Assessing the Allocative Efficiency of Integrated Energy Grid Networks

Thiviya Kumaran

December 2020

Abstract

Integrated energy grids have gained popularity for allegedly increasing energy security and reducing the emissions from inefficient energy production. While national grids have indeed allowed countries to make energy production more efficient, the desirability of international grids remains to be proven. Factors such as national energy prices and production methods complicate the use of interconnected grid networks such as the Synchronous Grid of Continental Europe and the tentative Asia Super Grid. This paper examines the allocative efficiency of integrated international energy grids by assessing the change in net energy imports in the European Union [EU]. First, the centrality of member countries is derived by applying the Coleman Model for Resource Exchange, in order to account for the asymmetry in trade that results from geographical borders. Next, the centrality results are used to weight the increase in individual grid capacities and examine the gains in energy efficiency for both member countries and the EU between 1990 and 2017. This is done by modelling a perfectly integrated grid as a Walrasian equilibrium and testing the weighted quantities of energy traded against it. Finally, the results are tested against commonly cited barriers to energy trade to determine the primary causes for inefficient grid integration. The results show that while the integrated grid in the EU has been mostly allocatively efficient, it has been in a manner that disregards the centrality of its countries. The inefficiencies with regards to centrality are highly correlated with the share of renewable energy sources, but do not depend on the type of renewable source.

Keywords: Efficiency, Energy, Networks
JEL Classification: C58,D58,Q40

1 Introduction

The assessment of energy markets has been of increasing concern given contemporary climate issues. Not only is the source of energy of extreme importance, but its efficient use is a matter that affects both the reduction of its wasteful production and the safeguarding of processes that rely on it. In recent history, especially following the Paris Climate Agreement of 2015, there has been increased focus on the production and trade of energy towards these ends.(EC 2014) In particular, the synchronisation of energy grids and the trade of energy has been regarded as an efficient way for countries to share the responsibility of producing sufficient energy while reducing the amount of carbon emissions in the process.

However, an adequate assessment of energy markets requires more than a surface analysis of the amount of emissions and level of energy security. Unlike markets where trade is made possible between multiple parties by better infrastructure and technology, the energy market is largely limited by the capacities of energy grids, the resources available to produce it, and importantly, where these grids are connected. It is evident then that the geographical location of a country determines its trading partners by way of grid connection, and determines the nature of trade through its local grid capacity and natural resources used to produce energy. Any measure of the efficiency of energy markets will therefore need to take into account these characteristics in order to determine if the energy and environmental objectives of both the network and its members are achieved.

Take, for example, the following two figures. The first shows where the emphasis on grid expansions should be given the clean energy producing potential of countries in the European Union. The second shows where the emphasis should be placed if we consider the influence each country has on the energy exchange market given their location.

