How Environmental Policies Spread ? A Network Approach to Diffusion in the U.S.

Côme Billard
Climate Economics Chair
University Paris-Dauphine PSL

Anna Creti
Climate Economics Chair
University Paris-Dauphine PSL

Antoine Mandel
Paris School of Economics
University of Paris 1 - Pantheon Sorbonne

Context (1) – The United States

- Contribution to Climate change
  - 10% of worldwide GHGs emissions in 2018 (WRI, 2021), 2nd larger emitter today and first in history (Carbon Brief 2021) !
- COP21 objective: « reducing U.S. emissions to at least 26% under 2005 levels by 2025 » (N.D.C.);
- Trump election (2016): Paris Agreement; + environmental rules rolled back (Harvard Law School, 2019).

Source : CNN

Context (2)– Back in the game

"Support for decisions at the city and state levels will be decisive. On that level, climate action has remained ambitious during the past four years, despite Trump. But a ***major challenge remains in the South and Midwestern states***, starting with those which are most dependent on fossil fuels: Texas, West Virginia, Wyoming, North Dakota, Oklahoma... Most are also Republican strongholds. We could see a dynamic opposite to that prevailing under Trump at the federal vs. state level.
Mostly, there is a risk of a growing geographical polarization on climate legislations, with a "*two countries*" dynamic (…)".

Maya Kandel, 2021

Context (3) - Federalism

- Federalism, a peculiar environment for policy diffusion :
  - States are connected in many ways (eg. history, culture, the exchange of goods, citizens' migration, media markets (Desmarais et al., 2015));
  - States tend to compete and learn from each other (Berry and Berry, 1990; Pitt, 2010);
- Policies regularly spread throughout the American states, driven by underlying forces (ie. competitive, cooperative, and imitative);
- **Scholars have mainly investigated the determinants of policy adoption and diffusion**

Context (4) - Federalism

- Main factors for Environmental Policy Adoption:
  - Internal : Citizens ideology (Matisoff, 2008); Partisan control of the state (Huang et al., 2007); State's economy (manufacturing & mining) and wealth (Matisoff and Edward, 2014);
  - External : Geographic proximity (Berry & Berry, 1990, 1992); Shared characteristics (Volden, 2006).

Gap in the literature :

- What about ***How Environmental Policies Spread ?***
- And ***the specific role of states in the transmission process ?***

Main Contributions & Objectives

- **Our objectives are :**
  - Infer the Environmental Policies Diffusion Network and identify states facilitating the diffusion, in a dynamic process;
  - Estimating the determinants of the inferred network (i.e. those maximizing the transmission likelihood between states).
- **This paper contributes to the literature by :**
  - Being the first to consider a network based approach to environmental policies diffusion/transmission in the U.S. over a long time horizon, from1974 onwards;
  - Understanding underlying forces that drive the transmission.

MODEL & DATA

Inferring the Network : Independent Cascade Model (1)

- Independent Cascade Model (ICM) to infer a network from series of observations (Gomez-Rodriguez, 2010);

- Weights of the network are interpreted as the rates at which the policy (a law enacted in a state) is likely to be transferred between a states-pair;

- These weights summarize effects of latent variables that govern bilateral diffusion and systemic roles of states in the network.

Inferring the Network : Independent Cascade Model (2)

- ICM : Infers the maximum likelihood network in which the probability of diffusion from node *j* to node *i* is parameterized by the transmission rate $\alpha_{j,i}$ that is to be determined.

- **Determines the matrix $A=[\alpha_{j,i}]$ of transmission rates, i.e. $\alpha_{j,i} > 0$ that maximise the likelihood of the set of cascades observed** *(ie. quantifies how likely it is that a policy spreads from node j to node i, given a redundancy of transmission + penalty for long time).*

Inferring the Network : Independent Cascade Model (3)

- Once a state has enacted a legislation, the probabilistic rate at which it diffuses it to one of its neighbor is constant over time: the diffusion follows a Poisson process and leads to an exponential model for the conditional density of diffusion overtime
- The Poisson assumption of a constant diffusion rate is a simple and natural benchmark in absence of specific information about the dynamic aspects of the diffusion. (a Poisson process emerges if diffusion opportunities are distributed uniformly across time).

Dataset of Environmental Policies

- Dataset : 74 policies, 51 states, 1974/2018, three initial databases:
  - Database of State Incentives for Renewables & Efficiency (DSIRE);
  - The Center for Climate and Energy Solution (C2ES);
  - US Congress Platform.

Scope (Number)	Policies Description
Climate Policies (5)	Action Plans and reduction targets
Climate Change Adaptation (9)	Plans to cope with current climate damages
Renewable support (24)	Promoting the use of clean energy
Energy Efficiency (9)	Targeting emissions in the dwelling sector
Transportation (8)	Promoting the use of clean fuels/vehicles
Circular Economy (7)	Targeting recycling/products efficient use
Environmental Concerns (12)	Regulating environment management/health

INFERRED NETWORK & ANALYSIS

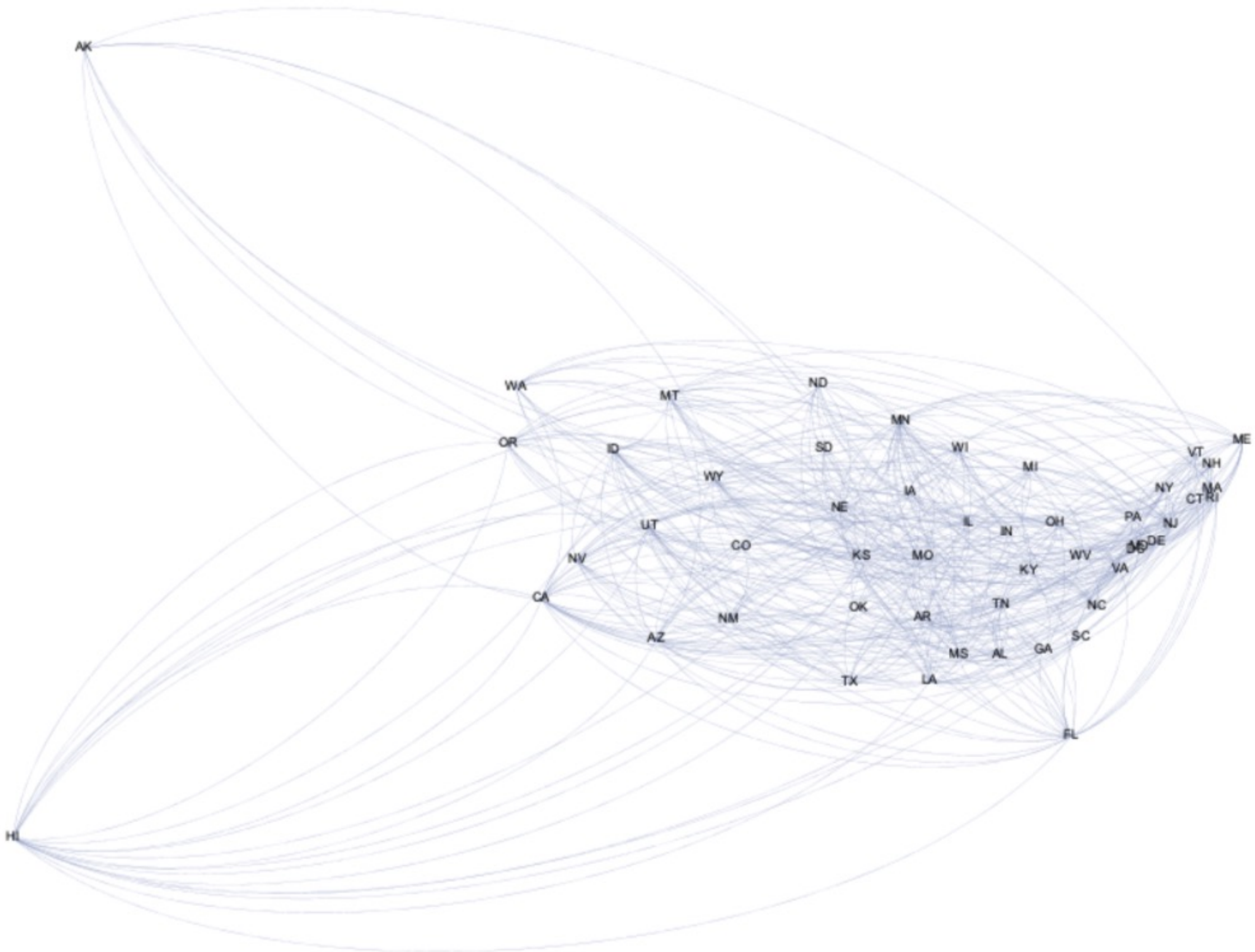
Networks : Generalities (1)

