Assessing the Allocative Efficiency of Integrated Energy Grid Networks

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Assessing Energy Markets

- Energy trade has been of increasing concern given its impact on climate change
- Many suggestions for integrated grid networks such as the Synchronous Grid of Continental Europe (SGCE) and Asia Super Grid (ASG)
- Energy markets seems to be doing a good job, with increasing gains from trade and decreasing environmental harm in some regions
- Does this mean integrated energy grids are the solution?

Importance of Efficient Energy Trade

- Clean energy and energy security are necessary for a consistent and environmentally friendly energy supply
- Production of energy can be variable, (especially renewable sources) and the investment in energy production depends on the ability to manage the variability in supply
- Investment in clean energy has been withdrawn in countries with clean energy producing potential, affecting not only the country in question but also the rest of the countries in the region

Importance of Efficient Energy Trade

- Ability to trade energy efficiently allows countries to manage variability in supply, which not only ensures a consistent energy supply but allows management of excess clean energy
- Given the large quantities of energy produced and traded, an efficient allocation of energy results in large gains in trade and less waste from excess production
- Allows the countries in the market to be more self-reliant as an entity (for various political or economic reasons)

Complexities of Energy Trade

- Energy production varies in both source and amount across countries
- Most importantly, the geographical location of countries determines who they can trade with
- Both these factors result in an asymmetric market
- As the number of members in such a market increases, it becomes difficult to determine the optimal allocation of energy through trade

Energy Market as a Network

- By modeling the market as a network, it is possible to characterize the asymmetry of the market
- By using the Coleman Model for Research Exchange, it is possible to obtain a cardinal ranking of the influence that each country has on the market
- The model allows us to take both the type and desirability of each country's endowment into account
- Once the centrality(influence) of each country is determined, this is used to measure how close the market is to a Walrasian Equilibrium in order to determine its allocative efficiency

Energy Market as a Network

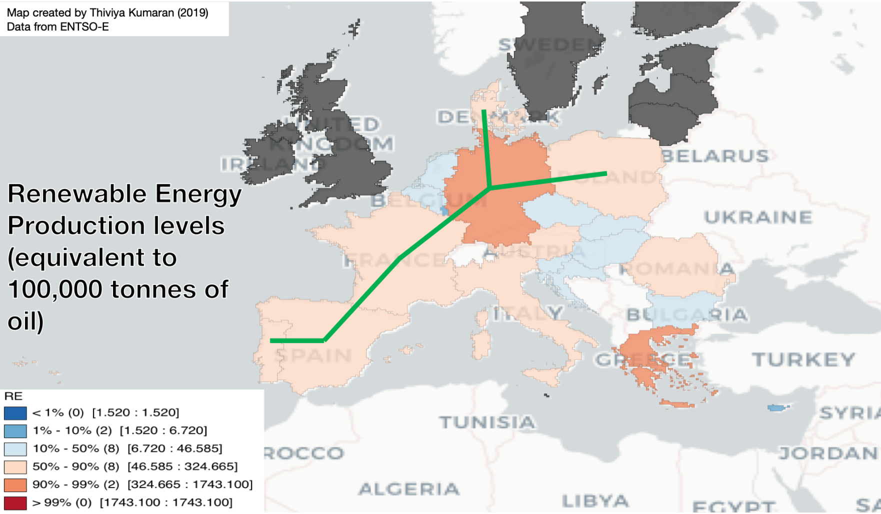
- Ability to trade depends on the borders and hence geographical location of countries
- Merely having more borders does not mean having more influence
- Influence of all trading partners must also be taken into account, resulting in a unique solution for the relative centrality of all members

The Coleman Model of Resource Exchange

- The Coleman Model gives us a solution for the relative centrality of all members of a network, given the desirability of their endowment
- The model is an application of Graph Theory, treating each member of the market as a node and the number of members it trades with as the number of bi-directional edges
- All members are given weights which sum to 1, therefore giving us the share of the market of which each member has command

