A thesis submitted to the Department of Environmental Sciences and Policy of

Central European University in part fulfilment of the

Degree of Master of Science

Assessment of energy security using social network analysis and food web analysis

Nga NGUYEN

May, 2012

Budapest

Erasmus Mundus Masters Course in Environmental Sciences, Policy and Management

MESPOM

This thesis is submitted in fulfilment of the Master of Science degree awarded as a result of successful completion of the Erasmus Mundus Masters course in Environmental Sciences, Policy and Management (MESPOM) jointly operated by the University of the Aegean (Greece), Central European University (Hungary), Lund University (Sweden) and the University of Manchester (United Kingdom).

Supported by the European Commission's Erasmus Mundus Programme

Education and Culture

Erasmus Mundus

Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

<candidate’s signature>

Nga NGUYEN

CENTRAL EUROPEAN UNIVERSITY

ABSTRACT OF THESIS submitted by:

Nga NGUYEN for the degree of Master of Science and entitled: Energy security using social network analysis and food web analysis

Month and Year of submission: May, 2011.

This thesis explores the applicability of network analysis, especially food web analysis metrics to assessing energy security. It identifies two "system" indicators (Average Mutual Information and Conditional Uncertainty) and two "local" indicators (Trophic Level and Omnivory Index). The system indicators reflect vulnerability and resilience of national energy systems and are relatively easy to calculate and interpret. The system indicators do not correlate with the level of economic development but do depend upon the geographic location of the country. They also correlate with the widely used measure of energy security: the diversity of energy sources. At the same time they provide more information into potential vulnerabilities of energy systems than merely aggregate diversity. The local indicators potentially reflect the quality of energy consumed at each energy level and the variance in the energy consumption. In this thesis they are applied to primary energy systems, electricity and three end-use sectors at the national level as well as to international gas and oil trade networks. These two indicators are not independent of each other and do not correlate with existing indicators, thus making interpretation more challenging. They more accurately reflect the role division in case of gas trade network than in case of oil trade network. Further work is required to make these indicators policy relevant.

Keywords: energy security, food web analysis, network analysis, energy trade

Acknowledgements

I am extremely thankful for my supervisor Aleh Cherp, who framed the idea behind the thesis. He continually encourages, shares expert knowledge on the topic and has gone beyond to help me secure data, connections with other people in the field. I would also like to thank my friends, Sarah Czunyi, Gabor Nyeki, and my mother, Phuong Tran, who helped me with their emotional support. Last but not least are acknowledgments to the European Commission and Environmental Department for financial support.

Table of Contents

List of Tables

List of Figures

1 Introduction

Energy security is "protection from disruption of essential energy systems" (IEA 2012a, Cherp et al 2012b). There is in general more agreement on what are "essential energy systems" than what are causes and consequence of likely disruptions.

Disruptions of national energy systems can be caused by unstable energy supply from external systems or a failure of systems to convert primary energy to secondary and secondary to tertiary. Both causes and consequences of energy systems disruptions may happen at various time scales. A disruption could unfold over a few decades, for example when reserves of coal, gas and oil are exhausted or when demand grows to exceed available supplies. A disruption could span a few days like in the 2009 Russian-Ukrainian gas dispute in (EC 2009a, EC 2009b). Or it could last a few hours like the blackout in 2003 Italy (Buldyrev, et al 2010) days in the case of North America (Watts and Strogatz 1998). From experiences of past disruptions we have learned that an energy system could return to the original operation after a hiatus. Such ability to withstand a disruption is called "resilience". A large part of energy security studies is about an indicator that can reflect energy systems' resilience.

However, to properly model and understand the resilience of a system, one would need to capture detailed information about the energy flow, the disruption and time takes to recover at a high spatial and temporal scale (similarly to Critical Infrastructure protection suggested by Farrell et al 2004), which is a grandiose task. This study proposes a more modest approach to use food web analysis to estimate energy system's security based on a "snapshot" of its characteristics. Food web analysis has been used since 1972 May (Ulanowicz 2009) to study the stability and development of food webs.

In many spatial, temporal, and structural aspects, energy systems are analogous to ecological systems. Spatially, energy systems are divided into communities, nations, and supra-national regions, while ecological communities inhabits niches or ecosystems (Leibold et al 2004). Temporally, the increases in demand, supply, the ability to return to operational state of an energy system is similar to that of population dynamics and resilience (Leibold et al 2004, Dunne 2006). Structurally, energy system have a clear distinction of primary, secondary and end use sectors with the former sector supplying energy to the latter sectors; this structure in ecology is similar to prey-predator relationship in food web (Emmerson and Raffaelli 2004, Leibold et al 2004).

In many other ways, energy systems resemble ecological systems, for example the behaviour of each individual species or the population (group of similar species) changes the outcome of that population's interaction with other population; this is equivalent to each energy sector having a different technological, social or economic adaptation and the aggregated effect of the "whole is different from the parts" (Meadows 2010). Another observed pattern in ecological community is that interaction among populations does not happen only inside the community, it also occurs outside due to dispersal, a process that resembles energy trading among countries. In this case, each community is seen as a country and the global trade pattern defines the meta-community's interaction.

The application of food web analysis to national energy systems is also based on theoretical equivalence of the two systems. Dunne (2006) listed "scale-invariant" characteristics of food web that are found in energy systems: constant proportions of top consumers, intermediate consumers/producers and producers (scaling laws Briand and Cohen 1984); the "low diameter" of the network (Cohen et al 1990); absence of loops (Pimm and Lawton 1980). Ulanowicz (2002 and 2009) suggested that ecological system indicators falls within a "window of vitality", which is also the boundary for other economic or social network. Given all these similarities, it is interesting to explore whether methods from food web analysis can be applied to characterize energy security. At the same time, such an analysis has only been rarely attempted which creates a gap in knowledge that this thesis aim to address.

1.1 Aims and objectives

The thesis aims to explore the applicability of network analysis, especially food web analysis or ecological network analysis to energy security assessment. The objectives of the study are:

1. To identify concepts and methods of food web analysis and ecological network analysis potentially applicable to analysis of energy security;
2. To develop energy security metrics based on these concepts and methods;
3. To evaluate national energy systems, vital energy sectors (Electricity, Industry, Transport, and Residential) and international trade in oil and gas, using the identified indicators
4. To explore the correlation of the indicators with economic development and geographic location of countries.

1.2 The structure of the thesis

The thesis includes six chapters including this introductory chapter. Chapter two explores existing literature on the definition and the current methods of assessment of energy security as well as current application of network analysis, especially food web analysis to energy security assessment. Chapter three explains the methodology used in this study, data collection process and data analysis procedure. Chapter four presents the key results. Chapter five discusses the most significant results how the new indicators compare to existing indicators of energy security. Chapter six summarized the findings of the thesis and outlines the future research agenda.

2 Literature review

The purpose of this literature review is to

1. overview concepts, methods and challenges of quantitatively measuring energy security

2. overview concepts from ecological networks methods that may help to resolve these challenges

3. overview the application of ecological network theories to assessment of energy systems so far and identify gaps in these efforts

2.1 Energy security

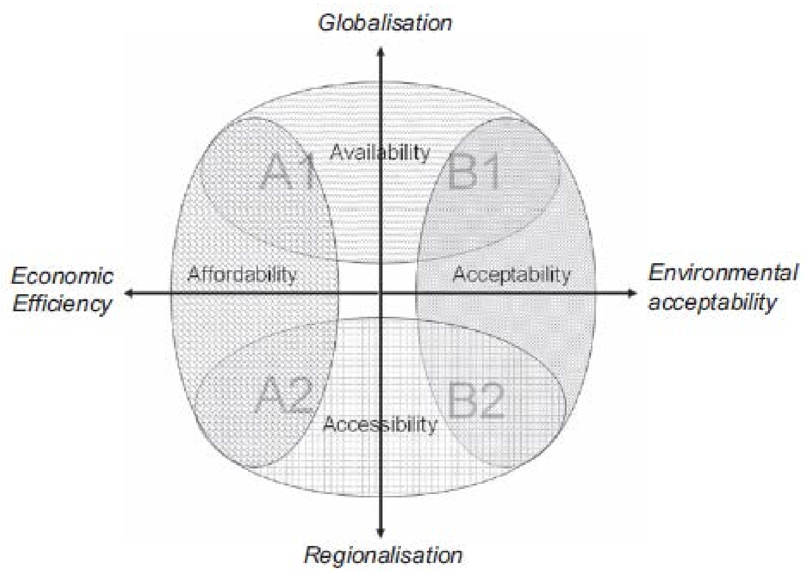
2.1.1 Definitions

There are different definitions of energy security revealing its "polysemic nature" (Chester 2010). There is for example a disagreement whether concerns such as environmental sustainability (Blyth and Lefevre 2004) or energy poverty should be included in the concept of energy security. The following definitions are most widely used:

Yergin (2006) defines energy security as "availability of sufficient energy supplies at affordable prices". The definition is rooted in history during which energy is tied with war and the supply of energy determined the fate of the nation. In line with this definition, Yergin proposes four principles of strengthening energy security: diversification of supply, building resilience against shocks, preparing for integrated of energy networks, encouragement of transparent information (on price, availability, technology).

Kruyt et al (2009) defines energy security according to the "4As": accessibility, availability, affordability and acceptability. This definition has an advantage of following the four emission scenarios of IPCC closely (Nakicenovic et al 2000) as seen in Figure 3-1, thus applicable to future prediction of energy security. However, notion such as affordability and acceptability is very difficult to quantify.

Figure 1-1 Energy security dimensions in relation to development scenarios



Source: Kruyt et al (2009)

Cherp & Jewell (2011) identify three perspectives on energy security: sovereignty (political), robustness (technical), and resilience (economic) and explain how each of the perspectives has its own disciplinary and historic roots. Table 3-1 summarizes the view behinds the perspectives.

Table 2-1 Three perspectives on energy security

Perspective	**Sovereignty**	**Robustness**	**Resilience**
Historic roots	War-time oil supplies and the 1970s oil crises	Large accidents, electricity blackouts, concerns about resource scarcity	Liberalization of energy systems
Key risks for energy systems	Intentional actions by malevolent agents	Predictable natural and technical factors	Diverse and partially unpredictable factors
Primary protection mechanisms	Control over energy systems. Institutional arrangements preventing disruptive actions	Upgrading infrastructure and switching to more	Increasing the ability to withstand and recover from various

Perspective	Sovereignty	Robustness	Resilience
		abundant resources	disruptions

Source: Cherp and Jewell (2011)

The Global Energy Assessment (GEA, Cherp et al 2012) defines energy security as "protection from disruption of vital energy systems". GEA focuses the analysis of energy security on (a) vital energy systems and (b) potential disruptions. This definition allows the analysis "propagation of energy disruption" from primary to secondary to tertiary level. The vital energy systems identified in Cherp et al (2012) - industry, transportation, residential and electricity – are also used for the analysis in this thesis.

2.1.2 Indicators and metrics

Indicators of energy security depend on the adopted definitions and concepts. Indicators differ with respect to the levels of energy systems they address (national, regional, primary, end use sector etc.), the type of risks and disruptions they cover (shocks or stresses, physical or economic risks, geopolitical or technical and natural risks etc.), and the level of aggregation employed.