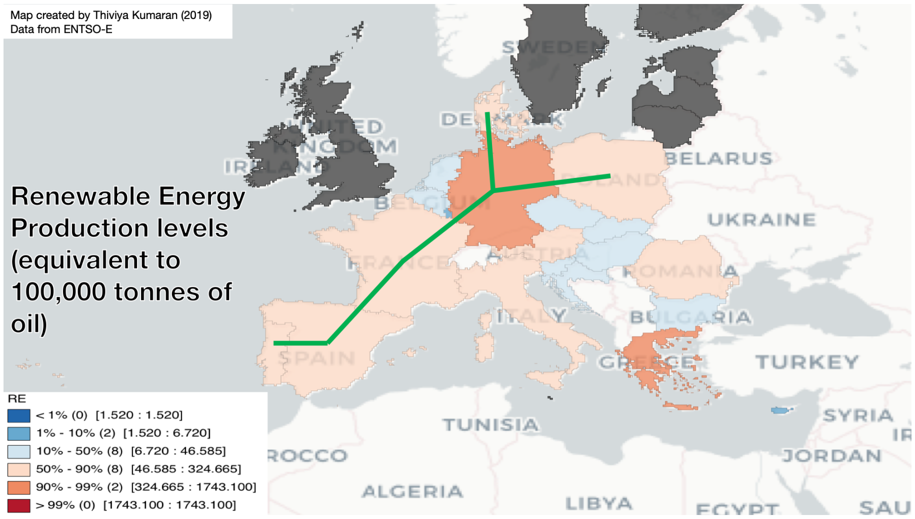

Figure 1: Clean Energy Grid Influenced Expansion

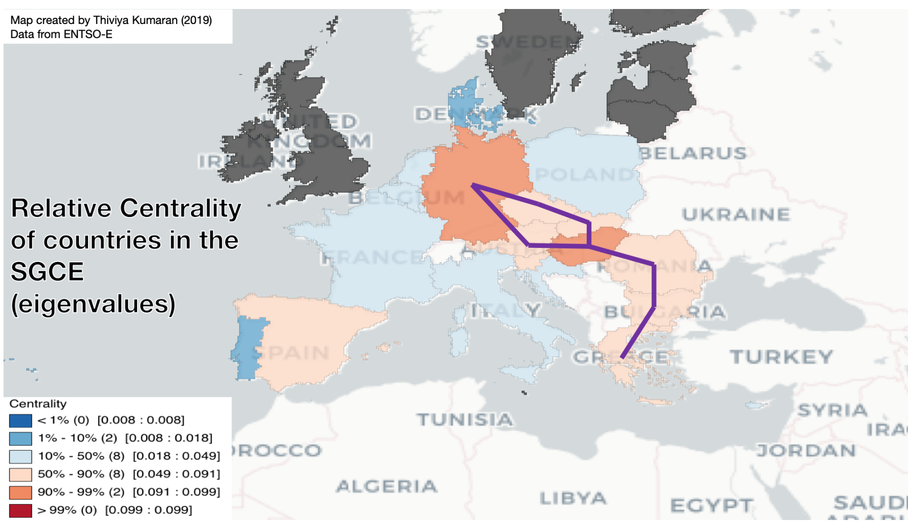

Figure 2: Centrality Influenced Grid Expansion

In this paper, the European Union is used as a study on the effectiveness of energy markets. This is because the EU has shown tremendous improvement in its energy and environmental goals (which have yet to be placed under scrutiny under the framework outlined above) and is largely based on the same landmass, thus forming a large and inherent network of connected energy grids. Moreover, its commitment to a synchronous energy grid in the form of the Synchronous Grid of Continental Europe allows for an analysis on whether such a policy is indeed desirable.(Stigler 2016)

In the following sections, the energy market of the EU will first be defined with regards to its network, largely under the influence of the Coleman Model for Exchange. This allows the geographical limitations of trade to be accounted for, thus producing a cardinal measure of the desirability of each country's energy grid with regards to the rest of the network, and hence the real value of the potential gains from trading with it. Next, energy data from 1990 to 2018 is used to understand the change in energy trade in EU countries. By weighting this information with the results of the Coleman Model, a more accurate measure for understanding the nature of energy trade in the EU is derived.

2 The Energy Network of the European Union

The trade of energy via its energy network is essential to Europe for two main reasons: it introduces competition into the largely monopolistic national energy markets of European countries and allows for greater energy security. (EC, 2017) As national energy grids are connected to those of other countries, consumers in any one country now have access to energy that is produced beyond their borders. Since the electrical energy being consumed is not differentiable in terms of its source, consumers are indifferent towards the source and method of production of their energy. This therefore makes the energy markets across Europe more elastic, and its implications are twofold; consumers in Europe enjoy lower energy prices, while energy produces are motivated to reduce any inefficiencies to maintain their profit shares in a more competitive market (Simon, 2018).