- The network inferred by maximum likelihood provides two main types of information.

1. The adjacency structure of the network indicates which routes environmental policies are likely to follow in their diffusion.
2. The weight of an edge gives an estimate of the speed at which diffusion is likely to occur between nodes

Network Analysis : Generalities (1)

Fig.1. Reconstructed environmental policies diffusion network in the U.S. using geographical layout.



Network Analysis : Generalities (2)

Table 2. General Properties of the Network.

Overall Network Characteristics	**Exponential Model**
Number of Nodes	51
Number of Links	440
Network Density	0.173
Mean Degree	8.627
Mean Path Length	2.075
Network Diameter	4
Mean Clustering Coefficient	0.211

The diameter and average path length hint at the existence of lags in the diffusion process as well as heterogeneity in terms of nodes attributes

Capturing Leaders / Followers in the Network (1)

- **Centrality measures (Jackson, 2008) :**
  - **The closeness** of node *i :* the average distance of *i to j*; *(ie. how fast a policy enacted in a state reaches, on average, another state).*
  - **The betweenness** centrality of node *i* : the share of shortest paths in the network on which node *i* lies *(ie. amount of flows through that state to other states in the network, thus acting as a bridge)*;

Capturing Leaders / Followers in the Network (1)

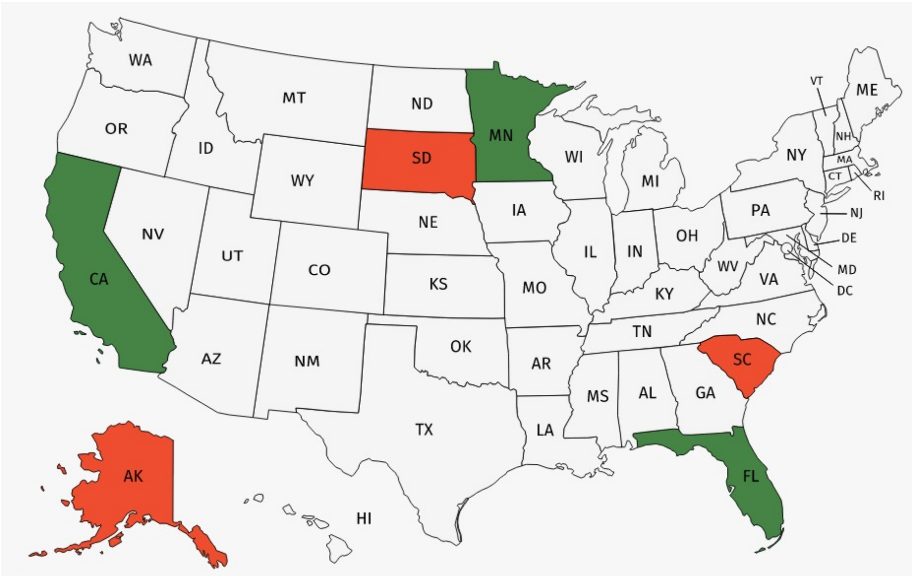
- There is only **partial overlap** between the different centrality measures and the distribution of centrality among top nodes and less integrated nodes is **relatively uniform.**
- The **network is multipolar** with at least three hubs: Minnesota (Midwest), California (West), Florida (South) and no single node appears as an evident center. New Jersey appears as the main hub in the Northeast region
- It is not straightforward to put forward a single node, nor a region, as the optimal target for the inception and the diffusion of new environmental and climate policies: **a group of states** are prominent spreaders in the process.

Capturing Leaders / Followers in the Network (2)

Closeness / Betweenness - Ranking (1-6/ 46-51)

Minnesota	Minnesota
California	California
Florida	Utah
Pensylvannia	Hawai
New York	Missouri
Wisconsin	Florida
...	...
...	...
...	...
West Virginia	Washington
Wyoming	Colorado
Arizona	Rhode Island
District of Columbia	Alaska
Alaska	South Carolina
South Dakota	District of Columbia