Sovacool (2011) produces a large list of over three hundreds potential indicators aligned against eleven dimensions of energy security. However, since the construction of this list were based on consultation with energy experts, an exhaustive list were proposed and the. At the same time Cherp (2012b) criticizes this approach on the grounds that energy security concerns should be prioritized.

Cherp and Jewell (2010) argue that generic indicators for energy security should be replaced by systematic assessment frameworks where the indicators used depend on the specific energy security problem under consideration.

The Global Energy Assessment (Chapter 5) uses circa thirty indicators to evaluate the present energy security in over 130 countries (Cherp et al 2012) and Chapter 17 (Riahi et al 2012) uses about ten indicators to evaluate global and regional energy security under long-term decarbonization scenarios.

Jewell (2011) uses thirty-two indicators focused on energy security of supply in OECD countries in the Model of Short Term Energy Security. Table 2-2 lists common indicators compiled from aforementioned sources based on the three perspective of energy security conceptualization (Cherp and Jewll 2010).

Table 2-2 Common indicators of energy security

	Sovereignty	Robustness	Resilience
Sectoral	Import dependency	Options of energy technologies	Diversity of PES
National	Import dependency Diversity of importers	Number of import/export routes Quantity and quality of infrastructure Rate of demand growth	Energy intensity Diversity of energy option
Global	Geographic concentration of energy related resources	Availability of resources	Diversity of fuel options in total global PES
Additional dimension	Political stability (Jansen 2004) Distance (Le Coq and Paltseva 2009)	Research and development	Storage capacity

Note: Compiled from Cherp et al (2012) Jewell (2011) and Sovacool (2009)

These indicators are then aggregated to get a unique indicator. The aggregation is either based on a simple weighted system of subjective weighting (Sovacool 2003) or weighted based on additional dimensions of security (Newmann 2004) or objective weighting based on principle component analysis (Gupta 2008) or cluster analysis (Gnagnosonou 2008). While the aggregation simplifies the indicators to a single unifying number, the final result might not be too meaningful due to subjective or objective assumptions made during the aggregation.

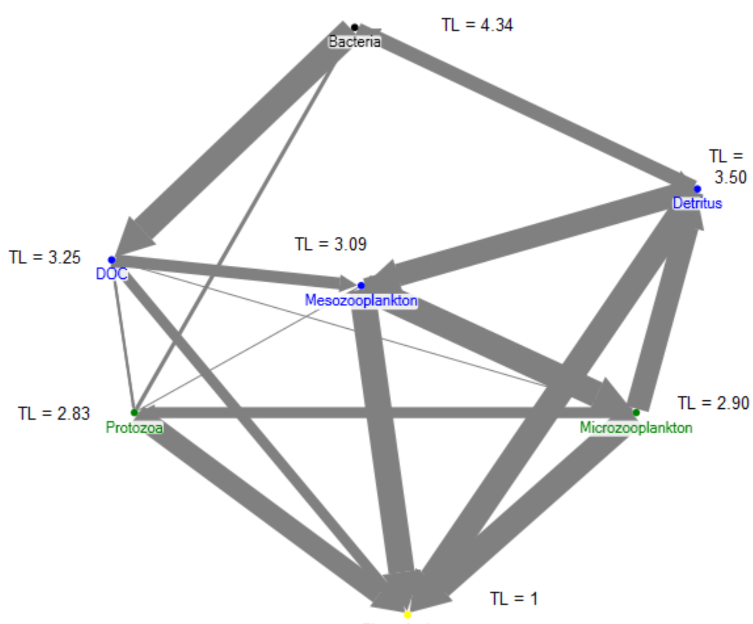
While all of these indicators have been widely used in measuring energy security at different levels, most of them do not reflect the ability of energy systems to respond to disruptions. The only exception is the diversity of energy sources originally proposed by Stirling (1994) and subsequently used by Jansen (2010) and many other authors. This thesis aims to explore whether food network analysis can suggest better indicators of resilience than diversity.

2.2 Food webs and food web analysis

Food web is a structural network of energy or material flow in a community. The study of food web and its structure is essential to ecology in the sense of preserving biodiversity, studying ecological responses to environmental changes, population dynamics (Lotka 1925) and interaction among different species in community (consumers, producers) (Hollings 1959). Food web analysis is the set of tools that used to analyze the current state of the community (system indicators) and individual species (local indicators).

In food web networks, the nodes are species or families of species, the links are interactions among the species (usually predation and prey). In this thesis, energy flow is the link among the species, thus, the network is a directed and weighted small-world network (Ulanowicz 2002). The direction is shows the relationship "who provides energy to who" and the weights of the link show the amount of energy transfer. The network is called a small-word network since there is a short path from one node to the other, in food web, the path is usually less than 6 (Ulanowicz 2002, Jordan and Scheuring 2004, McCann, Hastings, Huxel 1998).

Table 2-3 Sample food web at Takapoto



HR = 2.63, AMI = 1.51, DR = 1.12.

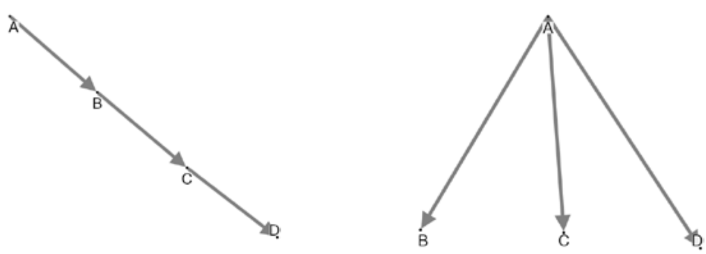
Note: Data obtained from Kones et al (2009) visualized using NodeXL.

2.2.1 System indicators

There is a long standing theory behind the structure of the food web and its stability (Dunne 2006, Ulanowicz 2003). Ulanowicz (2009, 2011) Zorach (2002) argues that the stability of a food web can be calculated mechanistically based on the structure of the energy flow, while others like May (1959) concentrates on the relationship between diversity and link density in a food web to deduce its stability, Ulanowicz's theory has its root in information theory and has a more rigorous establishment as well as implication.

According to Ulanowicz (2002), the stability of the food web depends on two factors: flexibility and efficiency in transferring energy. These two factors are captured by Average Mutual Information (AMI) and Conditional Uncertainty (DR) respectively.

Table 2-4 Sample network configurations

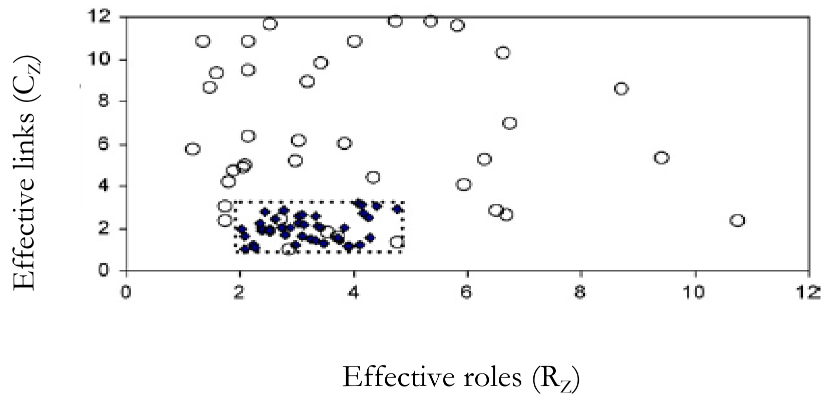


AMI = 1.6, DR = 0, roles = 4   AMI = 0, DR = 0, roles = 2   AMI = 0.92, DR = 1.1, roles = 3

Note: all networks were constructed with 3 links and 4 nodes

While food web analysis has not been applied to other networks, both Matutinovics (Ulanowicz 2004) and Ulanowicz (personal communication) agrees that such indicators are not only applicable to other networks but also carry an approximate "window of vitality" (Ulanowicz 2002, 2004). The window of vitality is the observed range of AMI and DR or effective roles (2^{AMI})and effective links ($2^{DR/2}$)respectively.

Figure 1-2 Effective links and Effective roles



Note: Random network simulation values are circle and ecological network values are solid square (Ulanowicz 2009)

The observed range of the effective link is (1, 3), and the range of the effective roles is (2, 4.5); which makes the window of vitality lies between (0, 3.17) for DR and (1, 2.17) for AMI. The former range is explained by the connectivity of the food web, so that the food web is one component without any outlier; this is equivalent to a national energy system in which all energy technologies are connected to each other. The upper bound of the effective link (3) is due to the construction of the metrics, giving a natural limit of $e^{e/3}$ (May 1972). The latter range is due to the assumption that there exists at least "two functions: production and decomposition in all ecosystem" (Fiscus 2002) and that the upper limit has generally been observed without theoretical explanation. When translate to a national energy system, the lower bound of effective roles of 2 is not applied since the function could be as little as one, either production or consumption.

2.2.2 Local indicators

- Trophic Level (TL)

The measurement reveals how far it is to get to the original source of production. This measurement encompasses both the "level" of material consumed (TL_i) and the relative amount of material being transferred $\left(\frac{T_{ij}}{T_{j.}}\right)$. The original material producer is considered to have *TL* of 1, this is either the import or the production of non-import primary fuel.

$$TL_j = 1 + \sum_{i=1}^{n} \frac{T_{ij}}{T_{j.}} \cdot TL_i$$

For example, in 2009, South Korea (KR)'s Electricity sector consume energy from the following sources:

Table 2-5 South Korea's Electricity sector energy consumption

Source	CO	OI	GA	NU	HY	GE	BI
TL_i	2	2.716*	2	1	1	1	2
Relative amount	0.470	0.043	0.114	0.367	0.002	0.001	0.003

Which gives:

$$EL\_TL_{KR} = 1 + (2 \cdot 0.470 + 2.716 \cdot 0.043 + 2 \cdot 0.114 + 1 \cdot 0.367 + 1 \cdot 0.002 + 1 \cdot 0.001 + 2 \cdot 0.003) = 2.660.$$

Note that Product oil (OI) has a TL of 2.716 due to import of oil, import of crude oil and process of crude oil into oil.

The *TL* tells us how far a node is from the original energy production source, thus the higher the *TL*, the more insecure the node is in term of energy consumption. This insecurity is either due to import disruption or internal disruption of services.

- Omnivory Index (OI)

Complementary to the *TL* measurement is the Ominvory index (*OI*) which gauges the consumption variances among the different *TL*.

$$OI_j = \sum_{i=1}^{n} \left(TL_i - \left(TL_j - 1\right)\right)^2 \cdot \frac{T_{ij}}{T_{j.}}$$

Using the KR example, the calculation is:

$$EL\_OI_{KR} = (2 - 1.66)^2 \cdot 0.470 + (2.716 - 1.66)^2 \cdot 0.043 + (2 - 1.66)^2 \cdot 0.114 + (1 - 1.66)^2 \cdot 0.367 + (1 - 1.66)^2 \cdot 0.002 + (1 - 1.66)^2 \cdot 0.001 + (2 - 1.66)^2 \cdot 0.003 = 0.277.$$

The *OI* takes into account of both the *TL* and the relative consumption, thus giving us a complimentary information on the level of consumption security. Ecologically speaking, species with high Omnivory Index has higher stability due to ability to switch prey. In translation to national energy system, a country with the same *TL* but higher *OI* (more varied consumption pattern) would have a higher consumption security than the other country with the same *TL* but lower *OI*.