Energy security on the other hand, refers to the reliability of the supply of electrical energy and the ability to dispose excess energy in a non-wasteful manner. While the demand for electrical energy is regular and relatively predictable due to consistent consumer preferences and business cycles, the production of electrical energy relies on less constant factors.(Bremen 2010) The constant availability of electrical energy for the consumer, in this case citizens and industries of a country, is therefore a goal that governments strive to achieve. On the other hand, countries that produce hydroelectric and wind energy are often subject to problems created by unpredictable changes in the weather and thus unexpected production of excess energy. In such a scenario, the excess energy has to be used in order to maintain the integrity of the local energy grid (which has a finite capacity), or is exported to the energy grids of neighbouring countries. Since the forced usage of excess energy is costly, the ability to export excess energy is what provides energy security to countries that face the risk of excess energy production. By connecting national energy grids to those of other countries, an interconnected grid therefore makes local energy markets more competitive because of the increased diversity of energy sources, and more secure because of their ability to rectify energy shortages and excesses. (Neff, 1997)

The connectedness of a country's national energy grid to those of other countries does not only affect its own options for energy interconnectedness, but that of the countries it is connected to. This is because energy can be exported to countries that do not share borders, via one or more neighbouring countries. For example, while Spain and Belgium do not share borders, energy can be exchanged between both countries through France, which neighbours both of them. Since this allows non-neighbouring countries to exchange energy with each other and because this capability is premised on the interconnectedness of each member country, the national grids essentially form a network that connects European countries that are mutually interested in exchanging electrical energy. Since the physical characteristics of a connected grid necessitate that this exchange to be two-way, this exchange network is symmetric in nature. Hence no country can exclusively export or import electrical energy from another member country and must instead be willing to do both. I will henceforth explain how the EU energy market should be modelled based on its characteristics.

3 Energy Networks as Markets

In this section, it will be explained how the geographical characteristics of a country affect its ability to trade energy with its neighbours. Instead of assessing the welfare gains of members in the market with a traditional (and overly simplistic) free market framework, using the energy network as the means of trade requires us to incorporate the geographical constraints of a country when assessing the potential gains from trade in the energy market. A general framework for assessing these gains will first be outlined, before an explanation on incorporating the geographical constraints through the Coleman Model of Resource Exchange is provided.

3.1 Assessing the gains from trade

In order for the network to result in a more desirable allocation of resources for all members involved, the following conditions would have to be met:

(a) There must be a non-negative change in welfare of each member of the network

(b) There must be a non-negative change in the aggregate welfare of the network

Supposing (a) and (b) are not satisfied, there must be sufficient risk to energy security that offsets the decline in welfare There must be greater reliance on energy sources from within the network The increase in energy grid capacity to enable greater intra-network reliance should be reflective of the centrality and resource characteristics of members involved

These conditions follow from the enforcement of Pareto Optimality and the Coleman Model for Resource Exchange. In particular, conditions (a) and (b) require that no member can be made worse off in order to increase the aggregate welfare of the system, and that any allocation of resources given the same constraints should result in at least the same amount of welfare, if not more, for both the members and the network.

However, this condition alone does not guarantee an optimal allocation of resources. This is because of the asymmetry of trade that exists in the network due to geographical constraints. In a simplified n- person endowment economy, Pareto Optimality relies on the total amount of resources and the utility functions of the members involved. An important assumption here is that there are no restrictions to trade in this economy. The network we are studying violates this assumption since energy grids have to be connected between international borders and are limited in the amount of energy they can transmit. In order to better understand how these limitations affect the optimality of energy allocation, Coleman's Model for Resource Exchange (hereafter referred to as the Coleman Model) is used to assign weights to countries based on their respective energy grid capacities and trading partners.

3.2 Incorporating the Coleman Model

The Coleman model of power, which is modified for the analysis of exchange networks, is an application of graph theory that allows us to analyse the characteristics of a given network. (Coleman, 1990) In particular, it allows us to understand the relative desirability and utility of members in the network, based on their control of and interest in specific resources. The Coleman model of power, which is modified in order to be used for the analysis of exchange networks, is itself premised on three key assumptions. The Coleman power model assumes that the system being studied is closed, that there exists a power vector that indicates the measure of power of an actor relative to the other actors in the network, and that the interest that each actor has in another actor's resources is known and quantifiable. It is therefore applicable to the countries in the EU, which satisfies these three assumptions. First, it is clear that the finite number of countries in the EU and their quantifiable grid capacities ensure that the network is a closed one. Next, the relative power of each country in the network can be characterised by the countries it is connected to.

