Predicting innovation dynamics in the technological ecosystem

An application to green energy technologies

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Motivation

- Innovation is path-dependent process which is function of knowledge base
- Diverse technological ecosystem entails heterogeneous innovation dynamics
- How to optimally support specific technologies such as green energy technologies?

[Arthur, 2009; Fleming, 2001; Usher, 1954; Youn et al., 2015; Napolitano et al., 2018]

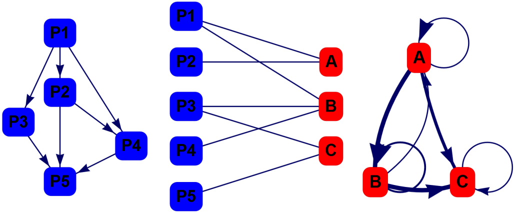
Data

- US utility patents from 1836 to 2017
  - 10 million patents
  - 91 million citations
- CPC 4-digits classifications as technological domains
  - $N = 649$ ... number of distinct technologies
- Temporal technology network $\{W_t : t = 1947, ..., 2017\}$
  - $W_{ij,t} := \frac{C_{ij,t}}{\sum_{j=1}^{N} C_{ij,t}}$
  - Share of technology j in i's knowledge base at time t

[Masuda and Lambiotte, 2016]

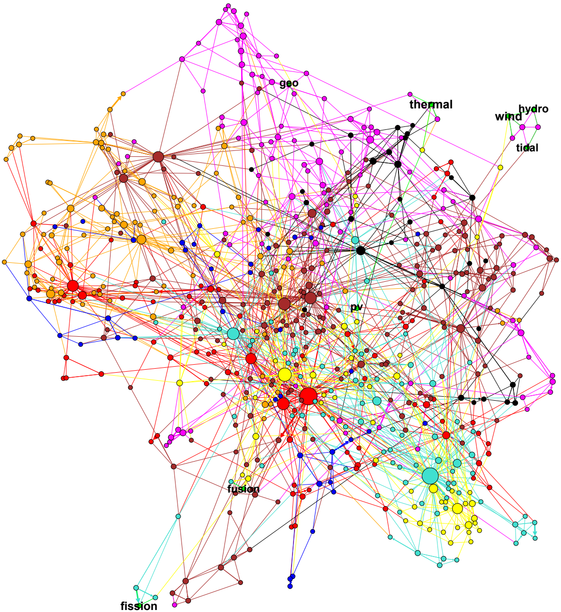
Construction of technology network

- H_{pq} … patent citation network $\rightarrow$ p cites q
- $\tilde{B}_{pi}$ … bipartite patent-technology network
  $\rightarrow$ patent p associated with technology class i
- $B_{pi} := \tilde{B}_{pi} / \sum_i \tilde{B}_{pi}$ … "share" of technology i in patent p
- $C := B^\top H B$ … technology citation matrix



$$H = \begin{pmatrix} 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad B = \begin{pmatrix} 0.5 & 0.5 & 0 \\ 1 & 0 & 0 \\ 0 & 0.5 & 0.5 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad C = \begin{pmatrix} 0.5 & 1.75 & 1.25 \\ 0.5 & 0.75 & 1.75 \\ 0 & 0 & 0.5 \end{pmatrix}$$