2.3 Social network analysis

Social network analysis has recently gain lots of attention due to its wide application in many different fields (Newman 2004, Newman et al 2006, Jackson 2009). The three major concentration of social network analysis is the study of centrality, clustering and role analysis (Nordlund 2010).

- Degree centrality (Jackson 2009)

Degree centrality tells us how many connections there are at node n_i. For importer, the more in-degree, the more resilient node i is against energy supply disruption (with the assumption that loss amount can be easily obtained from alternative supplier). Since we are concerned with supply security only, exporter degree centrality are not in our calculation.

- Betweeness centrality (Jackson 2009)

Betweeness centrality is a measurement of how a node acts as a gateway in the network. The higher the betweeness centrality of a node, the more shortest paths through that node connecting other nodes.

In terms of energy security, having a high betweeness centrality is equal to having a high import diversity,

- Clustering coefficient (Jackson 2009)

The clustering coefficient reveals how well-connected the neighborhood of node i is. Since connection means a transfer of material between the two nodes, the clustering coefficient tells us if the trade partner of node i re-import or re-export the material from other nodes in the neighborhood. In term of energy security, import dependency, the lower the clustering coefficient the more secured it is for node i, i.e. node i is not importing re-export from others in the network.

This coefficient is complimentary to TL in ecological network analysis in the sense that the higher TL is, the more portion of material consumption is from re-exporter, thus, the more re-exporter in the neighborhood and higher clustering coefficient.

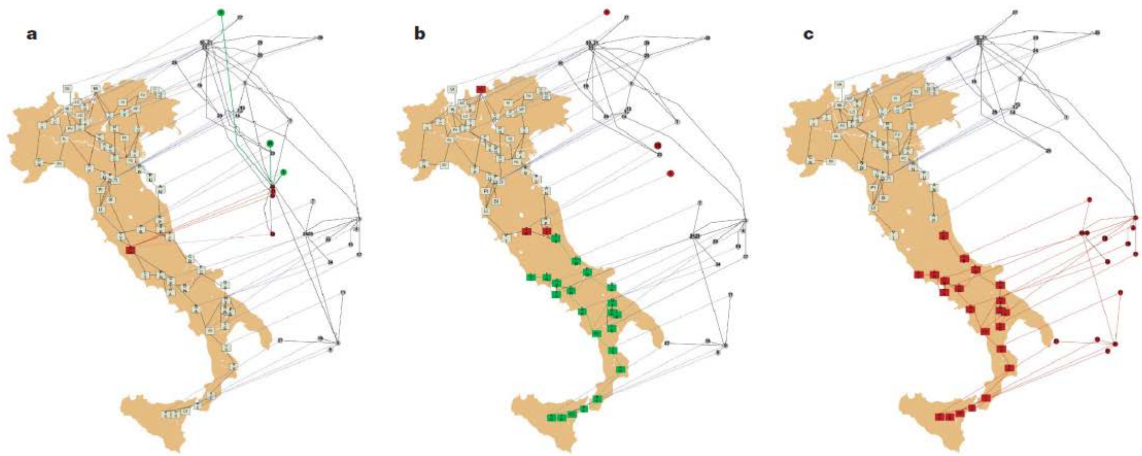
- Hierarchical community clusters (Nordlund 2010, White and Reitz 1983, Newman 2004, Newman et al 2006)

Community consists of nodes that are similar. The similarity here is chosen to be regular equivalence (Nordlund 2010). The definition is recursive: nodes are regularly equivalent if they are connected (both directions in directed network) to regularly equivalent nodes (White and Reitz 1983). Luczkovich et al 2003 have used regular equivalence to define trophic level.

2.4 Network analysis for energy security

The most common application of network analysis in energy studies is for the analysis of electrical grids. Prominent research in this area is by Buldyrev, et al. (2010). The research studies catastrophic cascade failures in interdependent networks, i.e. networks of electrical grid and the Internet (). The study used the assumption that the electrical grid powers the internet, which in turns deliver information to control the power plant so that electricity are produced at the right amount at the right time. The study used the topological networks of electrical grid and internet and simulated step-wise node removal according to the blackout to study the stability/resilience of the networks. The study noted that both networks are scale-free, with a few major hubs and large number of small degree nodes, which is highly resilient against random technical failure in the meantime not subjected to high redundancy. However, the advantage of scale free characteristic is undermined when the two networks are interdependent on each other, causing much lower resilient against random catastrophe. The study showed a promising application of network analysis, however, it is not highly applicable to vital energy sectors since the relationship among sectors are not truly dependent, and if there is any dependency it would be financial which is not the unit of energy.

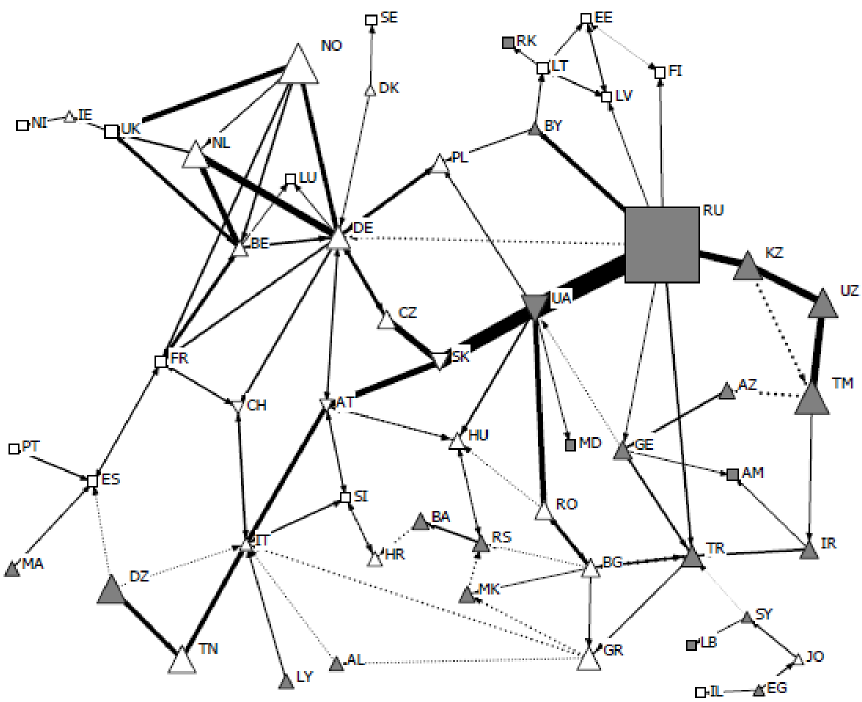
Figure 1-3 Italy's September 2003 black out simulation



Note: Electrical grid are layered over map of Italy whereas internet network is super imposed on top of the grid. The connection between the electrical plant and closest internet hub is shown. Red nodes are affected nodes which are disconnected from the system, green nodes are infected nodes which will be disconnected from the system in the next step (Buldyrev, et al. 2010)

Scotti and Vedres (2012) study supply security in the European natural gas pipeline network (). This study covers the physical infrastructure of gas pipeline in at different time scale (present, immediate future and near future) of the network. The study concluded that the expansion of the network through the construction of Nabucco and other pipelines will not likely increase energy security of each country. This is congruent with findings in food web analysis which believes that diversity and complexity do not necessarily lead to stability (Dunne 2006, Ulanowicz 2002). Scotti's and Vedres' study is among the few that relies on not only trade data but also physical infrastructure of the network and nouvelle node removal algorithm to measure supply and demand security.

Figure 1-4 Pipeline structure of 2008 and national energy security indicators

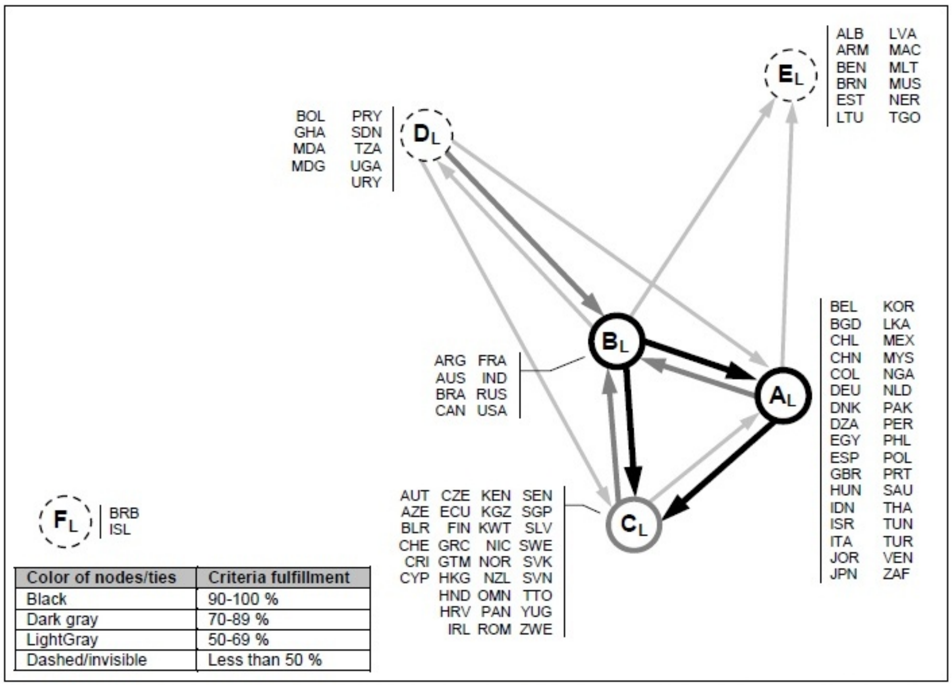


Note: The dash lines represent proposed pipeline constructions in 2030, the solid lines represent current network configuration. The thickness of the link shows the variation in maximum pipeline capacity, the size of the nodes is proportional to their export influence (the bigger the node, the more influence it has on other nodes' import), the shape of the node illustrates the trend from 2008 to 2020, square equals no change, the direction of triangle illustrates the direction of change up-positive and down-negative, the shades of the nodes are political stability, grey nodes are less stable than white nodes (Scotti and Vedres 2012).

Another application of network analysis to energy system is by Dassisti and Carnimeo (2012). The study proposed the use of regular network metrics on the electricity trading network in Europe to explore future research areas. There was a fundamental miscalculation of clustering coefficient and closeness centrality which depicts completely different nature of the network, the former one shows the interconnectedness of a node's neighborhood, whereas the latter one showed the accessibility of a node. Despite the mistake, the study was able to show the overall trend of electricity trading in Europe with Germany being the bottle neck, playing a central role with the trading network becoming denser over the year. The study fails to explain what happened in 2003 that caused a rises in diverging energy strategies. Nevertheless, Dassisti and Carnimeo's exploratory analysis was a promising application of network analysis on similar networks.

Nordlund (2011) also studies trade network, however, his intention comes from unequal ecological exchange in which he compares different commodity trade flows, including fuel (coal, oil) to derive the role each country plays in the international market and how it differs over the year or how it differs from one commodity to another.

Figure 1-5 Regularly equivalent positions in Trade of Agricultural Products



Note: Chapter 4 (Nordlund 2011)

This study is closest to Nordlund in the sense that role analysis (by equivalent trophic position) is applied in primary energy trade network.