The interconnectedness of energy grids imply that countries need not neighbour each other in order to exchange energy; however, the connections of neighbouring countries greatly affect that tertiary connections that each country has access to. Therefore the relative desirability, and hence power of a country in the EU, can be characterised by the countries it is connected to, as well as the countries its neighbours are connected to. Lastly, the interest of any country in the EU can easily be characterised by the countries it is connected to. While this is more a result of geography than actual interest, it should be pointed out that a country should be indifferent about where it is exporting or receiving energy from. This is because there is no perceivable difference between energy sources in terms of its use from the perspective of the consumer in, as well as the fact that any connection to the grids of non-neighbouring countries has to pass through the grids of neighbouring countries in the first place. (Thereby making countries primarily interested in their neighbours)

Any interest in the grids of non-neighbouring countries is therefore analogous to the sum of interest in the grid of a neighbouring country and that same neighbour's interest in the grid of the desired country. Since the Coleman model accounts for the interconnectedness of neighbouring countries when measuring relative power, any interest that a country in the EU has over the grid of another country can be represented simply as the aggregation of every country's interest in the grids of their neighbours. In short, any interest in energy interconnection may be characterised by the neighbours that a country is connected to.

Moreover, because a unit of electrical energy can only be consumed by precisely one member at any given time, we can assume that the amount of electrical energy exchanged in the EU is perfectly divisible. Because of the indifference towards the source of electrical energy, we can represent the interest in another country's grid as an equal fraction of all the grids that a given country is interested in. For example, if a particular country's grid is connected to precisely two neighbours, its interest in each of those neighbours' grids is exactly half of its total interest to be interconnected. (in this case, 0.5 of its total interest) The EU therefore satisfies the assumptions that the Coleman model of is premised on.

In modifying the Coleman model of power for the analysis of exchange networks, we perceive the interest in another actor's resource as the interest to control that actor's resource. In other words, this is a measure of utility, and not merely preference. The relative power of an actor is then characterised not as the amount of resources they possess, but the desirability of that resource by other actors in the network. Lastly, it is assumed that each actor is equally interested in non-exchange. In other words, they are all equally interested in controlling their own resource.

The EU satisfies all of these assumptions as well. Since we are discussing the exchange of electrical energy, an interest in another country's energy grid is essentially the desire to use it for its own electrical energy needs. Hence by connecting the local energy grid to its neighbours, a country is signalling its interest to use those neighbouring grids for its own utility. (Both in terms of giving and receiving energy) Moreover, since the source of power does not matter to the consumer and the use of power does not concern the producer, being connected in the EU is far more important than the capacity of a neighbour's grid. This is because energy can be exchanged with non-neighbouring countries, if neighbouring grids are not sufficient to produce/consume the energy being exchanged. Finally, this indifference is caused not only by the nature of energy production and consumption, but by the assumption that each country is primarily interested in its own energy needs. In other words, if every country could produce and consume a precise amount of electrical energy within its own energy grid, it would. Hence while the need for energy exchange exists and motivates the EU network, we can assume that each country is equally (and primarily) interested in its own energy resources. It is therefore possible to model the EU with the Coleman model of exchange networks.

4 Quantifying the Effects of the Network

Analytically, the characteristics of the EU energy market listed above imply that the following two requirements should be met in order to signal the effectiveness of the interconnected network:

(i) The reliance on energy imports from without the network must decrease, accounting for the change in demand of energy within the network

(ii) The change in grid capacity for each member of the network should reflect their relative weights as defined by the Coleman Model

While (i) alone is sufficient to indicate a more optimal allocation of energy, (ii) allows us to determine if the allocation is indeed Pareto optimal by taking into account the asymmetry of trade between members of the network. Any statistical measure of the network's effectiveness should therefore be consistent with these requirements.