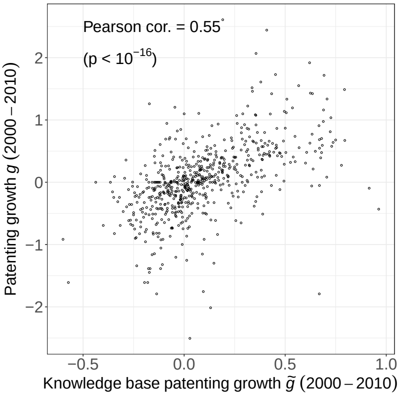
Technology network in 2017

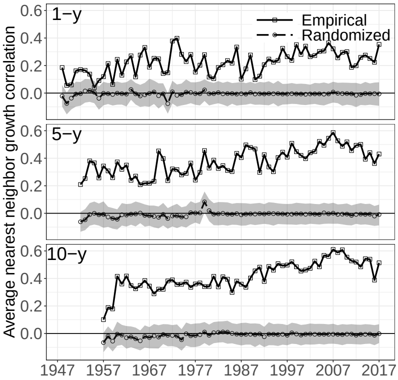


	Y	Energy
	A	Human necessities
	B	Operations and transport
	C	Chemistry and metallurgy
	D	Textiles
	E	Fixed constructions
	F	Mechanical engineering
	G	Physics
	H	Electricity

Empirical evidence of co-evolving technologies

- Growth rate of technology i
  - $g_{i,t} = \log\left(\frac{P_{i,t}}{P_{i,t-l}}\right)$
- Knowledge base growth rate of technology i
  - $\tilde{g}_{i,t} = \sum_{j=1}^{N} W_{ij,t}(1-\delta_{ij})g_{j,t}$





Model of network-dependent knowledge creation

$$\dot{K}_i(t) = \theta_i R_i(t)^\alpha \prod_{j=1}^{N} K_j(t)^{\beta W_{ij}}$$

- $K_i(t)$ ... knowledge stock
- $R_i(t)$ ... research effort in domain i at time t
- θ_i ... productivity parameter
- $\alpha \geq 0, \beta$ ... knowledge output elasticities
- W ... technology network

Romer [1990]; Aghion and Howitt [1990]; Grossman and Helpman [1991]; Romer [2012]

- Assumption: $R_i(t) = R_{i,0} e^{\lambda_i t}$
- $g_i(t) := \dot{K}_i(t)/K_i(t)$ ... knowledge growth

$$\dot{g}_i(t) = \alpha\lambda_i g_i(t) + (\beta W_{ii} - 1) g_i(t)^2 + \beta g_i(t) \sum_{j=1}^{N} W_{ij} g_j(t)(1 - \delta_{ij})$$

- Steady state: $\dot{g}_i(t) = 0$

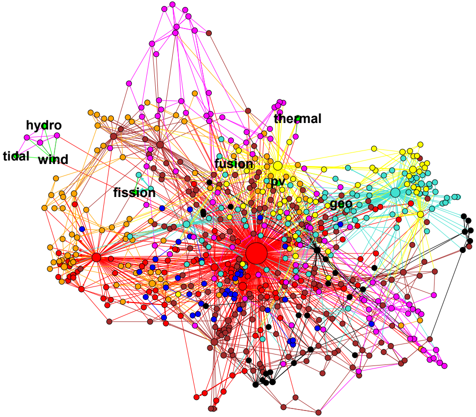
$$\boxed{g_i^* = \frac{\alpha\lambda_i}{1 - \beta W_{ii}} + \frac{\beta}{1 - \beta W_{ii}} \sum_{j=1}^{N} W_{ij} g_j^* (1 - \delta_{ij})}$$