2.5 Conclusions

There is a wide variety of methods to measure energy security but so far they do not include internal network aspects of energy systems. At the same time there is a large body of analysis of food webs and other ecological networks which is potentially applicable to energy security assessment. Particularly promising are information theory measurement of network structure and role equivalence (equivalent trophic level).

Still the few existing studies make only marginal use of these concepts and approaches. They have only been applied to electric grids and gas infrastructure and they did not take into account energy flows between different fuels, carriers and end-use sectors. The method proposed in the next section seeks to close this gap.

3 Methodology

3.1 Scale of analysis

3.1.1 Data source

Data was used from various sources, based on data gathering, conversion and calculation documentation, the needed data was converted in the corresponding unit with acceptable statistical differences (10-12% difference for the case of BP and IEA data). The following table lists the data sources:

Table 3-1 List of data and sources used

Type	Name	Unit	Source
International	Natural gas trade	Billion cubic meter	BP 2010
	Crude oil trade	Kg	UN Comtrade 2011
Development Indicators	GDPpc	2000 USD	World Bank Indicator 2011
	GDP	2000 USD	
National	Energy balance	ktoe	IEA 2009
	Fuel consumption		BP 2010
	Fuel production		

Note: Natural gas global trade data was aggregated from British Petroleum (BP 2010) for trade values of both pipeline natural gas transfer and Liquefied Natural gas shipping.

- International data

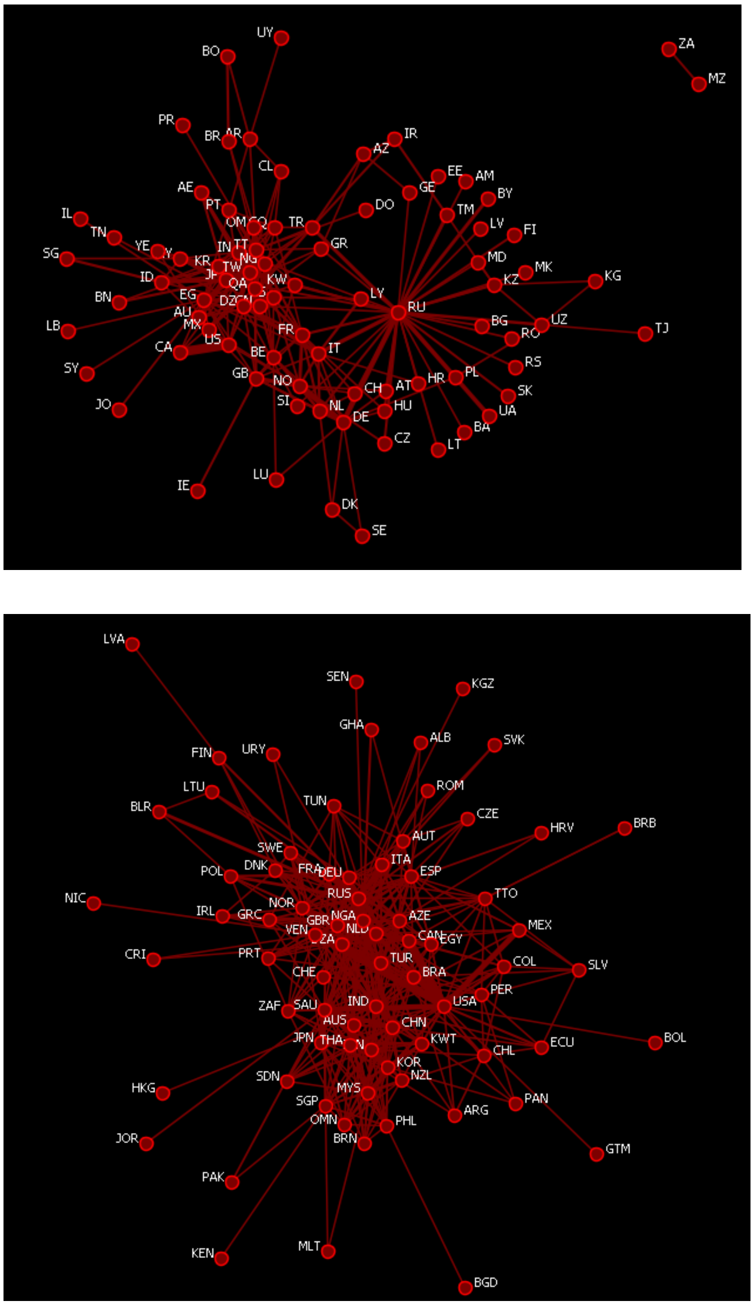
International trade data was taken from BP 2010 (for Natural gas) and UNComtrade 2011 (for Crude oil). The data are then further filtered at different cut of values that covers more than 80% of the trade flow but do not create a complete network.

Due to the Trophic Level and Omnivory Index algorithm used, only net import or export value were used i.e. if A exports 10 ton to B and B exports 8 tons to A, then link from A to be would weight 2 and B to A would have a weight of 0. This recalculation is done for to both BP and UN Comtrade data of gas and oil respectively.

BP 2010 is the main source for fuel consumption and production, missing data was taken from CIA's archived data in IndexMundi..

Other developmental and energy related indicators were taken from the World Bank Indicator data portal (WBI 2011). Figure 3-1 shows that there are 87 countries in the natural gas trade in 2009, and 236 links among these countries. The links represent the annual amount of net gas flow.

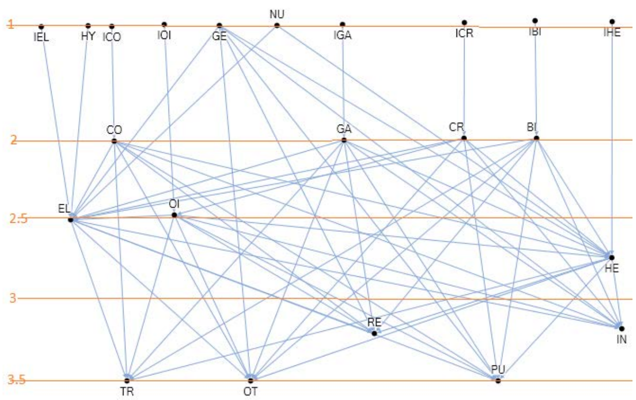
Figure 3-1 International trade flow of natural gas (top) and crude oil (bottom)



Note: Visualization done in ORA (citation)

- National data

Figure 3-2 National energy flow



Note: data from IEA (2011), Visualization done in NodeXL (citation)

Figure 3-2 is an example of energy flow in European OECD countries. The nodes are energy technologies, the links are energy flows. The number on the left is the calculated Trophic Level of a particular energy sector. Index I_ indicates import and thus, have a TL of 1, all other non-import primary energy sector also has TL of 1. Coal (CO), gas (GA), crude oil (CR), biofuel (BI) has trophic level 2 due to import. Electricity (EL), product oil (OI), heat (HE) has TL level between 2-3 due to import and consumption from primary energy level. End use sectors transport (TR), residential (RE), public (PU), Industrial (ON) and other (OT) have trophic level higher than 3.

3.1.2 International analysis

Both graph theory and ecological network were applied to international analysis, yielding indicators for global characteristic of energy flow and national indicators of energy security.

The graph theory analysis reveals the different structural roles there is in trade data. The following table lists the variables of interested derived from global trade data

The international analysis is mostly in line with previous researches on energy security which calculates energy security at a national level.

Since the international trading does not conform with the characteristic of food web, network analysis using social network indicators were applied to international gas trade. The nodes are the countries and the link are the significant net trade flow between the countries. The network analysis would reveal the "roles" in the network each country plays.

3.1.3 National analysis

The energy flows from primary fuel to secondary fuel and end use sector were analyzed for network characteristic and characteristics of each end use sector security. The same indices were used for

Table 3-2 List of indicators for each country

Indicator	Index	Description
Identification	ISO2, ID	Identification of each country either by ISO2 code or numeric ID
Node	N	Number of energy "options", listed below, in primary (maximum 7 + 4 import options), secondary (maximum 3 + 3 import options) and end-sectors (maximum 6 options).
Total	T..	The total energy flow in the system, size of the energy system
AMI	AMI	Average Mutual Information measures how constrained the system is
Stat. Unc.	HR*	Statistical Uncertainty measures how diverse the system is
Con. Unc.	DR*	Conditional Uncertainty measures
Sys. Dev.	RU*	System Development measures how developed the system is
GDP	GDP	Gross Domestic Product is a proxy for the size of the economy
GDP per capita	GDPpc	Gross Domestic Product per capita is a proxy for development
Structural suffix		These energy vulnerability indicators were calculated for most energy options in the network
	_TL*	Trophic Level suffix indicates how far from the original source the consumer is
	_OI*	Omnivory Index suffix indicates how varies the energy supplier is
	_DI	Diversity suffix indicates how evenly distributed the energy import is
	_IM	Dependency suffix indicates how much the sector is dependent on import
Primary Energy Technologies	GA, CR	Natural gas and Crude Oil were the two fuel whose global trade network was studied closely. The analysis was done 2002 – 2010 for natural gas to study global gas consumption, production and trading trend before and after the financial collapse. Crude Oil network analysis was studied in 2009 only to demonstrate the versatile of the indicator.
Secondary Energy Technologies	OI, HE, EL	Secondary energy consists of Product Oil, Heat and Electricity. Product Oil is considered as secondary energy due to the distillation process from crude oil. All of the options for secondary energy are traded globally (only Denmark import heat) however, due to data quality and availability, these networks were not included in this thesis.

Tertiary Energy Technologies	TR*, IN*, PU*, RE*	Transportation, Industry, Public and Residential were considered vital energy sectors (Cherp 2012); their energy vulnerability indicators were calculated, except for Dependency of import due to lack of data or inconsistent conversion from monetary value to energy equivalence

** indicates indicators or analysis not previously applied in energy security literature.*

3.2 Social network analysis

Network analysis uses measurements from social network analysis, thus, concerning itself with the three major indicators: centrality, clustering and equivalence. Role analysis was done to compare to the TL calculated for the network. However, due to the result not showing substantial findings, centrality, clustering coefficients are now shown in the thesis.

3.3 Ecological network analysis

3.3.1 Structural network nomenclature

The following notations were used in the calculation of ecological network indicators.

Table 3-3 Nomenclature of symbols used in calculation

Term	Description
n	Number of internal nodes in the network, excluding 0, n + 1 and n + 2
$j = 0$	Production of node i
$i = n + 1$	Consumption at node j
$i = n + 2$	Export at node j (export and loss occurs during transfer)
T_{ij}	Flow from node j to i, where j represents the columns of the flow matrix and i the rows
$T_{i.}$	Total inflows to node i
$T_{.j}$	Total outflows from node j

Note: excerpted from Kones et al 2009

3.3.2 System measurements

The dimensionless measurements serves as indicators of the material transfer system's property regardless of the size of the system. These measurements are useful in comparison across systems and carries network properties.

The following indicators are based on that hypothesis and the "window of vitality" is explained further.