4.1 Assessing the effect on the EU

First, an assessment of the first requirement is done by studying the effects of the network on the EU as a whole. In order for the energy market of the EU to be deemed effective, we first examine if it has led to a more allocative efficient outcome for the market as a whole. In other words, whether the existing resources from within the EU are distributed in a manner so that the EU relies less on imports from outside its network. If the trade of energy has resulted in such an outcome, then it is evident that aggregate welfare in the EU is at least equal, and possibly greater, as a result of reading using the network. The following metric for evaluation is proposed:

$$E_{u_t} = M_{u_t} - \frac{C_{u_t}}{C_{u_{t-1}}} M_{u_{t-1}} \tag{1}$$

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

The above metric is used to determine if the allocative efficiency of the market has indeed increased as a result of trade. If the growth in grid capacity and trade has been successful, then the change in net imports, accounting for growth in consumption, should decrease over time. Since the change in consumption of energy is exogenous to its production, the decrease of net energy imports implies a more efficient allocation of the energy produced within the EU.

4.2 Assessing the effect on a member of the network

While the aggregate energy imports could have decreased, it cannot be assumed that a Pareto optimal outcome has been achieved in the market. It is clear that such a result could be achieved if the loss in welfare of some countries is offset by the gain in others. Hence, a separate metric to evaluate the desirability of market outcomes for individual countries is necessary. The following metric is proposed:

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

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

This metric is used to determine if the market is used to distribute energy effectively. First, by factoring in the amount of grid expansion in a country, we are able to determine how much energy a country could theoretically consume the following year. Then, by subtracting the net imports of that country, the amount of wasted potential that is incurred by the grid expansion is derived. The decrease in this metric therefore signifies the waste from investing in grid capacities and therefore the ability to trade in the market. Given a highly efficient network where energy is redistributed according to each country as is necessary, this value should indeed be expected to be as low as possible.

4.3 Evaluating the market

Revisiting the requirements of the market stated at the beginning of the section, it is clear that there should be some variable that provides information about the effectiveness of the market based on weighted gains in welfare. To this end, the following equation is used:

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

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

There are three possible cases that should be considered:

$LHS < RHS$

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 centraluty measures of its members.

$LHS > RHS$

This case indicates that the market is allocatively inefficient.

It should also be noted that while these cases provide information on the nature of the market in general, a closer observation of the metrics of each country is essential in order to determine its actual condition. This is a consequence of using the aggregate, instead of the summands, to derive our conclusions. For example, while the aggregate value of the metrics could be equal (the second case above) and suggest that the network is indeed being used effectively, it is possible that each E_i/E_u has a value that is rather large in magnitude . This suggests that while the network is being used efficiently, the gains from trade are still minimal. The data section will discuss these scenarios in greater detail.

5 Assessing Allocative Efficiency

First, this section will provide information on the relative weights of countries in the EU as per the results of the Coleman Model, and use them to inform the allocative efficiency of the network as defined in the previous section. These measures will then be used to assess the allocative efficiency of the EU energy market and observe the correlation of allocative efficiency with the indicators such as proportions of non-renewable energy production and of various renewable energy sources. The data used in this section was obtained from Eurostat, the statistical division of the EU.

5.1 Coleman Model Data

First, the results of the Coleman Model are collated in order to weight the trade of energy. This is done by recording the number of grids each country's grid is connected to, and deriving the relative influence of each country's grid relative to its geographical location as discussed in the second section of this paper. The relative weights of each country, as a factor between 0 and 1,(where 0 implies no influence and 1 implies complete control) are presented below:

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 3: Centrality Values

5.2 Allocative Efficiency

Next, the centrality measures are used to obtain the variables in equation (3).