Mapping Leaders/Followers



Network Analysis : Regions

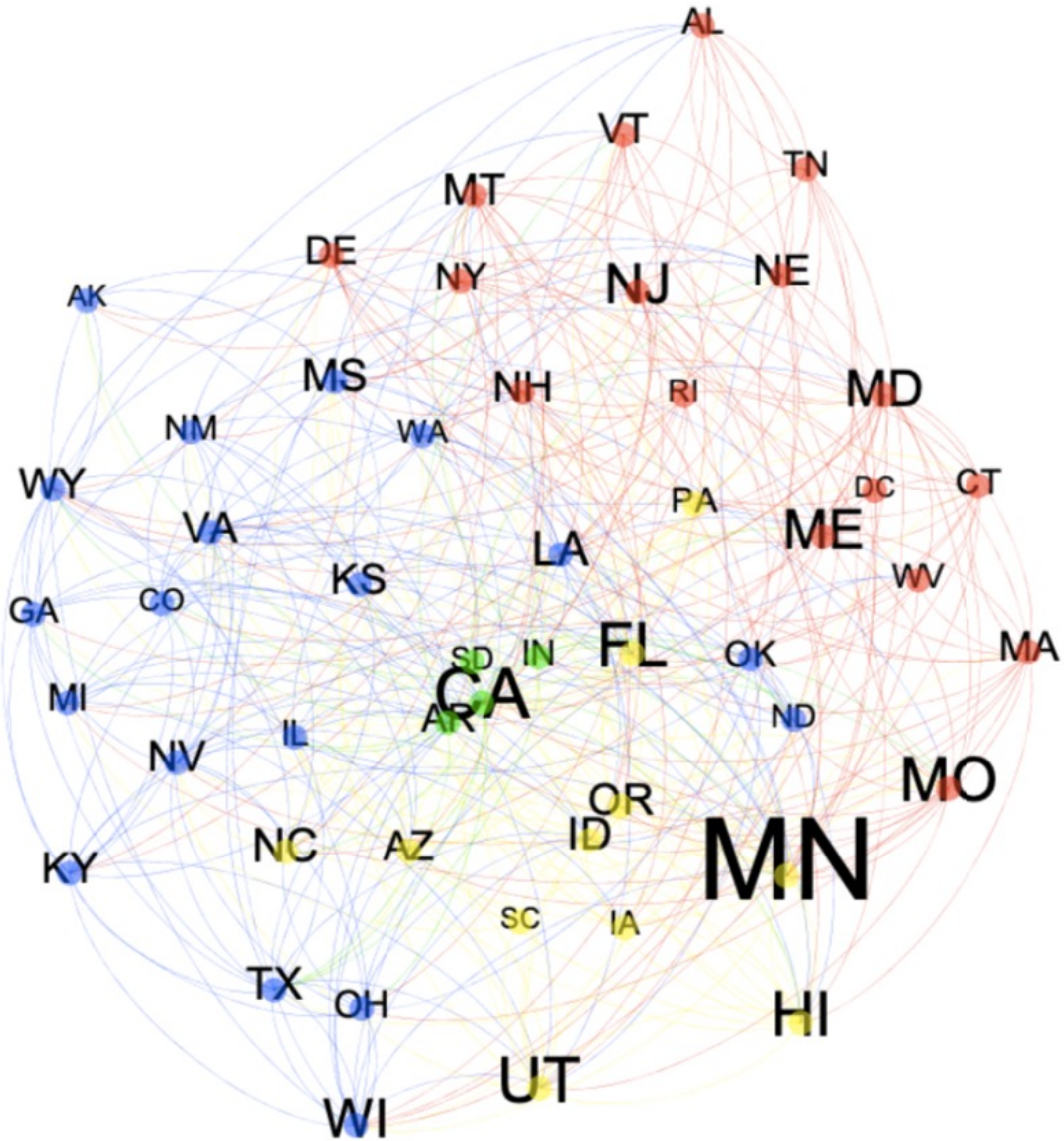
- We implement a regional-level analysis (geographical) as well as a network communities evaluation.
- …and we provide complementary perspectives on local characteristics in terms of geographic patterns and nodes' proximity in the network. We base our regional setting on the U.S. Census Bureau

Table 4. Matrix of intra-interregional connections.

Region	Northeast	Midwest	West	South
Northeast	23	14	24	28
Midwest	10	30	29	29
West	11	29	34	39
South	15	36	43	46

Network Analysis : Communities

Fig.2. Reconstructed network using Force Atlas layout.



- **4** communities

  The notion of “community” corresponds to a subset of nodes that are more densely connected among themselves than with the nodes outside the subset.

- **Not geographical Except Northeastern States !** (red);

- Less ambitious states (ie. env. pol.) belong to the same community ! (eg. Oklahoma, Texas, Wyoming).

THE DETERMINANTS OF TRANSMISSION

Methodology (1)

- Given observations of a set of cascades of different policies, we can estimate the determinants of bilateral diffusion by maximum likelihood - i.e. determine the coefficients for which the likelihood of the observed diffusion patterns is maximal.

  - A natural approach would then be to try to estimate the diffusion probability between state *i* and *j* using a logistic model

Panel Data

- Enrich our dataset with characteristics that can be associated to a state as a source, as a target, the relationship between pairs of states.

  - Economic and Political characteristics : GDP per capita, population density, citizen ideology, **federal government (eg. Republican/ Democratic);**

  - Contiguity (Bromley-Trujillo et al. 2016);

  - **Environmental variables** : Expected economic cost due to global warming (Hsiang et al., 2019), the Genuine Progress Indicator (Fox and Erickson, 2018).

Determinants of Transmission Likelihood

Constant	-3.67** (-128.51)
Contiguity *(Relationship)*	**1.69** (41.09)**
GDP per capita *(Source)*	**0.03** (4.60)**
Population Density *(Source)*	-0.49** (-28.78)
States Governors Party	**-0.03** (-4.71)**
Federal Government Party	-0.00 (-0.62)
Citizen Ideology	-0.00** (-9.00)
Climate change Economic Impacts (>5% GDP)	**-0.34** (-21.04)**
Genuine Progress Indicator *(source)*	**0.51** (33.84)**
Coal Mining State *(Source)*	-0.04** (-2.69)
McFadden R^{2*}	0.05

Contiguity : *the odds of transmission are 5.41 higher compared to the reference category;*

GDP Per capita : *Increases the odds of transmission*;

Climate change Economic Impacts : *odds of transmission are lower compared to the reference category;*

GPI : green economic system increases the odds of transmission.

Conclusions and Takeaways (1)

- An epidemic-like model to estimate the network of environmental policies transmission likelihood across American states + evaluate determinants from adoption data.
- "Inefficient" Network organization with key states and vice versa (Minnesota, California, Florida vs. South Dakota, South Carolina, Alaska). **Policy —> Targeting specific states to maximize diffusion;**
- **NorthEastern States display highly concentrated diffusion (Community approach); Suggests different areas + dynamics of diffusion.**

Conclusions and Takeaways (2)

- **Contiguity**, **GPI :** key determinants of transmission + **states governors party** vs. eg. expected climate change economic losses. **Policy —> Vulnerability does not imply actions !**

Thank you very much !

Basics and Generalities on Networks

- Recap on definitions :

  Node: One of many points (eg. agents) in a Network;
  Edge: connects nodes in a Network;
  Network: A set of Nodes (eg. agents) and Edges (eg. relationships).

Possible applications:

Social networks, **Innovations**, **Rumors, Internet, Bank failures systemic risks, Policies etc…**

Context (1) - Environmental Policy Needs

- Environmental and climate policies are put forward prominently
  - (eg. COP21 Paris Agreement, G7, Youth for Climate).

- Global Warming of 1.5◦C - IPCC (2019) :
  - Net zero by 2050;
  - *« the need of "rapid and far-reaching" transitions in land, energy, industry, buildings, transport, and cities and give policymakers and practitioners the information they need to make decisions that tackle climate change […] ».*

- **1,500 environmental laws and policies globally (GRI, 2018).**
  - ***« Since the Kyoto Protocol, increased by a factor of more than 20 » (Climate Change Laws of the World, Special Report, GRI, 2018).***

Inferring the Network : Independent Cascade Model (4)

- Building block of our approach is $f(t_i|t_j;\alpha_{j,i})$, the probability that node *i* gets activated by node *j* at time t_i, given node *j* was activated at time t_j and assuming a transmission rate $\alpha_{j,i}$ between nodes *j* and *i*.