- Statistical Uncertainty (H_R)

The statistical uncertainty (H_R) follows the Shannon diversity measurement (MacArthur 1955), which gives the diversity of the system's material transfer's channel. The statistical uncertainty has a higher value when either the relative amount of material being transferred $\left(\frac{T_{ij}}{T_{..}}\right)$ is higher or the "uncertainty" of that material being transferred $\boldsymbol{log_2}\left(\frac{T_{ij}}{T_{j.}}\right)$ is high. Thus, the higher the statistical uncertainty, more "even" the flows are among the channels or simply more transfers.

$$H_R = -\sum_{i=1}^{n+2}\sum_{j=0}^{n}\frac{T_{ij}}{T_{..}} \cdot log_2\frac{T_{ij}}{T_{..}} = AMI + D_R$$

The statistical uncertainty is broken down to two components, the Average Mutual Information and the Conditional Uncertainty. The former measures the constraint there is in the system or the "coherent of the flows"; the latter measures the flexibility or the "freedom that remains" (Ulanowicz 2002). Since both characters are needed for a stable system, a balance between the two components gives the highest stability in ecological networks.

- Average Mutual Information (*AMI*)

The AMI measures how constrained the material flows within the system. The higher the *AMI* the more efficient the system is (Ulanowicz 2009). In social system, high AMI means bypassing of important components, thus high AMI is associated with vulnerability (Scotti and Vedres 2012).

$$AMI = \sum_{i=1}^{n+2}\sum_{j=0}^{n}\frac{T_{ij}}{T_{..}} \cdot log_2\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}$$

- Conditional Uncertainty(D_R)

The conditional uncertainty measures the redundancy or disorder of the system (Ulanowicz 2009). The higher the conditional uncertainty, the more redundant the system is.

$$D_R = \sum_{i=1}^{n+2}\sum_{j=0}^{n}\frac{T_{ij}}{T_{..}} \cdot log_2\frac{T_{ij}^2}{T_{i.}T_{.j}}$$

In ecology, high AMI means that the system has a high efficiency, this is gained by bypassing intermediary species; similarly in national energy system, this happens when end users have the capacity to produce their own energy from primary energy sources. Thus, having the same energy technologies, a country would have a higher AMI when there are less link between tertiary energy consumer and primary energy producers. Thus, having a higher AMI means less security for the energy system. Scotti and Vedres (2012) also equates higher AMI means higher insecurity, but not at national level but at international level.

- Window of vitality (2^{AMI} vs $2^{DR/2}$)

Computational biologist believe that the system's stability is best described by the balance between the average mutual information (the efficiency of the flow) and the conditional uncertainty (the redundancy of the flow), or the balance between the link density and the effective trophic levels of the food web (#citation Ulanowizc.

Due to the construction of Conditional uncertainty (D_R), the weighted geometric mean of the link density C_Z is calculated as:

$$C_Z = \prod_{i=1}^{n}\prod_{j=1}^{n} \frac{T_{ij}^2}{T_{i.}T_{.j}}^{-T_{ij}/_{T_{..}\cdot 2}} = 2^{D_R/_2}$$

And the geometric mean of the effective roles (or effective trophic levels) are based on the average mutual information

$$R_Z = \prod_{i=1}^{n}\prod_{j=1}^{n} \frac{T_{ij}T_{..}}{T_{i.}T_{.j}}^{T_{ij}/_{T_{..}}} = 2^{AMI}$$

3.3.3 Node measurements

- Trophic Level (TL)

The equivalent trophic level is a food web metrics that measures the role equivalent in the network. The measurement reveals how far it is to get to the original source of production based on the percentage of consumption. This measurement encompasses both the trophic level of material consumed (TL_i) and the relative amount of material being transferred The original material producer is considered to have *TL* of 1. Since this coefficient is "self-reference", the calculation used a generalized reverse matrix to generate the minimum ordinary least square.

For each of the energy technology, TL is regressed against GDPpc, DR and AMI to find a significant and important contributing factor for a high TL. Spatial analysis is done on TL to find the spatial cluster of high values (hot spots) and low values (cold spots).

- Omivory Index (OI)

Similarly to TL, the spatial cluster is analyzed. In addition to that, correlation with GDPpc, system's indicators AMI and DR is also tested.

Due to construction OI has a minimum value for each given TL, thus, the correlation between OI and this minimum value is analyzed for each continent and each quintile of GDPpc.

- Minimum curve

Here the trophic level indicators give us information on how far from the original energy source the sector is consuming i.e. the lower the value, the more secure from disruption, and the Omnivory index gives us the variance of that consumption, with the higher the value, the more secure. There is a minimum curve $OI_j = -(TL_j - 2.5)^2 + 0.25$. The formula of the curve is empirically observed from the from the relationship between TL and OI and congruent with the formula for both indicators. The curve shows that the lowest variance occurs at TL = 2 and 3, which means that TL=2 or 3 usually have 100% consumption on the immediately lower TL, i.e. 1 or 2 respectively.

3.3.3.1 Source diversity (DI)

Source diversity is a Shannon index measurement of the evenness of sources contributing to energy (Stirling 1994, 2007, 2010). The higher the DI, the more evenly distributed across the supplier the import. High DI implies high energy security (in terms of resilience). Due to construction, DI is highly correlated with DR.

$$DI = -\sum_{j=1}^{n} \frac{T_{ij}}{T_{i.}} \cdot log_2 \frac{T_{ij}}{T_{i.}}$$

3.3.3.2 Import dependency(IM)

Import dependency reflects the amount of energy the country is reliant on external source. High IM implies low energy security (in terms of sovereignty).

$$IM = \frac{T_{i.}}{T_{i.} + T_{i0}}$$

3.4 Statistical analysis

- Correlation test

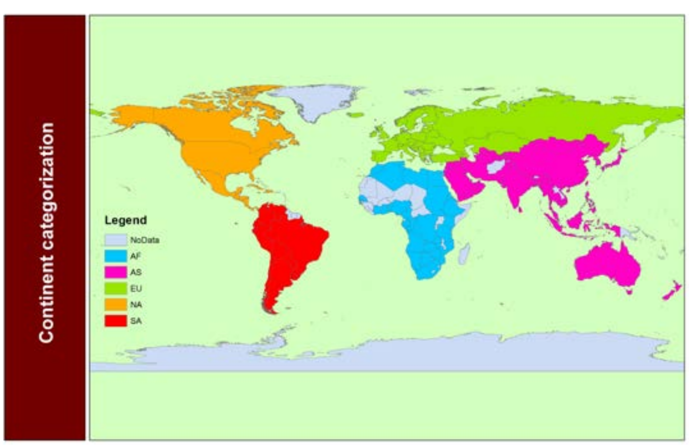
The correlation test were ran to see how the new local indicators (TL and OI) perform against established indicators (DI and IM). The global indicator (AMI and DR) are also compare against (GDPpc, and TPE_DI)

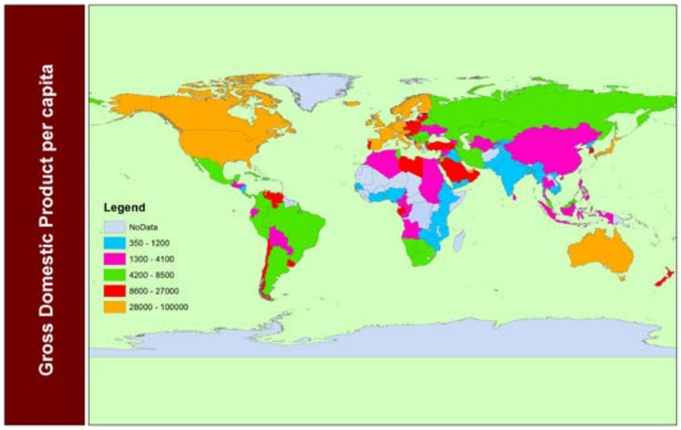
Correlation test were also used to see what factor contributes to a high energy security and if high energy security in one sector means energy security in the other.

- Analysis of variance

Analysis of variance based on regression of possible contributing factors to high energy security. The higher the variance, the more that factor contributes to the energy indicator. The contribution is then studied by correlation test. Continent as a proxy for location and GDP per capita were used as categorization for regression.

Figure 3-3 Continent and GDP per capita maps





Note: Data from WB (2011)

3.5 Spatial analysis

Spatial clustering in the form of hotspot analysis is used in this thesis. The analysis exhibits the spatial cluster there is, which is useful to see spatial pattern in the network (a feature that is ignored due to network construction).

Hotspot analysis uses the Getis-Ord Gi* statistic to identify spatial clusters of high values (hot spots) and spatial clusters of low values (cold spots) (ESRI 2011). The spatial relation used in the analysis were the default option in which the number of neighbors for analysis were chosen based on the distribution of the data. The interaction here is proportional to distance since geographical data represents shared natural resources underground or connected infrastructure above ground.

The result is given in both Z scores and p value. Low Z score corresponds with spatial cluster of low values, whereas high Z scores means spatial cluster of high values. The p-value dictates the significance of this correlation.

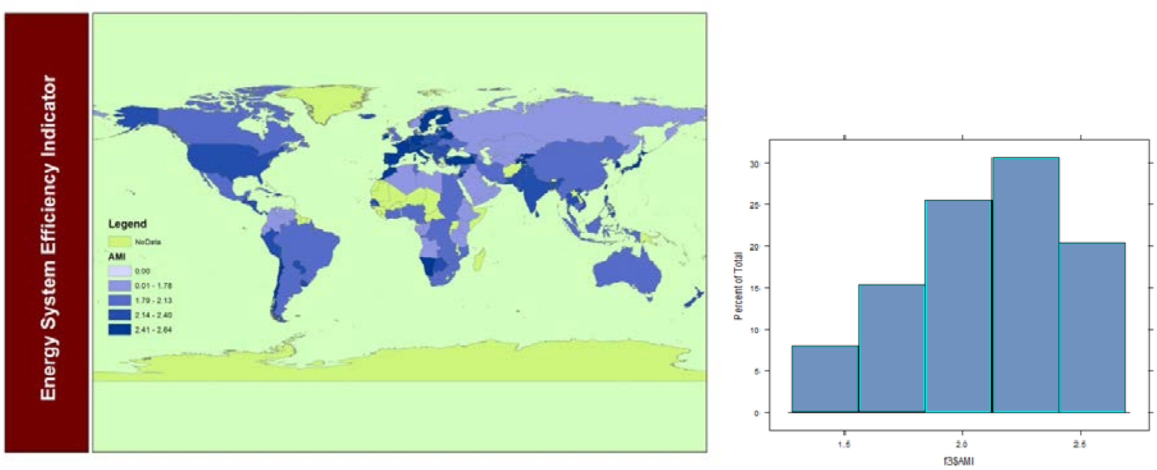
4 Results

This chapter consists of three sections reporting the results of applying ecological indicators to energy systems for assessing energy security. The first section deals with national energy systems, the second section deals with electricity and the third section deals with end-use sectors: transportation, industry, public and residential sector.

4.1 National energy system security

The Literature Review (Chapter 2) identifies several indicators widely applied in food web analysis. The stability of an ecological system is reflected in the efficiency (AMI) and redundancy (DR) of energy flows linking primary, secondary and tertiary consumers. This section explores the application of AMI and DR to the analysis of energy security.