Steady state in matrix form

- $g^* = \alpha L\lambda$ ... where $L := [\mathbb{I} - \beta W]^{-1}$

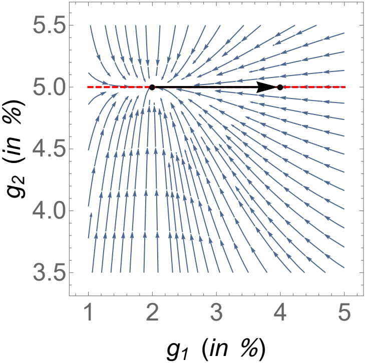
Research impact on focal technology

- $\frac{\partial g_i^*}{\partial \lambda_j} = \alpha L_{ij}$

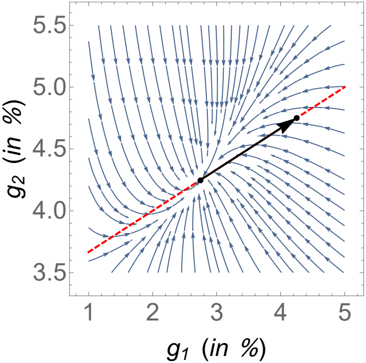


Impact of research effort growth in a toy example

(a) No network effects



(b) Network effects



- Initial research growth: $\lambda_1 = 0.02$, $\lambda_2 = 0.05$
- Black arrow: effect of doubling λ_1
- Red dashed line: Steady state as fct of λ_1
- Parameters: $\alpha = \beta = 0.5$

Estimating the model

- Steady state
  $$g_i^* = \frac{\alpha\lambda_i}{1-\beta W_{ii}} + \frac{\beta}{1-\beta W_{ii}} \sum_{j=1}^{N} W_{ij} g_j^* (1 - \delta_{ij})$$
- Econometric model
  $$g_{i,t} = \frac{a_i}{1-\beta W_{ii,t}} + \frac{\beta}{1-\beta W_{ii,t}} \sum_{j=1}^{N} W_{ij,t} g_{j,t} (1 - \delta_{ij}) + \epsilon_{i,t}$$

	Dependent variable: patenting growth		
	(1-y)	(5-y)	(10-y)
average $\hat{a}_i$	0.01	0.03	0.07
$\hat{\beta}$	0.84***	0.90***	0.89***
	(0.0077)	(0.0108)	(0.0146)
$\hat{\sigma}^2$	0.11	0.20	0.30
Log-likelihood	-13,383	-5,464	-3,612
Observations	43,651	8,734	4,348
Note:			***p$< 10^{-16}$

- How well does the model predict?
- How good is it compared to time series models which ignore network effects (ARIMA)?

Two prediction exercises

1 Conditional forecasts

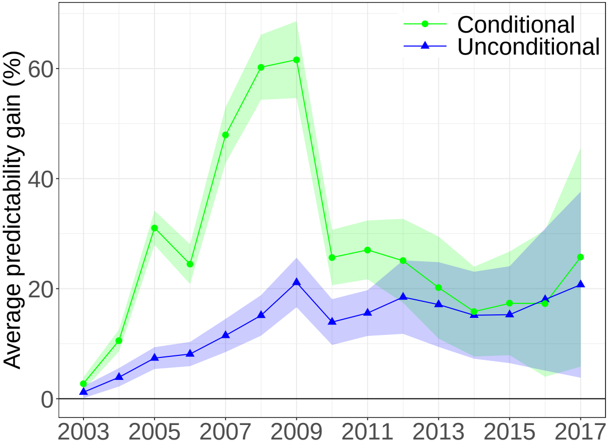
- $\hat{g}^{cond.}_{i,t+\tau} := \mathbb{E}\left[g_{i,t+\tau} \mid \{g_{j,t+\tau} : j \neq i\},\ \mathcal{F}_{i,t}\right] = \frac{\hat{a}_i}{1-\hat{\beta}W_{ii,t}} + \frac{\hat{\beta}}{1-\hat{\beta}W_{ii,t}} \sum_{j=1}^{N} W_{ij,t} g_{j,t+\tau}(1-\delta_{ij})$

2 Unconditional forecasts

- $\hat{g}^{uncond.}_{t+\tau} := \left(\sum_{k=0}^{k'} \hat{\beta}^k W_t^k\right) \hat{a} \approx \mathbb{E}\left[g_{t+\tau} \mid \mathcal{F}_t\right],$