- Given the conditional density $f(t_i|t_j;\alpha_{j,i})$, we can infer the likelihood of a set of cascades $\{t^1,\ldots, t^{|C|}\}$ given a network $A = [\alpha_{j,i}]$ as follows :

  - First, given a cascade $t^c = (t_1^c,\ldots,t_N^c)$, the likelihood of node *i* being

$$f(t_i|t_1,\ldots t_N \setminus t_i; A) = \sum_{j:t_j \leq t_i} f(t_i|t_j;\alpha_{j,i}) \times \prod_{j \neq k, t_k \leq t_i} S(t_i|t_k;\alpha_{k,i})$$

Inferring the Network : Independent Cascade Model (5)

- One can then compute the likelihood of the activations in a cascade before time T:

$$f(\mathbf{t}^c_{\leq T}; A) = \prod_{t_i \leq T} \sum_{j:t_j \leq t_i} f(t_i|t_j; \alpha_{j,i}) \times \prod_{k:t_k < t_i, k \neq j} S(t_i|t_k; \alpha_{k,i})$$

- Further, the likelihood of a cascade accounts for the fact that some nodes did not get activated (we consider that nodes not activated before time T never get activated). It is therefore given by:

$$f(\mathbf{t}^c; A) = \prod_{t_i \leq T} \prod_{t_m > T} S(T|t_i; \alpha_{i,m}) \prod_{t_i \leq T} \sum_{j:t_j \leq t_i} f(t_i|t_j; \alpha_{j,i}) \prod_{k:t_k < t_i, k \neq j} S(t_i|t_k; \alpha_{k,i})$$

- Finally, the likelihood of a set of cascades C = {$\boldsymbol{t}^1$,..., $\boldsymbol{t}^{|C|}$}, assuming each cascade is independent, is the product of the likelihoods of the individual

$$f(\{\mathbf{t}^1, ..., \mathbf{t}^{|C|}\}; A) = \prod_{t^c \in C} f(\mathbf{t}^c; A)$$

Inferring the Network : Independent Cascade Model (6)

- Objective is to find $A = [\alpha_{j,i}]$ such that the likelihood of the observed set of cascades $C = \{\boldsymbol{t}^1, ..., \boldsymbol{t}^{|C|}\}$ is maximized. We use CVX (MATLAB) - solving convex programs (Grant and Boyd, 2015) and the algorithm NETRATE.

- Structural assumptions about the diffusion process are embedded in the functional form chosen for the function f.

  - The probabilistic rate is constant over time (ie. a Poisson process —> exponential model for the conditional density (Kingman, 1993) : $f(t_i|t_j\,;\alpha_{j,i}) = \alpha_{j,i} e^{-\alpha_{j,i}(t_i - t_j)}$, (if $t_j < t_i$ and zero otherwise).

Policies collected

Adaptation to climate change: Climate Adaptation Plan, Fire prevention policies, General Hazard Plan, Water Plan, Droughts Plan, Droughts Laws (NCLS), Flood Programs, Adaptation plan, Harvesting Water Program;

Renewables support: Wind Energy Support, Interconnection Standards, Electricity Portfolio Standards, Standards for Electricity Power plants, Solar rebate, Water rebate program (solar heating), Energy Efficiency Loan, Solar/Wind access Policy, Public Funds for RES, Performance Based Incentives, Training Program, Sales Tax Incentives, Loan Program, Personal Tax Credit, Property Tax Exemptions, Pace Program, Grant Program, Green Purchasing Power, Hydrogen, Biogas, Solar/Wind Permitting Standards, Mandatory Net Metering, Renewables Portfolio Standard, Corporate Tax Credit);

Circular economy: Water Efficiency, Composting, Beverage Program Nuclear Waste, Stewardship Recycling, Plastic Bag Recycling Policies, Electronic Recycling Program);

Climate Policies: Carbon pricing, GHGs Regulation, Carbon Capture and Storage, GHGs Emissions Targets, US Climate Action Plan);

Energy Efficiency: Smart Meter Policies, Energy Audits Refrigerator/Cooling, Air Conditioner Policies, Energy Efficiency - Analysis/services, Rebate Program, Energy Efficiency standards and targets, Building Energy Code, Energy Standards for Public Buildings;

Environmental Concerns: GMO Laws, Wildlife Conservation, Bees Keeping Policies, Land conservation, Fracking/Shale gas restrictions, Pollinator Laws, Farmers Markets, Drinking Water Conservation, Forests Management, Environmental Cleanup, Pesticides, Indoor Air Quality;

Transportation (eg. Biofuel Policies, LEV Californian standards, Motor Fuel gas Tax Increase (2013 and so forth), Hydrogen Vehicle, Natural Gas Vehicle, Electric Vehicle Policies, Alternative Fuel Policies, Plug in electric vehicle Policies.

Regions

Description of U.S. Census Bureau - Regions

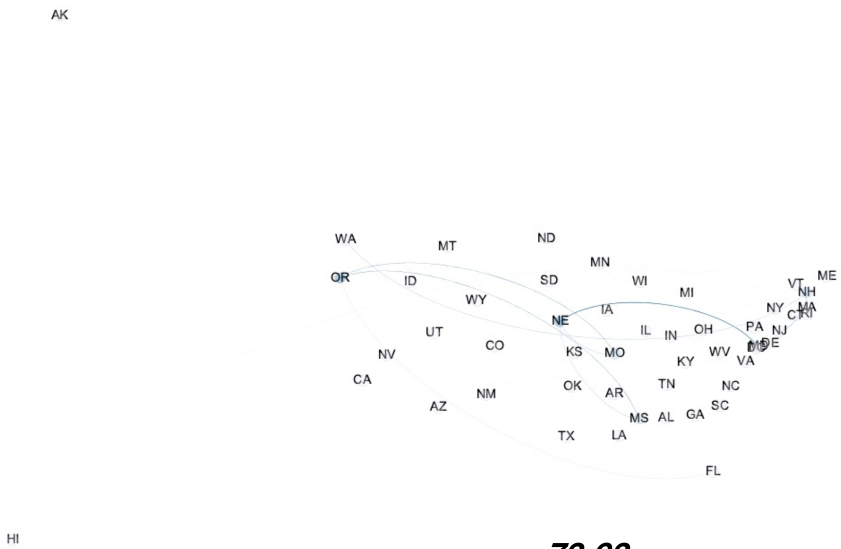
Northeast	**Midwest**	**South**	**West**
Connecticut	Indiana	Delaware	Arizona
Maine	Illinois	District of Columbia	Colorado
Massachusetts	Michigan	Florida	Idaho
New Hampshire	Ohio	Georgia	New Mexico
Rhode-Island	Wisconsin	Maryland	Montana
Vermont	Iowa	North Carolina	Utah
New Jersey	Kansas	South Carolina	Nevada
New York	Minnesota	Virginia	Wyoming
Pennsylvania	Missouri	West Virginia	Alaska
	North Dakota	Alabama	California
	South Dakota	Kentucky	Hawaii
	Nebraska	Mississippi	Oregon
		Tennessee	Washington
		Arkansas	
		Louisiana	
		Oklahoma	
		Texas	