Figure 4-1 Energy System Efficiency (AMI) Indicator and Spatial clusters



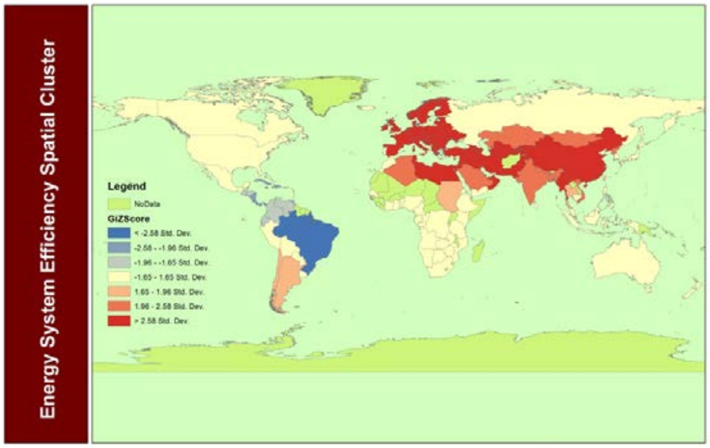
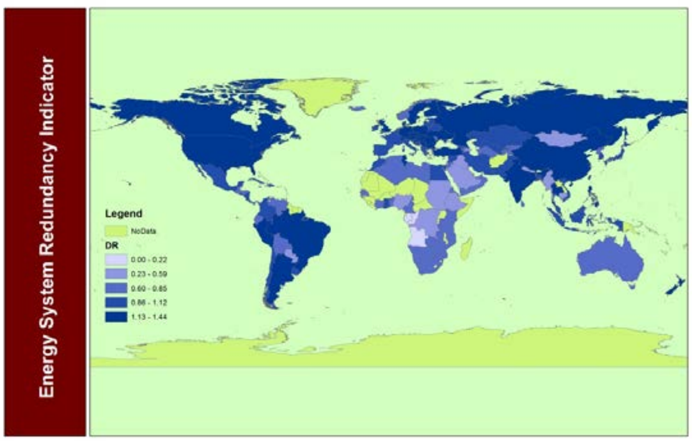
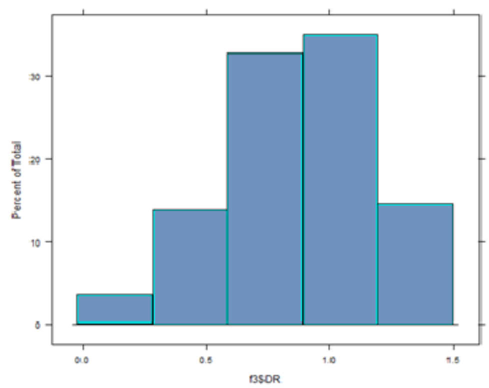
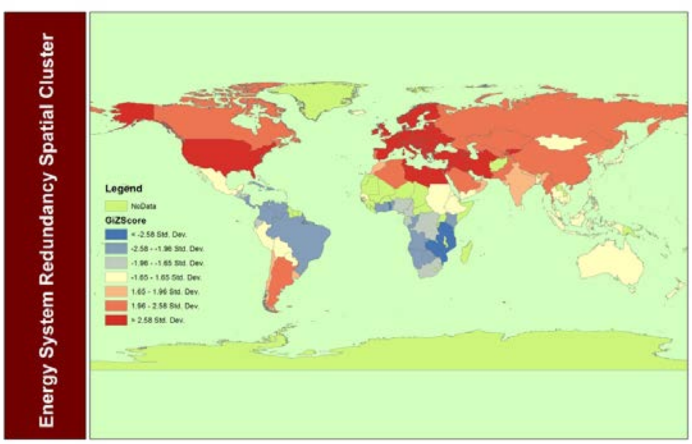


Figure 4-2 Energy System Redundancy (DR) Indicator and Spatial clusters







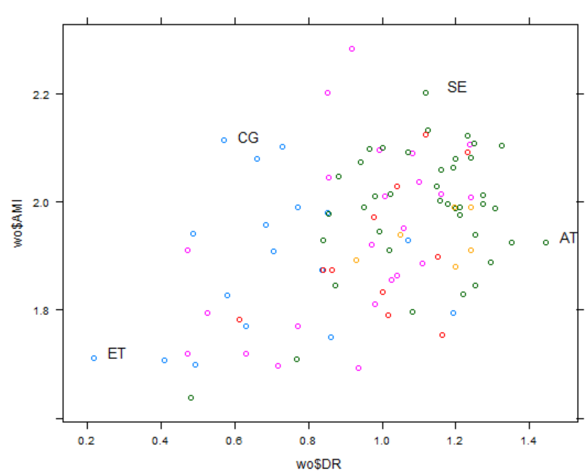
Note: The colors represent Z scores, red is high Z scores and blue is low Z scores. The darkness of the color represents p-value, darker colors mean higher significance.

For both figures, there is a clear spatial cluster of Europe and Middle East having high values of AMI and DR. Also, part of South America also share the same pattern of low AMI and DR. This pattern is observed in other indicators (TL, OI …)

The maps show the relative values of AMI and DR, however, the indicators when presented separately created a confusing picture, in which both seems to show that high AMI and high DR are from energy secured country. Figure 4-5 shows that in fact high energy security means high DR and low AMI, medium energy security means low DR, low AMI or high AMI, high DR and low energy security means low DR and high AMI.

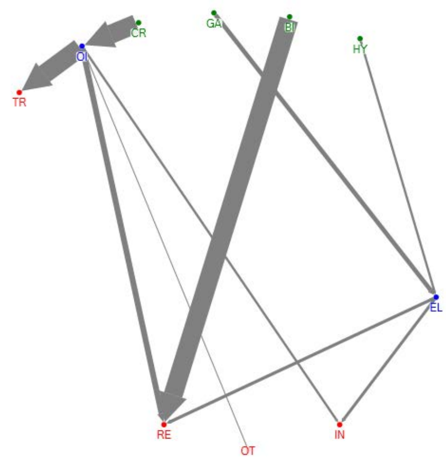
Figure 4-3 Sample four regions of national energy system security and corresponding national energy system by continent and quintiles of GDPpc

Figure 4-4 Average Mutual Information versus Conditional Uncertainty

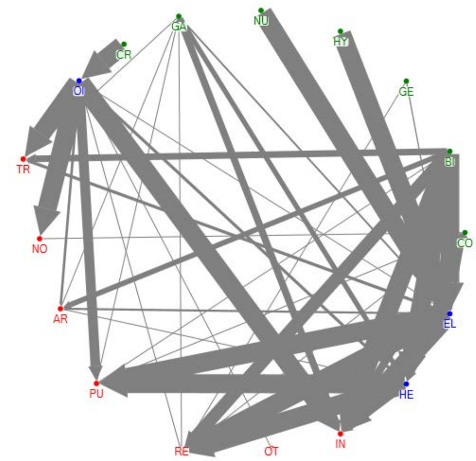


Note: o Africa, o Asia (including Oceana), o Europe, o North America, o South America

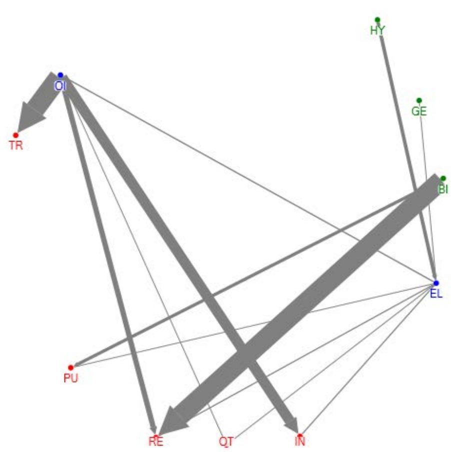
Figure 4-5 Four distinctly different national energy systems



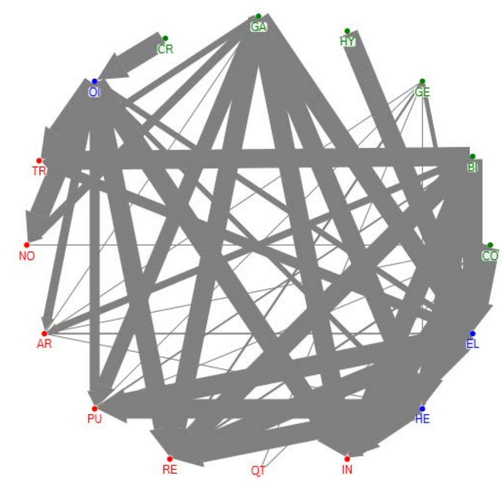
CG, AMI = 2.11, DR = 0.57, GDPpc = 2,000



SE, AMI = 2.20, DR = 1.12, GDPpc = 43,000



ET, AMI = 1.71, DR = 0.22, GDPpc = 400



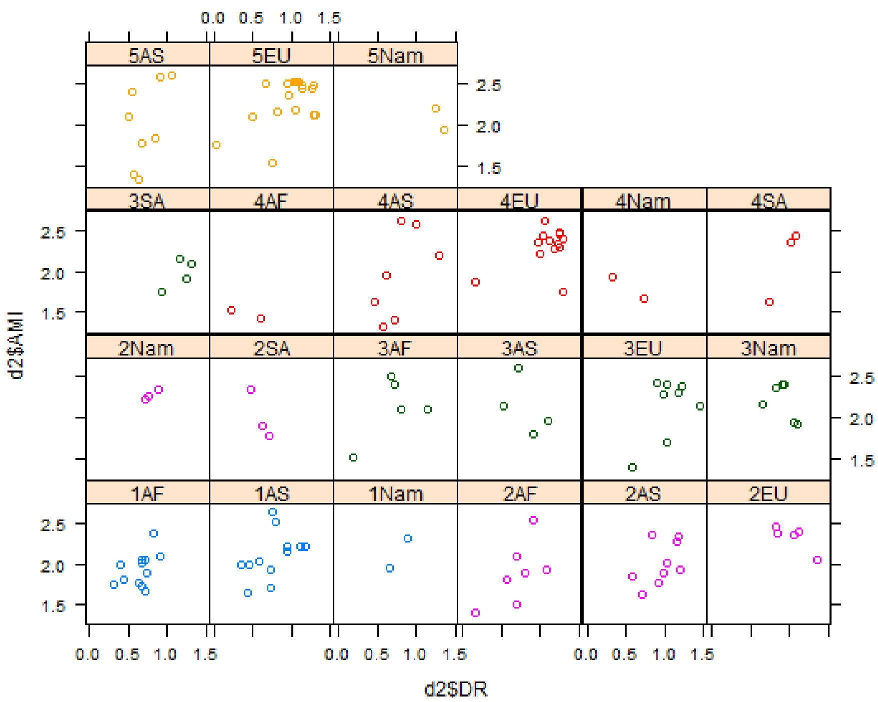
AT, AMI = 1.92, DR = 1.44, GDPpc = 40,000

Figure 4-3 shows four extreme examples of energy systems. Congo has the relatively highest AMI and the lowest DR, which is intuitively the most fragile structure of energy system with many potential vulnerabilities and few redundancies.

Ethiopia has much lower AMI but still low DR, thus, there are fewer risks because of shorter supply and conversion chains however there is still little resilience should there be any disruption. Sweden and Austria has much higher DR, which means that there is diversity and redundancy in their energy technologies, allowing for replacement energy flows to be used in case of a disruption. Austria has a lower AMI than Sweden, meaning that Austrian energy system has fewer links which can be potentially disrupted which may signal a higher security of its energy system

The correlation between these two indicators and various national characteristics were tested. According to the analysis of variance, continent or the location of the country plays a more substantial and more significant role than GDPpc in AMI and DR (the variance is higher) (see Table 4-1.