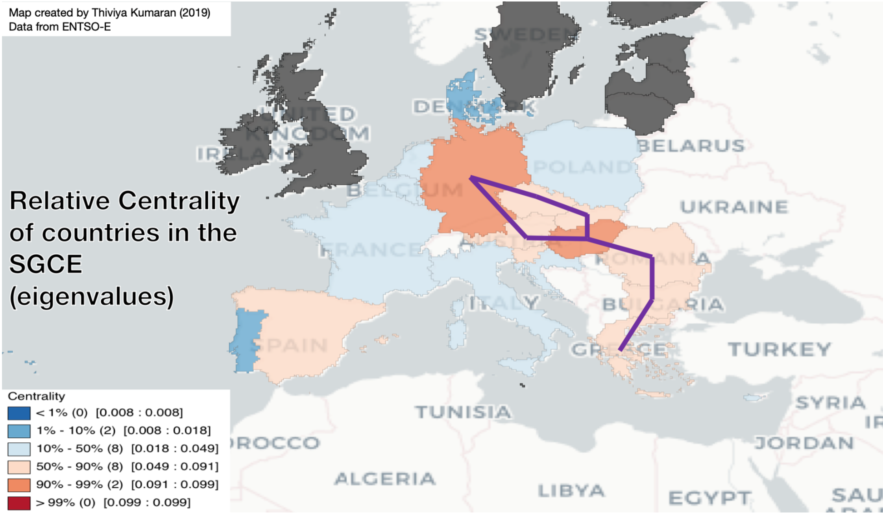
Incorporating Centrality

- Observing unweighted data gives us a simplistic view of the market



Incorporating Centrality

- Weighted data tells us a different story



Results of Coleman Model

Belgium	0.058	Lithuania	0.021
Bulgaria	0.001	Luxembourg	0.036
Czechia	0.05	Hungary	0.032
Denmark	0.035	Malta	0.029
Germany	0.09	The Netherlands	0.036
Estonia	0.007	Austria	0.061
Ireland	0.018	Poland	0.048
Greece	0.022	Portugal	0.027
Spain	0.036	Romania	0.001
France	0.062	Slovenia	0.023
Croatia	0.018	Slovakia	0.054
Italy	0.051	Finland	0.023
Cyprus	0.009	Sweden	0.047
Latvia	0.018	United Kingdom	0.009

Figure: Centrality Values

Measuring Allocative Efficiency

- Centrality values are used to characterize asymmetry
- The rate of grid expansion and hence ability to trade is weighted by centrality values to measure changes in allocative efficiency
- We study the European Union (EU) energy market
- Data from Eurostat, the statistical division of the EU, is used to observe the market from 1990-2017

Measuring Efficiency of the EU

- The following variable is used to measure the efficiency of grid expansion in the EU as a whole

$$E_{u_t} = M_{u_t} - \frac{C_{u_t}}{C_{u_{t-1}}} M_{u_{t-1}} \quad (1)$$

E_{u_t}: Efficiency of market for EU in period t
M_{u_t}: Net import of energy in the EU in period t
C_{u_t}: Consumption of energy in the EU in period t

Measuring Efficiency of Countries

- The following variable is used to measure the efficiency of grid expansion of countries in the EU

$$E_{i_t} = (\frac{Q_{i_t}}{Q_{i_t-1}} - 1)C_{i_{t-1}} - \Delta M_{i_t} \tag{2}$$

E_{i_t}: Efficiency of market for the country in period t
M_{i_t}: Net import of energy in the country in period t
C_{i_t}: Consumption of energy in the country in period t
Q_{i_t}: Energy grid capacity in the country in period t

Measuring Weighted Allocative Efficiency

- The aforementioned variables are combined to derive the condition for allocatively efficient trade