Network formation overtime

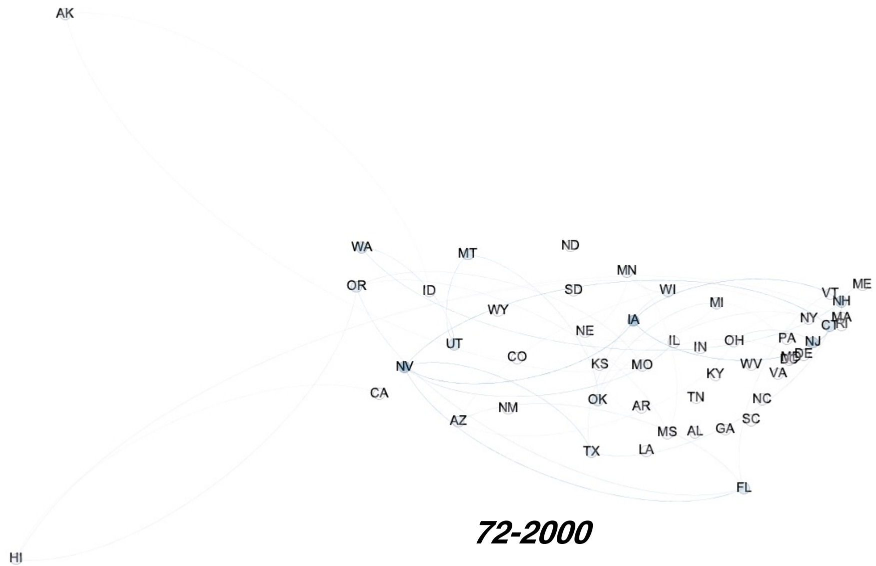
Communities description

1 - Blue	2 - Red	3 - Yellow	4 - Green
Wyoming	Alabama	Arizona	Arkansas
Alaska	Connecticut	Florida	California
Colorado	District of Columbia	Indiana	Idaho
Georgia	Delaware	Iowa	South Dakota
Illinois	Massachusetts	Idaho	
Kansas	Maryland	Minnesota	
Kentucky	Maine	North Carolina	
Louisiana	Missouri	Oregon	
Michigan	Montana	Pennsylvania	
Mississippi	Nebraska	South Carolina	
North Dakota	New Hampshire	Utah	
Nevada	New Jersey		
Ohio	New York		
Oklahoma	Rhodes Island		
Texas	Tennessee		
Virginia	Vermont		
Washington	West Virginia		
Wisconsin			
New Mexico			