Table 4-1 Analysis of variance for Average Mutual Information and Statistical Uncertainty

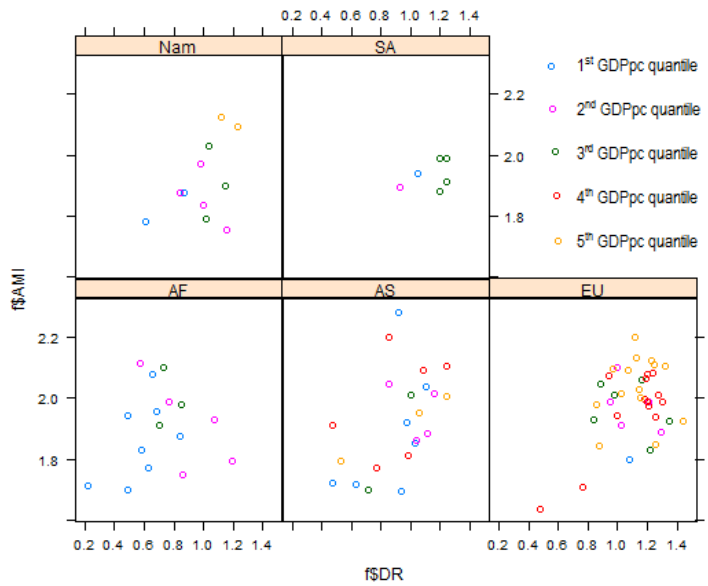


	AMI	DR
GDPpc	0.558	1.210 **
Cont.	2.320 ***	1.943 ***
Res.	12.039	7.984

*Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. The number preceding the continent signifies the level of development (GPD per capita as a proxy)*

Table 4-1 shows the correlation between AMI and DR in relation to the continents and GDPpc, the table was used to produced Figure 4-5.

Table 4-2 Average Mutual Information and Conditional Uncertainty



Cont.	Corr.	p-val	Signif
AF	0.224	0.387	
AS	0.480	0.020	*
EU	0.374	0.017	*
Nam	0.455	0.159	
SA	0.369	0.470	
All	0.436	0.000	***

GDPpc	Corr.	p-val	Signif
1st	0.446	0.049	*
2nd	-0.377	0.111	
3rd	0.018	0.942	
4th	0.582	0.009	***
5th	0.399	0.080	*

*Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

There is a moderately significant positive correlation between the two indicators, which means that countries with high redundancy would also have higher complexities of their energy systems and vice versa. This correlation holds true for the poorest and richest countries (except for the middle quintile countries). The correlation is also significant for Africa, Asia and Europe. The correlation is further explained in the discussion section.

4.2 Security of Primary Energy Sources

This section analyzes seven types of primary energy sources:: coal and peat (CO), crude oil (CR), natural gas (GA), biofuels and waste (BI), nuclear (NU), hydro (HY), geothermal solar and other renewable energy (GE) (IEA 2009). The first four types are traded internationally. Of these four, crude oil and natural gas trade networks have been studied before using food web indicators such as Trophic level (TL), Ominvory index (OI) and other indicators such as Import dependency (IM) and Import diversity (DI).

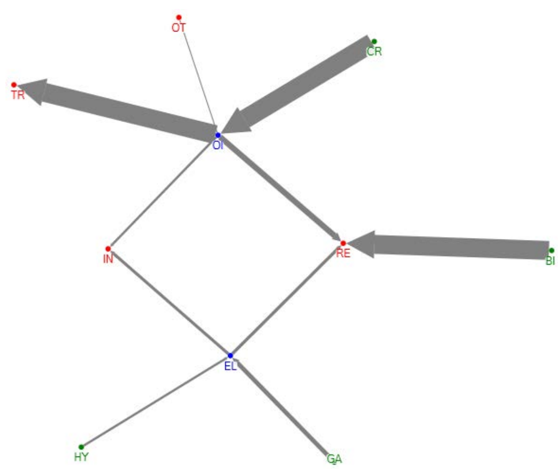
In this section, any imported primary energy source will be assigned a trophic level of 2 so that energy supply insecurity will propagate to end use sector. Due to the simplification of the assignment, the result is not shown here. A separate section on food web analysis apply to international network of primary energy trading further analyzes the security of primary energy.

4.3 Security of energy carriers (Electricity)

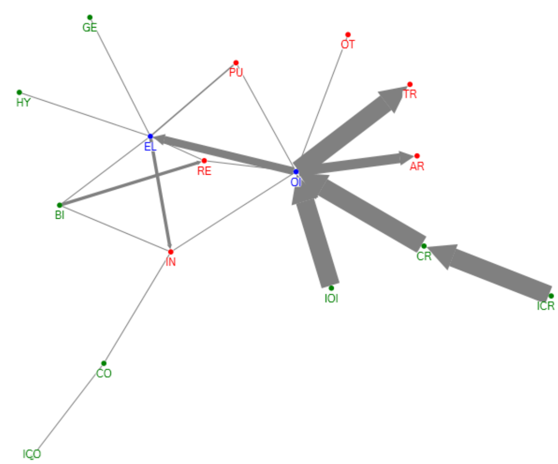
Secondary source of national energy system are electricity, heat and product oil. Since there is international trading in all of the secondary energy technologies (with Denmark being the only country to import heat), the import is also included in the analysis. The secondary source of interest here is electricity, in which the security is propagated from primary source security and import supply security. Security of electricity is measured by Trophic Level and Omnivory Index.

TL of electricity ranges from 2.0 to 3.3, with a sample average of 2.5. This average along with standard deviation of 0.4 do not vary significantly across the different categories of GDPpc or continent

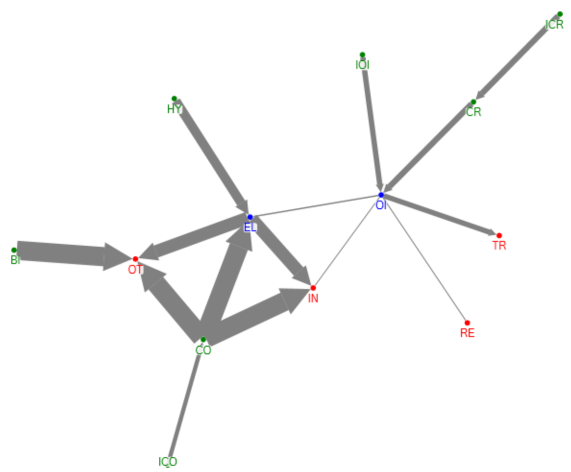
Table 4-3 Example of four energy systems



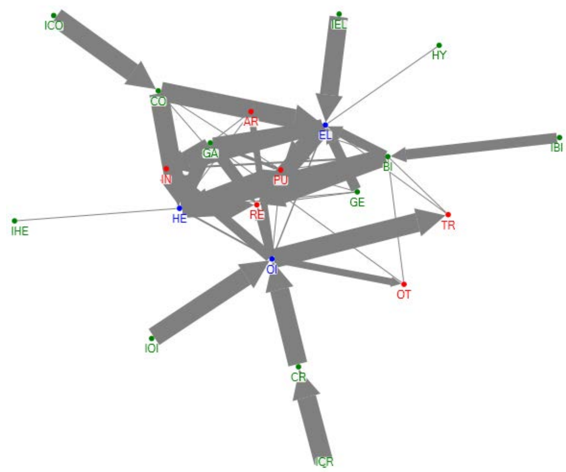
CG, EL_TL = 2.00, EL_OI = 0.00, EL_DI = 1.51 , AMI = 2.11, DR = 0.17, GDPpc = 2,000



JM, EL_TL = 3.34, EL_OI = 0.13, EL_DI = 0.42 , AMI = 2.37, DR = 0.82, GDPpc = 4,500



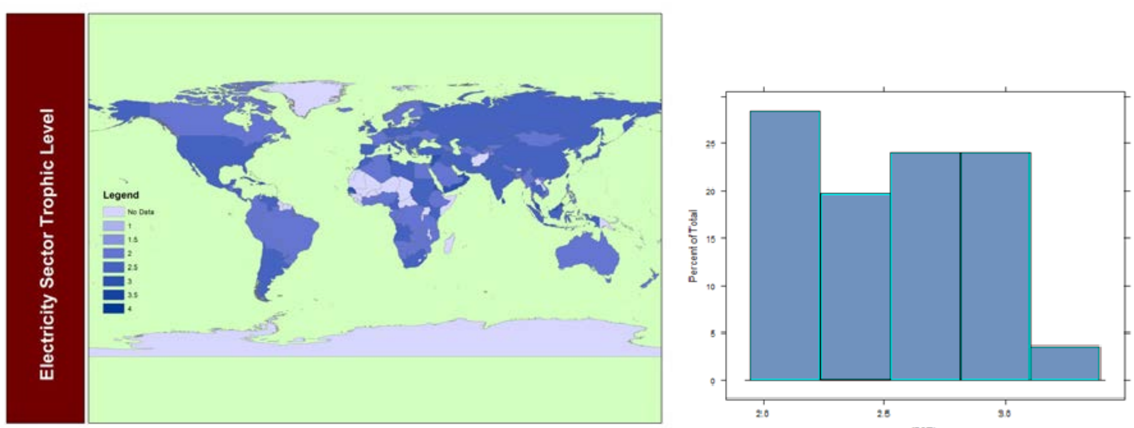
KP, EL_TL = 2.48, EL_OI = 0.46, EL_DI = 1.77 , AMI = 1.93, DR = 0.74 , GDPpc = 500



DK, EL_TL = 2.51, EL_OI = 0.28, EL_DI = 2.34 , AMI = 2.13, DR = 1.28 , GDPpc = 56,000

As we can see, TL is a difficult to KP and DK has a similar value of 2.48 and 2.51 respectively, however the two countries' energy systems are completely different (The difference is reflected in the AMI and DR, OI and DI indicators.)

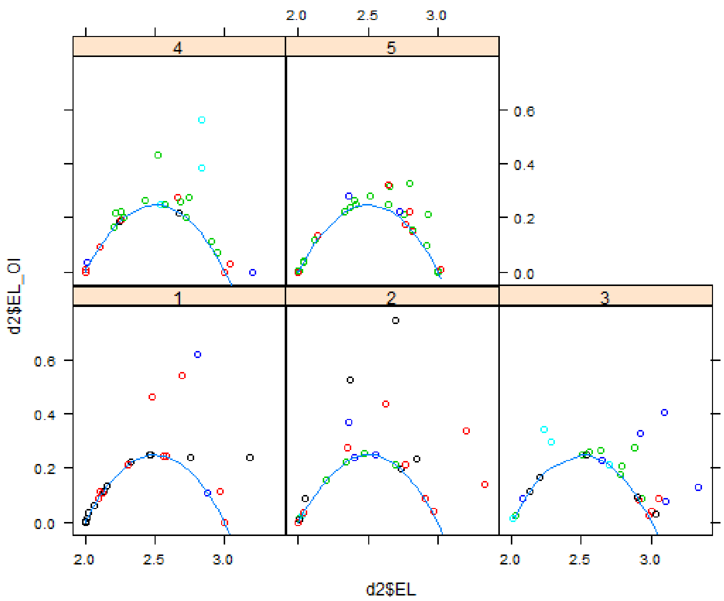
Figure 4-6 Electricity Sector Trophic Level



The map and the histogram show that there EL_TL is relatively evenly distributed, with less than 5% of large values.