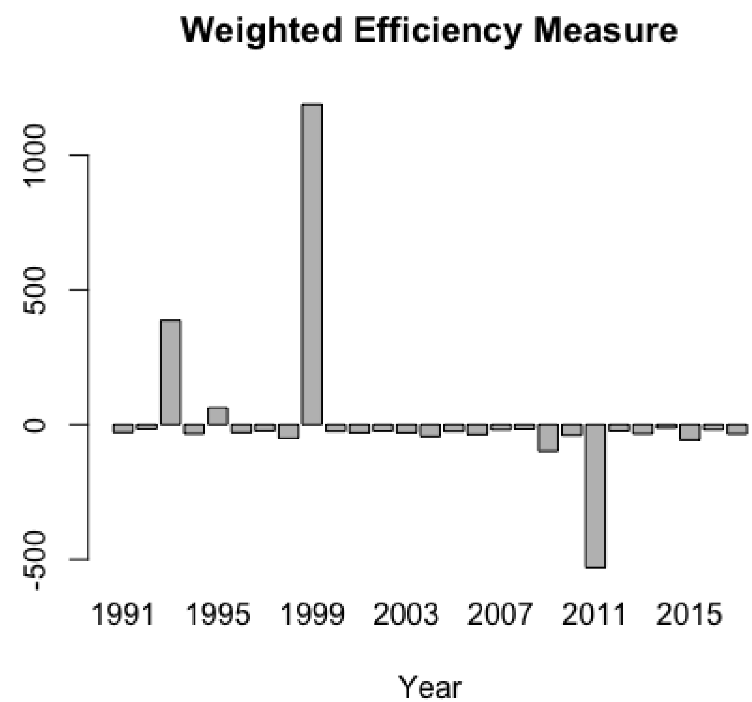

Figure 4: Weighted Efficiency Measure

It appears that the EU was indeed allocatively efficient in its redistribution of energy. The exception, however, are the years 1993, 1995, and 1999. These years coincide with significant years in EU history; 1993 was the year the EU became an official entity, 1995 saw the first significant expansion of the EU since its founding, and 1999 marked the adoption of the Euro as a common currency. It remains to be proven how these events were indeed the causes of trade frictions and allocative efficiency in those years, though there is sufficient evidence to suggest that they could have motivated autocratic and speculative tendencies that led to this result.

Nonetheless, it is evident that while the EU was allocatively efficient for the majority of the last two decades, it was not in a manner that was informed by the centrality measures of its members.(While the figure above is distorted due to its sizing, the magnitudes of the results are significantly large) In essence, countries were not expanding their energy grids and participating in intra-EU energy trade at a level that corresponds to the amount of influence they have in the market and the pace at which the collective EU grid was expanding. A closer look at the individual values of grid expansion ratios reveals that nearly all countries were responsible for this result, though to varying degrees. The following section examines possible causes for this behaviour.

5.3 Disregarding Centrality

Since it appears that countries have not been expanding their grids at a rate that corresponds to their centrality, there should ostensibly be some other variable that informs grid expansion strongly. Such a reason, beyond explaining the rate of grid expansion in the EU, could possibly explain why centrality measures have not been strongly adhered to as well.

At this point, it is worth mentioning that centrality measures may not be an important factor in determining the rate of grid expansion or the desirability of trade. Even if one assumes that EU countries were aware of their influence, it is indeed a stretch to believe that they would expand their energy grids while taking it into consideration. However, it is possible for us to assume that a more central country in the EU, with greater influence over the market, would stand to gain more from trade. This follows from the Coleman Model which allows us to determine the relative gains from exchange in a network, as well as from a simple demand and supply perspective that implies that a country either has greater energy security or profits from energy trade, depending on their level of energy consumption.

If we therefore assume that countries should implicitly expand their grids according to their centrality measures, the causes for the lack of this behavior remain to be identified. In order to do so, the main causes for the difference in energy production between countries should be considered. This would greatly influence the amount of energy that a country intends to trade, and therefore influence its grid expansions. Moreover, the source of production determines how easily a country can respond to changes in demand in the market, and therefore trade energy more efficiently.