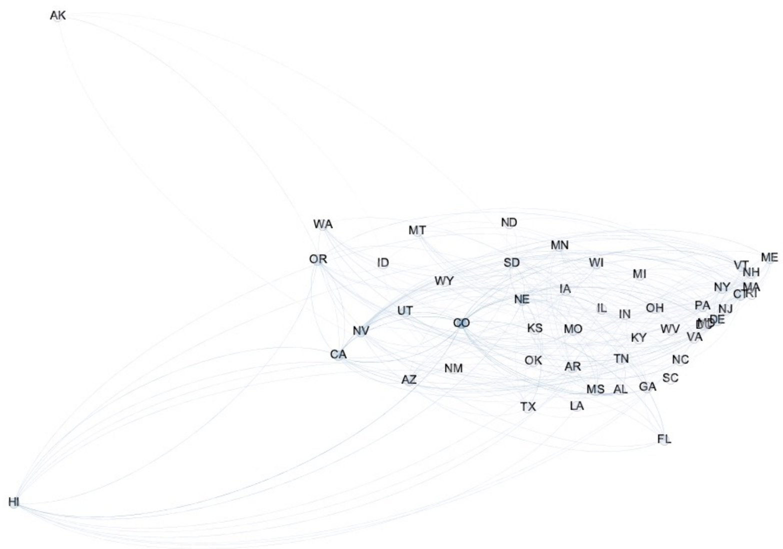
Network formation overtime



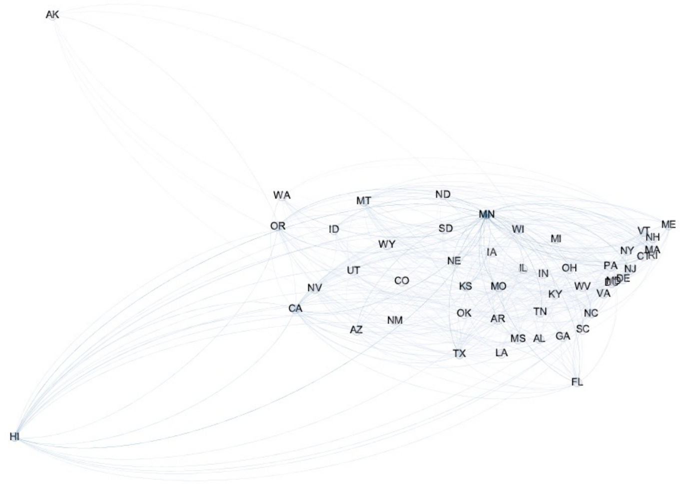
72-92



72-2000

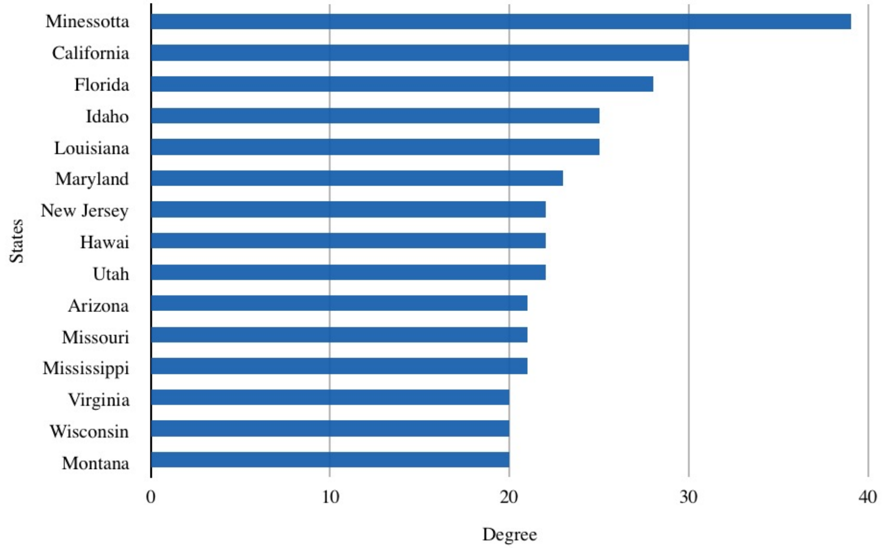


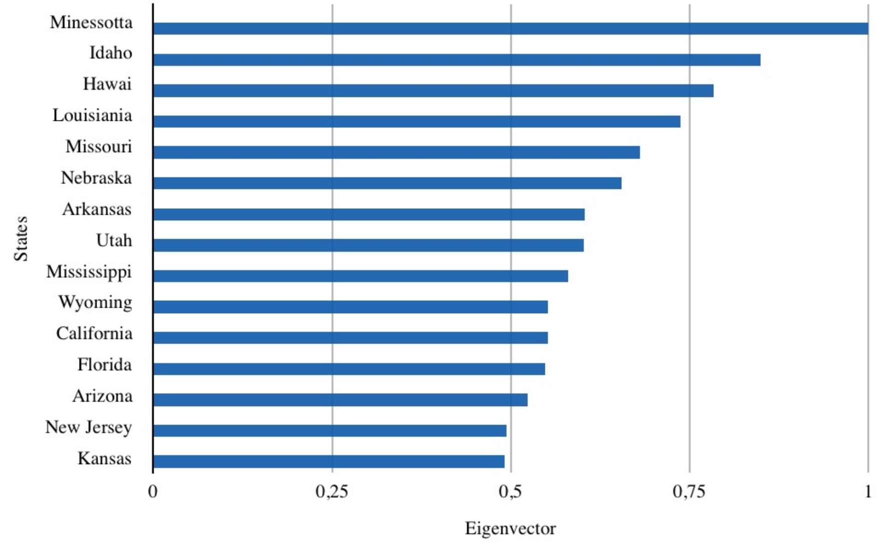
72-2008

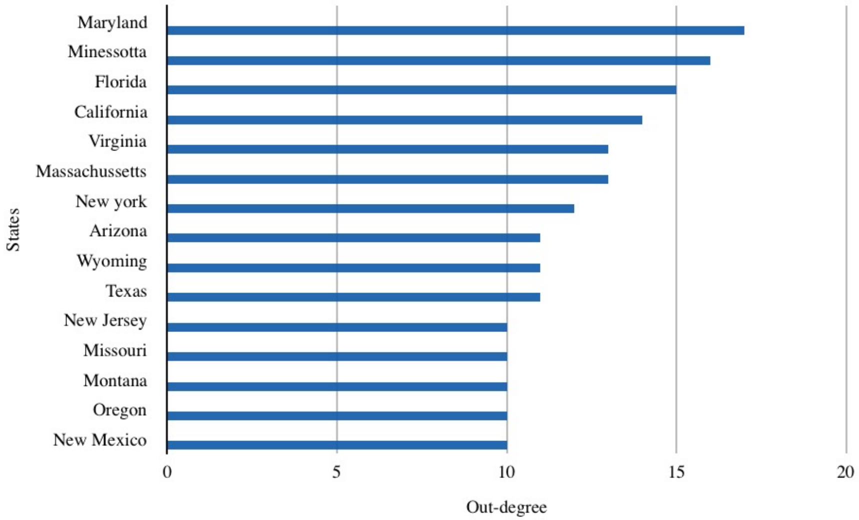


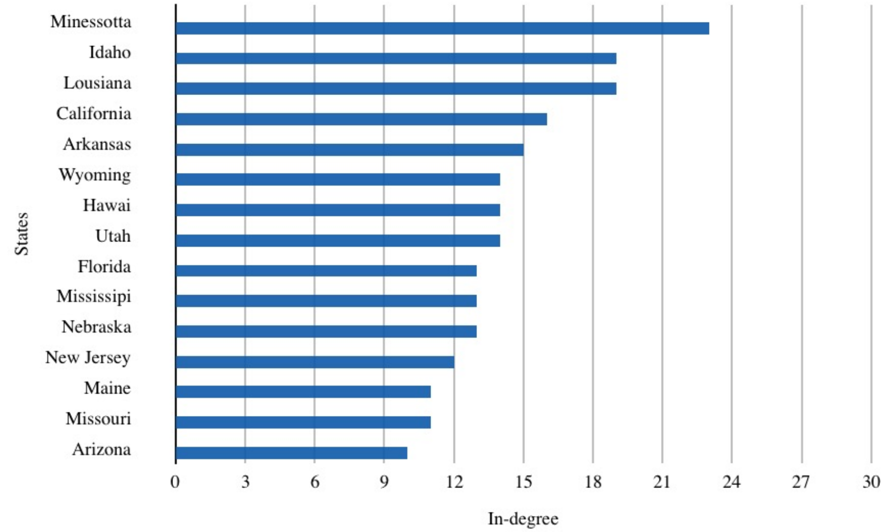
72-2016

Backup - Leaders Centrality Measures

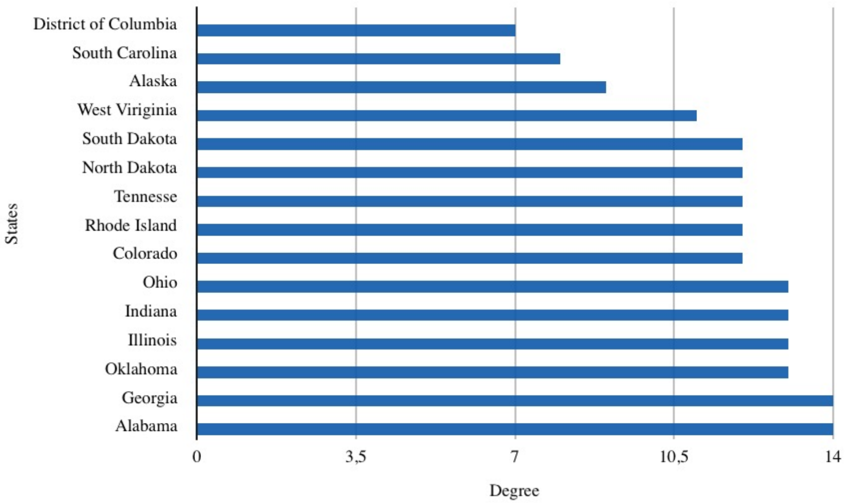


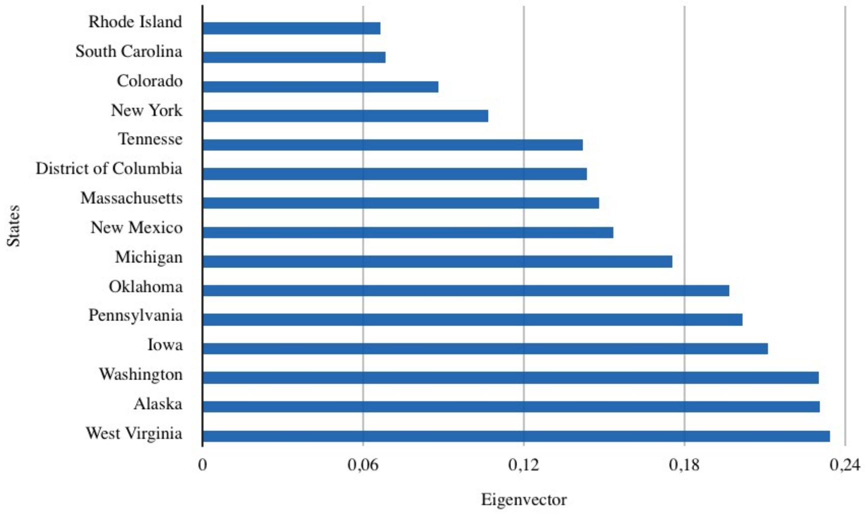


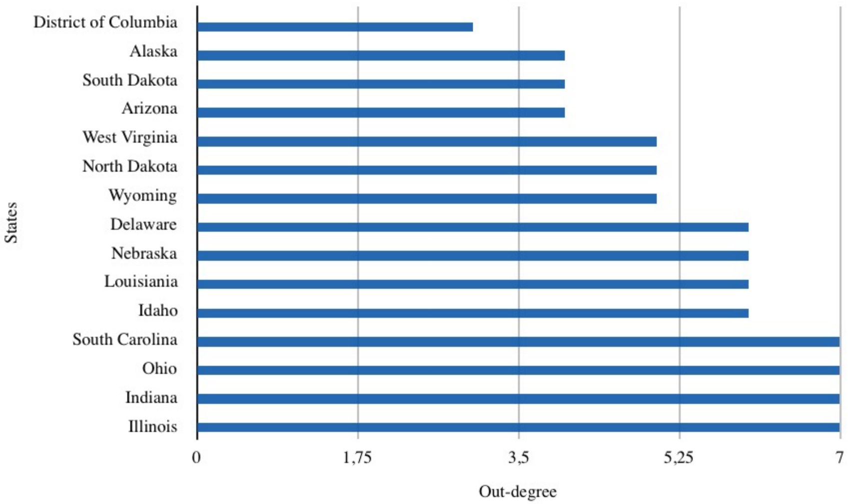


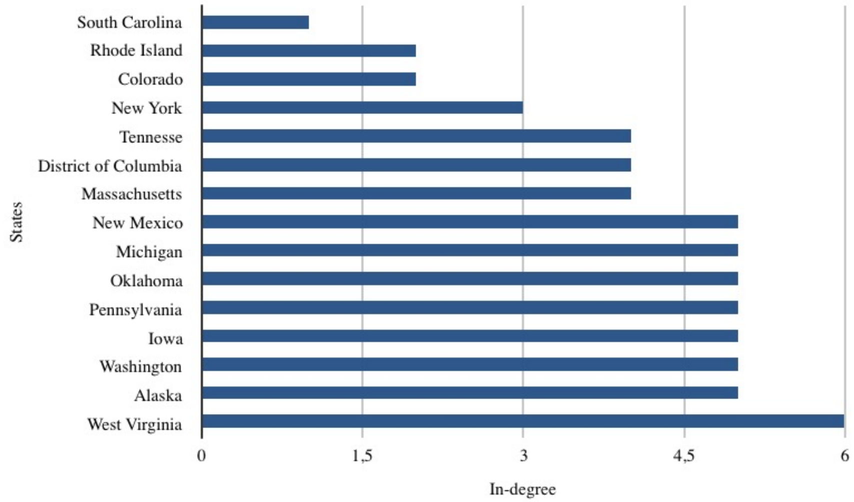


Backup - Followers Centrality Measures



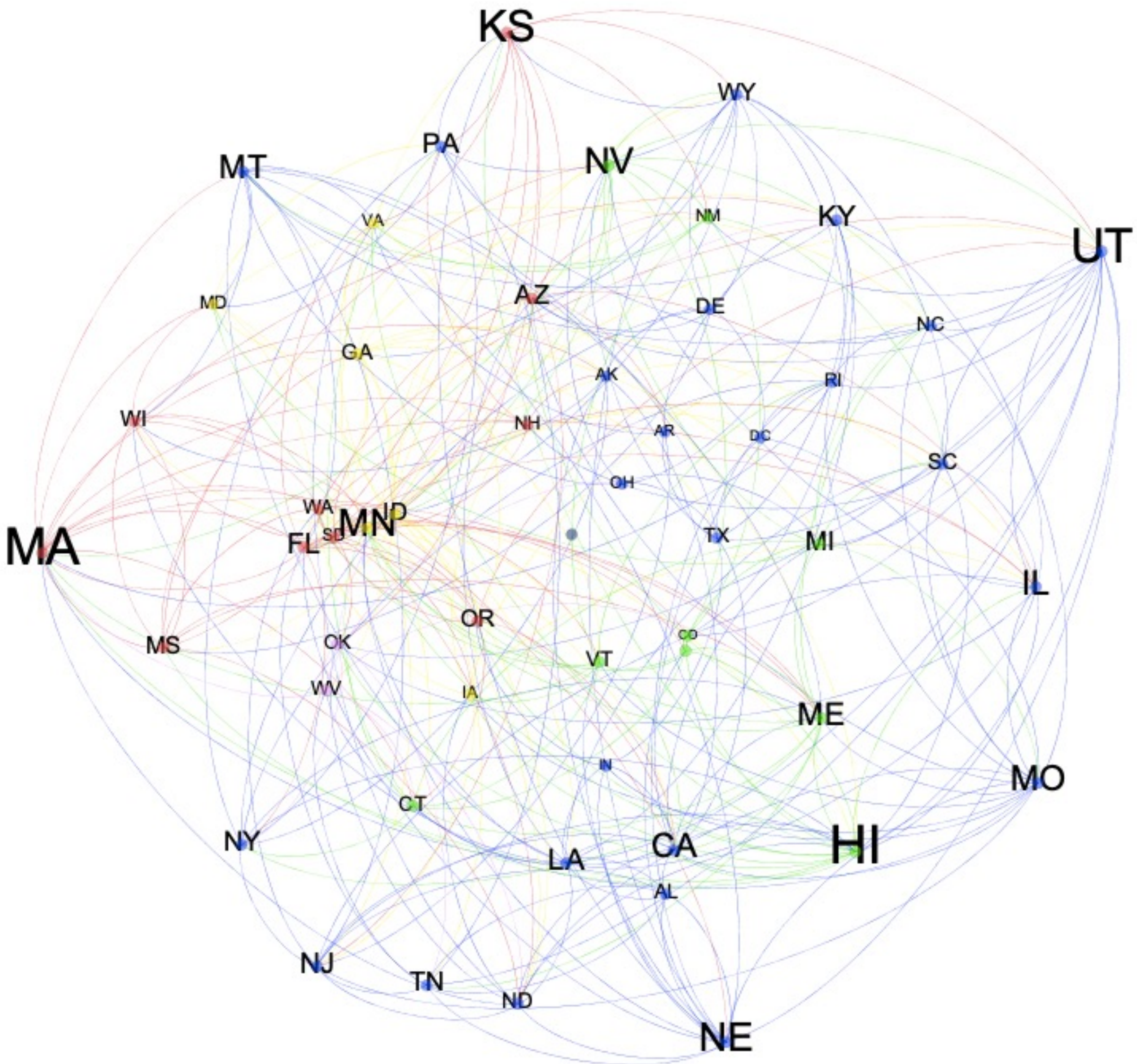






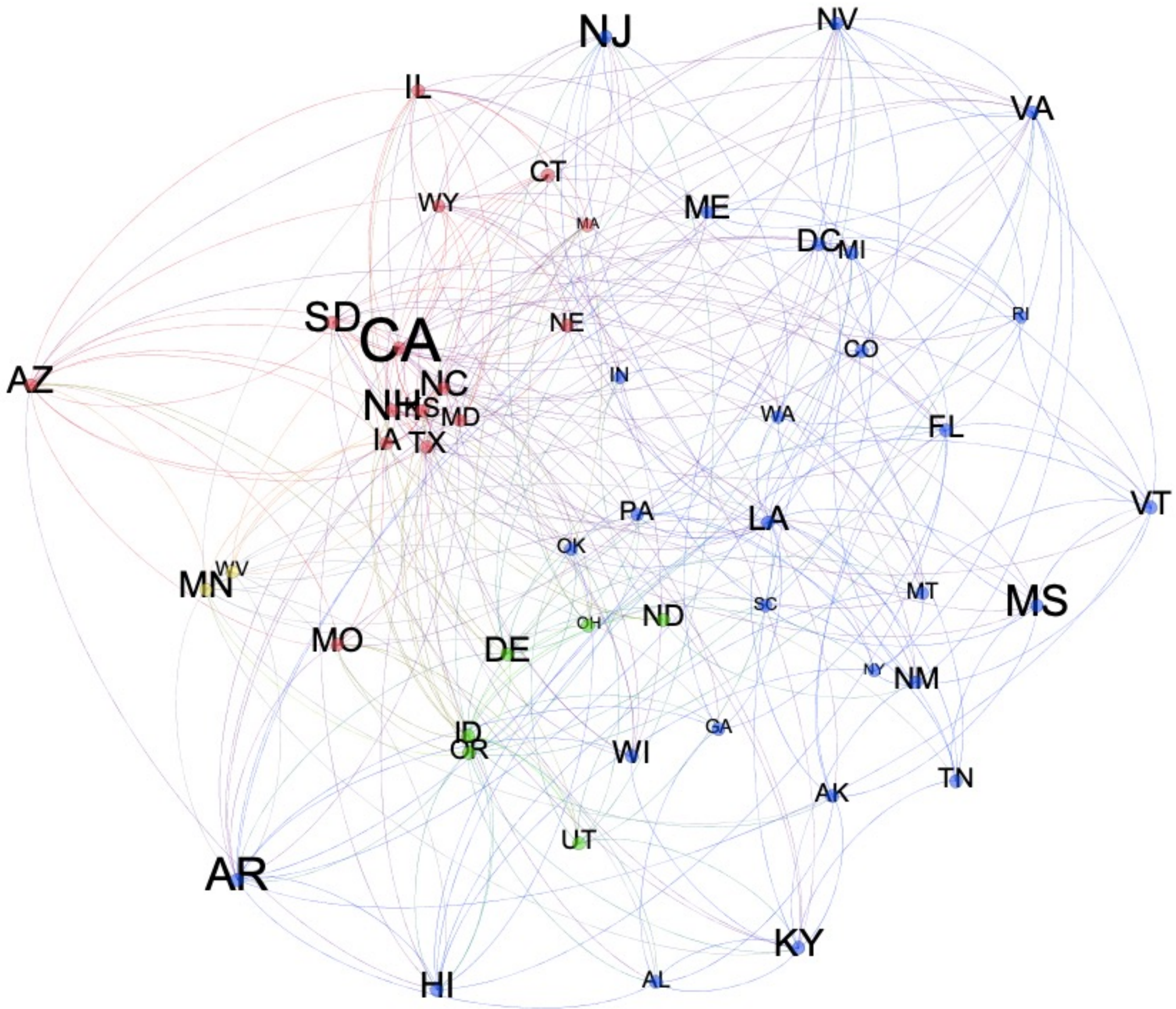
Splitting Networks

Climate and Environmental concerns



Splitting Networks

Energy



Econometrics Developments

Methodology (1)