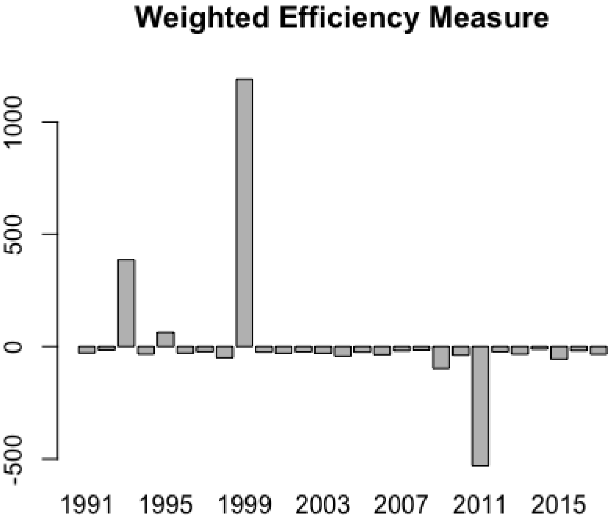
$$\sum_{i=1}^{I} \frac{R_i E_i}{E_u} = I - \sum_{i=1}^{I} \frac{(1 - R_i) E_i}{E_u} \tag{3}$$

R_i: Centrality of country i based on Coleman model
E_i: Expansion of national grid capacity by country i
E_u: Expansion of total network grid capacity

Measuring Weighted Allocative Efficiency

- $LHS < RHS$: This indicates that the market is allocatively efficient in a manner that does not adequately respond to the centrality measures of its members.
- $LHS = RHS$: A strict equality indicates that the market is efficient and that it responds perfectly to the centrality measures of its members.
- $LHS > RHS$: This case indicates that the market is allocatively inefficient.

Results of Proposed Condition



Results of Proposed Condition

- The EU has been mostly allocatively efficient according to the proposed measure
- The years 1993, 1995, and 1999 when it was inefficient were all coincided with significant EU events that could have created speculative shocks
- While the EU was allocatively efficient, it was not in a manner that took centrality into account (individual weighted efficiency values were significantly large)

Exploring Causes

- The results are regressed against the amount of energy consumed, share of renewable/non-renewable energy produced, and the possible types of renewable sources used
- Both unweighted and weighted models are used, as well as models that consider the proportions of energy sources against the total amount

Regression Results

	Dependent variable:			
	Standard	Weighted	Proportional	Weighted Proportional
	(1)	(2)	(3)	(4)
Energy Consumption	−1.126	−0.055*		
	(1.213)	(0.032)		
Non-Renewable	−0.041	−0.003***		
	(0.035)	(0.001)		
Nuclear	0.0003	−0.0001		
	(0.035)	(0.001)		
Hydro	−0.038	0.002		
	(0.121)	(0.003)		
Wind	−0.120	−0.005		
	(0.206)	(0.005)		

Figure: Standard Model

- $*p < 0.1, **p < 0.05, ***p < 0.01$

Regression Results

Non-Renewable Proportion	-0.003^{*}	-0.0003^{**}
	(0.002)	(0.0001)
Nuclear Proportion	-0.003	-0.0003
	(0.003)	(0.0002)
Hydro Proportion	0.005	0.0004^{*}
	(0.003)	(0.0002)

Figure: Proportional Model

- $*p < 0.1, **p < 0.05, ***p < 0.01$

Exploring Causes

- Amount of energy consumed and the amount of non-renewable sources used seem uncorrelated at first, but are significant when using the proposed weighted model
- Even when we consider the shares of sources for each country, therefore accounting for their varying sizes and hence varying production/consumption, these factors are significant
- Hydroelectric energy is significant at the 10% level in the proportional model, but otherwise the source of renewable energy does not matter as much as its share

Policy Implications

- Flat target for buffer capacity set in the Paris Agreement is not the most efficient solution as we need to account for centrality
- Expanding the grids of countries that produce less renewable energy will in fact increase the trade of and hence investment in clean energy sources
- Weighted expansion is more efficient than total expansion, and it is more cost effective

Further Study

- Increasing the granularity of study will provide a more detailed understanding of the energy network (use plants as nodes instead of countries)
- Pricing regulations and other barriers to trade could be included into the model to make the centrality values more accurate
- Other policy measures could explain centrality trends or promote trade
- For example, protectionist policies and national energy market conditions could significantly impact centrality values and hence efficiency

Thank You

- Questions?
- Please email tkumaran@uchicago.edu with any comments