects)
- $\mathbf{F}_{it}$: Firm-level exposure to fossil-fuel and electricity prices
- $\mathbf{X}_{it}$: Firm-level exposure to economic indicators (GDP and GDP/capita)
- δ_{ji}: firm fixed effects
- δ_{jt}: year fixed effects

⇒ Estimate with fixed-effects Poisson regression

Estimation results: Baseline model

Probability to innovate in storage, renewable, and nonrenewable technologies

Dependent variable: storage/renewable/nonrenewable patent count

	Storage	Renewable	Nonrenewable
Past innovations (L3):			
Storage	-0.00927**	0.01092**	0.00243
	(0.00354)	(0.00308)	(0.00395)
Renewable	0.00136*	-0.0032**	-0.00199
	(0.00056)	(0.00103)	(0.00135)
Nonrenewable	-0.00093*	-0.00047	-6.8e-05
	(0.00041)	(0.00038)	(0.00021)
Regional spillovers (L3):			
Storage	0.00033	0.00032†	-0.00029
	(0.00028)	(0.00019)	(0.00028)
Renewable	-6.8e-05	-9.2e-05**	2.7e-05
	(5.7e-05)	(3.3e-05)	(5.5e-05)
Nonrenewable	5.7e-06	4.7e-06	-3.9e-05
	(3.5e-05)	(2.3e-05)	(3.5e-05)
Energy prices (L1):			
PCoal	-0.3045	-0.3397**	-0.3871*
	(0.2236)	(0.127)	(0.1786)
PElectricity	0.1312	0.2167	0.3259†
	(0.2331)	(0.1842)	(0.1804)
Economic controls (L1):			
GDP	0.1308	-0.0767	-0.04017
	(0.1314)	(0.08384)	(0.09254)
GDPcap	0.9574	1.4650*	1.0500†
	(0.7476)	(0.587)	(0.6001)
Observations	13241	59265	38932
No. of groups	1335	8681	5107
Chi^2	6330.65	1304.89	493.22

Significance levels: **: 1% *: 5% †: 10%

Storage helps both renewable and nonrenewable

Result 1

Q1: How does storage affect innovation in electricity generation?

- Renewable: Better storage technologies ⇔ more innovation in renewable technologies
- Nonrenewable:
  - Better storage technologies ⇒ more innovation in efficiency-improving nonrenewable technologies
  - However, overall effect (all nonrenewable technologies) positive but statistically non-significant

⇒ Electricity storage not only benefits renewable energy, also conventional production → intermittency problem and ramping issue

⇒ Electricity storage affects both the speed and direction of technical change in electricity generation

Complements or substitutes?
Result 2

Q2: Are renewable and nonrenewable electricity inputs complements or substitutes?

- Our empirical results match the theoretical predictions when renewable and nonrenewable are substitutes
- Exception: A higher fossil fuel price yields less innovation in renewable generation, rather than more

$\Rightarrow$ Intermittent renewable electricity currently rely on (base/peak) electricity from fossil fuels, but not the other way around

Fossil fuel prices
Result 3

Q3: How does the fossil fuel price affect innovation in the electricity sector?

- Contrary to what we expected, the coal price has a negative impact on innovation in all three technologies: renewable, nonrenewable, and storage
- With current storage solutions, renewable electricity relies on backup from traditional fossil-fuel based electricity (grid balance, peak/off-peak)

⇒ Policies seeking to promote renewable electricity by raising the price of fossil fuels (ex: CO_2 tax) might not have the intended effect (yet) – unless combined with other policy efforts

Robustness

Results are robust to various specifications:

- More fixed effects: Firm + year + country + country-by-year FEs
- Selection of patents (tech definition)
- Extent of spillovers
- Lag structure: 1 to 5 years
- Fuel prices: coal, natural gas, oil

Summary and conclusions

- We study the role of storage on innovation in electricity:
  - We propose a stylized model of innovation and production in the electricity sector
  - Estimate the effect of innovation in electricity storage on innovation, and the direction of technological change in electricity generation using global patent data from 1969 to 2011

Summary and conclusions

- We study the role of storage on innovation in electricity:
  - We propose a stylized model of innovation and production in the electricity sector
  - Estimate the effect of innovation in electricity storage on innovation, and the direction of technological change in electricity generation using global patent data from 1969 to 2011
- We find that electricity storage significantly affects both the speed and direction of innovation in electricity generation:
  - Firms with more storage knowledge more likely to file patents related to renewable and efficiency-improving nonrenewable generation
- Positive feedback between innovation in storage and renewable generation (not between storage and nonrenewable)

Policy implications

- Better storage promotes emissions reductions in electricity generation through innovation
- R&D subsidies and private efforts toward innovation in electricity storage key to increase the share of renewables
  - ...but also efficiency improvements in conventional generation
- Until more efficient storage solutions exist, higher fossil fuel prices (coal, natural gas) might hurt innovation in renewable/storage technologies