- Given observations of a set of cascades $S=(S_v)_{v \in V}$, V different policies, we can estimate the determinants of bilateral diffusion by maximum likelihood - i.e. determine the coefficients for which the likelihood of the observed diffusion patterns is maximal.

Panel data about source countries $X = (x_{i,t})_{i=1\cdots N,\ t=1\cdots T}$, target countries $Y = (y_{j,t})_{j=1\cdots N,\ t=1\cdots T}$, and relationship characteristics $Z = (z_{(i,j),t})_{i=1,\cdots,N,\ j=1\cdots N,\ t=1\cdots T}$, one can compute the likelihood of a cascade S_v (see. Halleck Vega et al. (2018)).

- Given the adoption status in period t, the probability for a non-adopting state *j* to remain non-adopting in period t+1 is :
- while the probab

$$\prod_{\{i|S_v(i,t)=1\}} (1 - P_{(\alpha,\beta,\gamma)}(x_i^t, y_j^t, z_{i,j}^t))$$

$$1 - \prod_{\{i|S_v(i,t)=1\}} (1 - P_{(\alpha,\beta,\gamma)}(x_i^t, y_j^t, z_{i,j}^t))$$

Methodology (2)

- Thus the probability of the transition from the adoption vector $S_v(\cdot,t)$ to the adoption vector $S_v(\cdot,t+1)$ is given by:

$$\prod_{\{j|S_v(j,t+1)=0\}} \prod_{\{i|S_v(i,t)=1\}} (1 - P_{(\alpha,\beta,\gamma)}(x_i^t, y_j^t, z_{i,j}^t)) \times \prod_{\{j|S_v(j,t+1)=1\}} (1 - \prod_{\{i|S_v(i,t)=1\}} (1 - P_{(\alpha,\beta,\gamma)}(x_i^t, y_j^t, z_{i,j}^t)))$$

- Therefrom, using the assumption that the diffusion process is Markovian, one deduces the likelihood of cascade S_v as:

$$\mathscr{P}^v_{(\alpha,\beta,\gamma)}(X, Y, Z) = \prod_{t=0}^{T-1} \prod_{\{j|S_v(j,t+1)=0\}} \prod_{\{i|S_v(i,t)=1\}} (1 - P_{(\alpha,\beta,\gamma)}(x_i^t, y_j^t, z_{i,j}^t)) \times \prod_{t=0}^{T-1} \prod_{\{j|S_v(j,t+1)=1\}} (1 - \prod_{\{i|S_v(i,t)=1\}} (1 - P_{(\alpha,\beta,\gamma)}(x_i^t, y_j^t, z_{i,j}^t)))$$