In this regard, the amount of non-renewable energy produced in a country and the amount of energy with nuclear, hydroelectric, and wind sources respectively are considered. Their values as a proportion of energy produced and consumed are also considered, and regressed against the weighted and unweighted rate of grid expansion in the country. The following regression equations are used:

$$\frac{E_i}{E_u} = C + NR + N + H + W + \epsilon_0 \tag{4}$$

$$\frac{E_i}{E_u} = \frac{NR}{Q} + \frac{N}{Q} + \frac{H}{Q} + \frac{W}{Q} + \epsilon_1 \tag{5}$$

$$\frac{RE_i}{E_u} = C + NR + N + H + W + \epsilon_2 \tag{6}$$

$$\frac{RE_i}{E_u} = \frac{NR}{Q} + \frac{N}{Q} + \frac{H}{Q} + \frac{W}{Q} + \epsilon_3 \tag{7}$$

Table 1: Energy Market 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)		
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)
Constant	4.106	0.100	−1.613**	−0.129**
	(2.519)	(0.066)	(0.728)	(0.053)
Observations	720	720	509	509
R^2	0.005	0.033	0.026	0.041
Adjusted R^2	-0.002	0.027	0.019	0.033
Residual Std. Error	49.315 (df = 714)	1.299 (df = 714)	16.082 (df = 504)	1.171 (df = 504)
F Statistic	0.779 (df = 5; 714)	4.917*** (df = 5; 714)	3.429*** (df = 4; 504)	5.391*** (df = 4; 504)

Note: *p<0.1; **p<0.05; ***p<0.01

Starting with the standard model, the data shows that there is no significant correlation between grid expansion and any of the factors that have been discussed. Naturally, this should raise some concerns, since one should expect the amount of energy that is produced and consumed in a country to be highly correlated with the amount of grid expansion it undergoes. Clearly, there must be some other factor that influences a country's decision to expand its grid. Weighting the countries with their centrality results, however, shows that the energy consumption of countries is highly correlated with their weighted energy consumption. This is far more akin to what should be anticipated, and provides some reassurance that the weighted model is a much more accurate indicator of energy trade and efficiency than typically unweighted models.

Next, the results indicate that the amount of non-renewable energy produced in a country is highly negatively correlated with the rate of grid expansion. In essence, countries that rely more heavily on non-renewable sources of energy, such as fossil fuels and petroleum, are far less likely to expand their grids in a manner that would benefit the market based on their centrality. This trend is also evident when the proportions of non-renewable energy produced are considered. When the variables in the standard model are taken as proportions of total energy produced, the share of non-renewable energy produced in a country is still significantly correlated with grid expansion. It is also worth noting that when the EU saw its most inefficient expansion of energy grids with regards to centrality in 1999, it was experiencing the aftermath of a large decrease in oil prices.

However, while the share of non-renewable energy produced is significant, and the share of renewable energy produced would therefore be significant as a result, the type of renewable energy produced does not seem to be significantly correlated with weighted grid expansions. This is true in both the standard and the proportional cases.

6 Discussion

6.1 Policy Implications

The main policy implication of the results in this paper would be regarding the setting of grid expansion targets in the EU. Following the Paris Agreement of 2015, the EU set a target of a minimum of 15% buffer capcity for all national energy grids for its member countries.(Paris Agreement, 2015) However, this would not be advisable. Not only would less influential countries be forced to expand their grids beyond what is necessary, but assuming less influential countries possessed sufficient buffer capacity, more influential countries should have to expand to a size beyond the mandated 15%. The inflence of countries on the market based on centrality measures alone imply that a fat target is not the best way to increase allocative efficiency and hence the gains from energy trade. Moreover, with regards to clean energy targets, it is evident that countries that produce smaller shares of renewable energy are not expanding their grids at a sufficient rate. This is especially pertinent given the variability in clean energy production and the fact that an increase in reliance on clean energy in order to meet the EU's environmental objectives is dependent on an increased ability to trade vast amounts of it. While countries that rely mainly on non-renewable sources seem to have less grid expansion, the geographical location of these countries could deter trade from clean energy producing coastal countries. It could also prevent landlocked and fossil fuel reliant countries from improving their energy security in the case of shocks to oil prices or infrastructure related problems.