Prediction gain through network effects

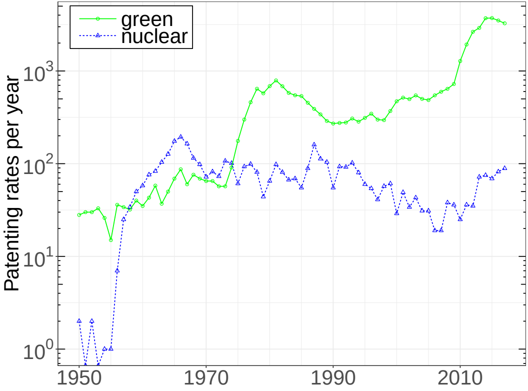
$$PG_{i,t} = \frac{|P_{i,t} - \hat{P}_{i,t}^{\text{ARIMA}}| - |P_{i,t} - \hat{P}_{i,t}^{\text{network}}|}{|P_{i,t}|}$$



Green energy technologies

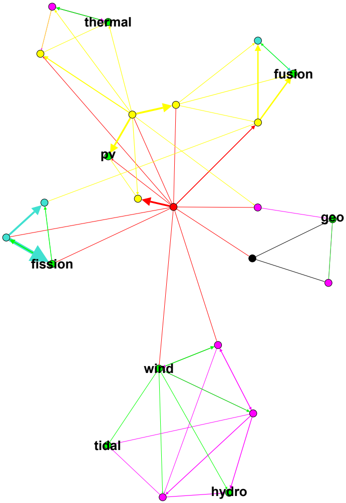
- Y02E codes classify "green" energy technologies

Y02E code	Energy technology	abbr.
Y02E10/1	Geothermal energy	geo
Y02E10/2	Hydro energy	hydro
Y02E10/3	Energy from the sea	tidal
Y02E10/4	Solar thermal energy	thermal
Y02E10/5	Photovoltaic energy	pv
Y02E10/7	Wind energy	wind
Y02E30/1	Nuclear fusion reactors	fusion
Y02E30/3	Nuclear fission reactors	fission

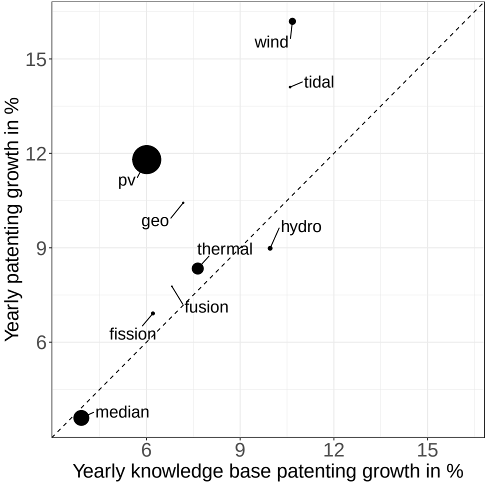


Green energy technology ecosystem in 2017

L_{2017}

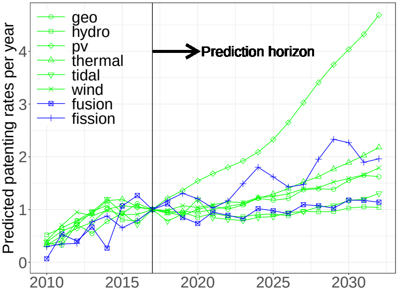


Green energy technology growth

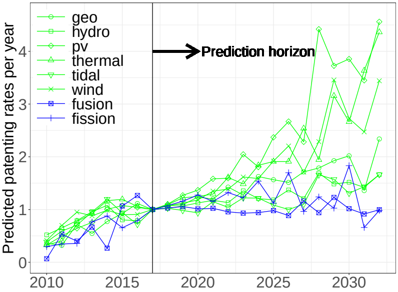


Tentative look into future innovation trajectories

ARIMA



Network model



Discussion

Conclusions

- Substantial impact of technology network on innovation dynamics
- Heterogeneous & fast improving environment of green energy technologies
- Research policy should consider technological ecosystem

Limitations

- Aggregation and fixed technologies [Lafond and Kim, 2019]
- No competition
- No costs and link to real economy

Next steps

- Tackle limitations
- Optimal intervention in technological ecosystem

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