It would therefore be advisable, given the results of the weighted model, to set grid expansion targets based on countries' influences on the market. Doing so would ensure that even countries that rely on non-renewable sources are able to aid in the trade of energy across the EU. The resultant gains from trade in clean energy could also encourage investment and production in renewable energy in the long term.

6.2 Further Study

While this paper provides a rudimentary analysis on the grid expansion and its possible market, the nature of energy trade and production necessitate more detailed study. This includes a more granular analysis of electricity production plant location and grid layouts, energy pricing methods, and trade policies.

A more granular study would be useful in assessing the exact locations of needed grid expansions and energy investments. While this study aggregated the energy produced and consumed within countries, these processes need not be distributed evenly geographically. Necessitating that an entire country increase its buffer capacity when only its capacity and energy production along the borders are insufficient, for example, would not be a very efficient strategy. Therefore, using power plants as nodes and more detailed grid layouts as the edges in the Coleman model would provide a more detailed and accurate indication of where the inefficiencies in EU energy trade lie. While it is difficult for the results of such a study to lead to a feasible EU mandated policy, it is nonetheless useful in understanding how energy trade could be expedited.

The energy pricing methods in the EU also deserve some attention in understanding the inefficiencies in trade. There have been several studies investigating the effect of more than one pricing method of pricing energy in the EU, which would continue to impede trade despite an increased capability to do so. This could also explain the shares of renewable energy production and investments in countries, which would improve the centrality measures and the currently observed effects of energy sources on grid expansion. Such a study would require an updated efficiency model that takes into account the frictions from trade (either pricing related or otherwise) and a more nuanced centrality measure as explained above.

Lastly, various trade policies that determine the nature of energy production and trade should also be considered for further study. The policy stances of various countries could also impede trade despite sufficient grid capacities, rendering the proposed targets based on centrality measures inaccurate. Moreover, if the share of renewable energy production is the result of certain policy measures or economic goals, it would be pertinent to study the effect that such policy measures have on grid expansions and efficient trade, rather than the nature of energy produced. As it stands, however, the significance of centrality measures on the efficiency of energy trade remains despite its potential causes.

7 Conclusion

This paper has introduced a method for assessing the allocative efficiency of a market based on the relative influence of each of its members. The level of influence was derived using Coleman Model of Resource Exchange, and then used to derive values for a measure of weighted allocative efficiency that was proposed. When applied to the energy market of the EU, the results show that the market has been largely allocatively efficient, though in a manner that does not take into account the relative centrality values of its member countries. The inefficiency in relative grid expansion based on centrality values are highly correlated with the share of energy produced using renewable sources, though the specific source does not matter.

This result has significant implications for EU energy policy. In particular, the flat target of an energy buffer capacity amounting to 15% of a country's total grid size is not advisable, since it disregards the centrality values that govern a country's influence on the market. Furthermore, if an increased reliance on clean energy is a specific goal for the EU, grid expansion targets based on centrality values would ensure the best way to target countries that do not produce large shares of clean energy, while allowing countries with more variable renewable energy sources to gain access to a larger and more efficient grid.

References

[1] Bremen L.V. 2010 Large-Scale Variability of Weather Dependent Renewable Energy Sources. In: Troccoli A. (eds) Management of Weather and Climate Risk in the Energy Industry.

[2] Coleman, James S. 1990. Foundation of Social Theory. Chapter 2. “Actors and Resources, Interest and Control”.

[3] Simon, Clea. 2018. “Global Power for Global Powers”. Harvard Gazette. April 19.

[4] European Commission. 2014. “Framework for Climate and Energy 2030”.

[5] European Commission. 2017. “Towards a sustainable and integrated Europe”.

[6] Kyle, Albert S. 1989. ”Informed Speculation with Imperfect Competition”.

[7] Neff, Thomas L. 1997. ”Improving Energy Security in pacific Asia: Diversification and Risk Reduction for Fossil and Nuclear Fuels”.

[8] Stigler, H. 2016. The European interconnection system between reality and utopia Does the market organization fit into the electricity network?. Innovative technologies for sustainable electrical grids, (p. v). Austria.

[9] Paris Agreement, United Nations, December 21 2015.