To understand the relationship between EL_TL and AMI, DR, EL_TL is regressed against AMI and DR. The Analysis of variance showed that both factors contribute equally (but not significantly) to EL_TL and correlation tests show that there is no correlation between EL_TL and AMI or DR. The same is found when categorized the regression into different quintiles based on GDPpc and continent.

Table 4-4 Electricity Sector Trophic Level and Omnivory Index



Cont.	Corr.	p-val	Signif
AF	0.568	0.002	**
AS	0.501	0.001	**
EU	0.893	0.000	***
Nam	0.415	0.124	
SA	0.606	0.063	.
All	0.540	0.000	***

GDPpc	Corr.	p-val	Signif
1st	0.573	0.002	**
2nd	0.429	0.026	*
3rd	0.383	0.049	*
4th	0.709	0.000	***
5th	0.930	0.000	***

o Africa, o Asia, o Europe, o North America, o South America

From the data, we can see that the non-linear correlation between OI and TL follows the minimum curve and that 15% of the countries have a value of 0. This correlation is significantly higher for European countries and countries with high income (4th and 5th quintile). This correlation means that higher income countries are more prone to a lower-diversified energy consumption in electricity sector, which is also the characteristic of a highly efficient national energy system of Europe (high AMI).

Country with the highest EL_OI, or highest variation in energy's quality consuming for electricity sector (0.75) is CM in Africa, EL_TL is 2.70. The high OI is due to the fact that CM uses a large amount of product oil) which is produced from imported crude oil and imported oil product) along with a large amount of Hydro power for electricity generation.

Other indicator for EL is Diversity of sources, EL_DI. The diversity of sources for EL does not take into account of the TL of the sources but mainly the evenness in the sources. For a system to be secured, both the DI and OI needs to be high. These two indicators are positively linear-correlated to each other due to their construction (60%). We can posit that the higher the OI, the higher the DI.

Figure 4-7 Electricity Sector Diversity

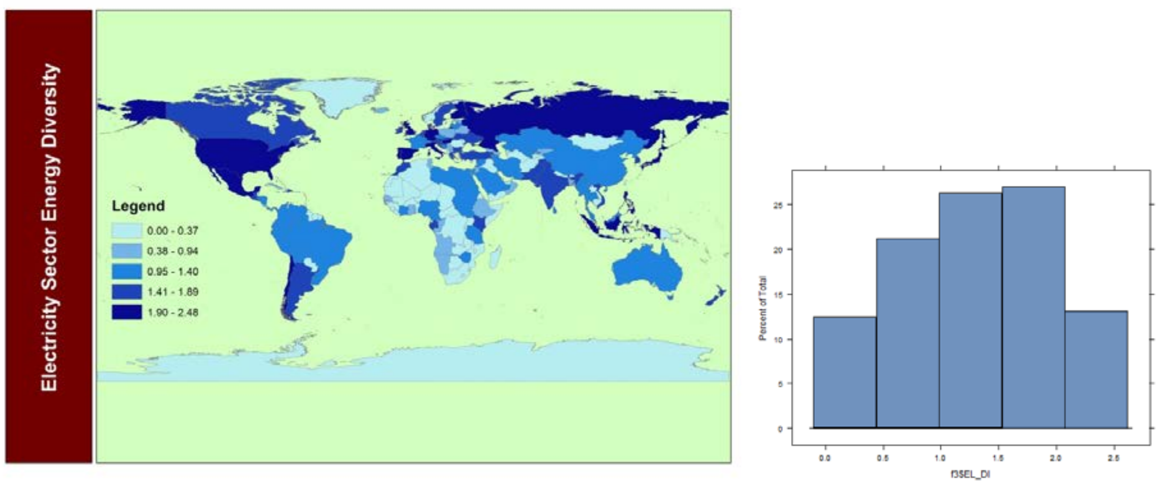


Figure 4-7 shows that the distribution of Electricity sector diversity do not correspond with location. However, the distribution is almost normal with the exception of 6% having 0 diversity. Statistical test shows that it does not correlate to GDPpc either. However, the Electricity sector diversity is 63.4% correlated to the Total Primary Energy Diversity (partly due to the construction of the indicator).

4.4 Security of Energy End Users

4.4.1 Transportation sector

Transportation sector insecurity is caused by insecurity of import, primary and secondary energy sources. Thus, to measure the transportation sector security, we rely on the main indicators of TL, OI and DI.

The minimum value of TR_TL is 2.6 and the maximum is 4 with the average being 3.3. These numbers mean that transportation sector is at least 2 degree away from the original source.

Considering that the main consumption of the TR sector is oil products, 2.5 is the smallest possible TL of TR. TM is the country with 2.6 TR_TL, this is due to TM's simple national energy structure, which consists of small import product oil, self-produced product oil from crude oil and natural supply to TR sector. BH and TT are the countries with highest TR_TL, due to the non-diverse propagation of energy, from import Crude oil (TL=1) to Crude oil (TL=2) to oil product (TL=3) to TR (TL=4).

Figure 4-8 Transportation Sector Trophic Level

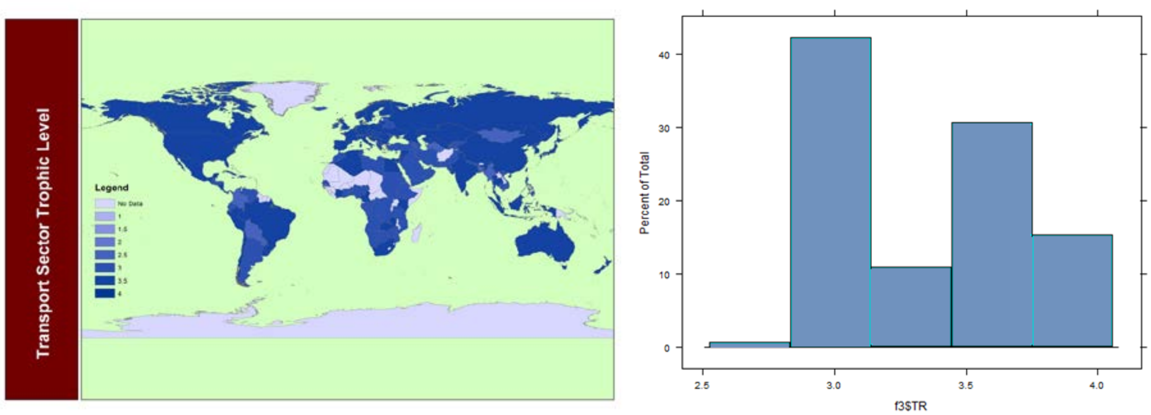
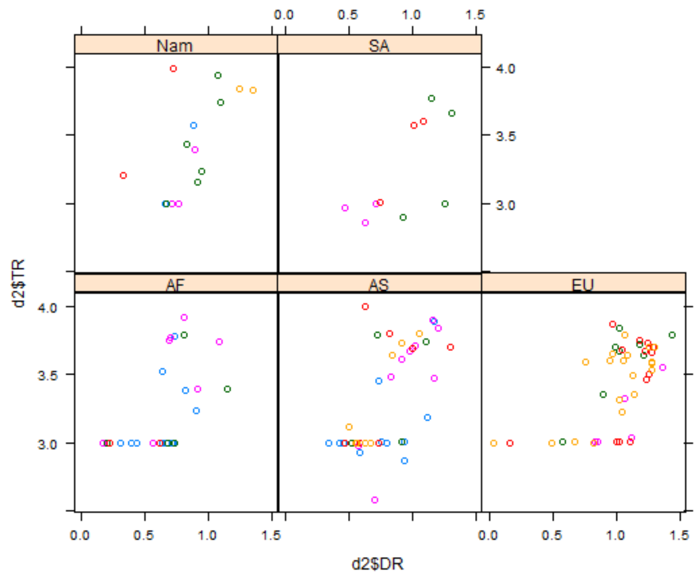


Figure 4-8 shows that there is a high value of TR_TL where is there a highly dense road network (proxy for a developed TR sector). The histogram shows that almost 30% of the TR's TL is 3. This number coupled with the fact that TR_OI value is mainly 0, we can see that the two indicators reflect a pattern that TR is highly dependent on OI (TL = 2) which is processed from CR (TL = 1).

TR_TL is regressed against possible contributing factors: GDPpc, AMI and DR. According to the analysis of variance, DR or energy system's redundancy plays the highest role in TR_TL's variation.

Table 4-5 Transportation Sector and Conditional Uncertainty



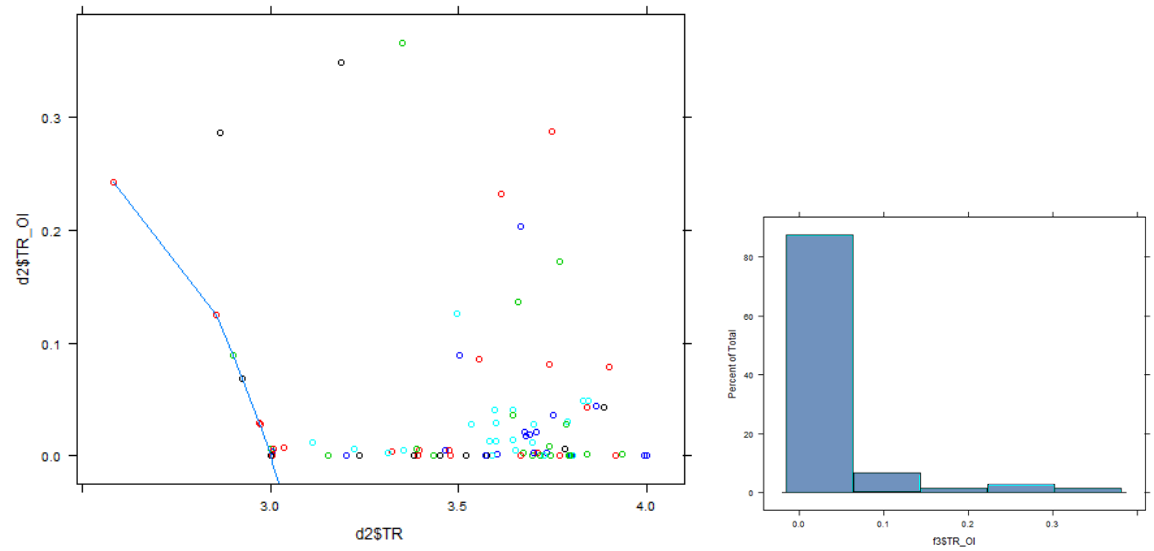
Cont.	Corr.	p-val	Signif
AF	0.527	0.005	**
AS	0.624	0.000	***
EU	0.616	0.000	***
Nam	0.626	0.013	*
SA	0.670	0.034	*
All	0.601	0.000	***

GDPpc	Corr.	p-val	Signif
1st	0.448	0.019	*
2nd	0.543	0.003	**
3rd	0.568	0.002	**
4th	0.494	0.009	**
5th	0.766	0.000	***

The high correlation between TR and DR could be attributed to the fact that the higher redundancy of the energy system allows connections between different TL, thus driving TR_TL higher.

Another indicator is OI. TR_OI ranges from 0 to 0.37 with the mean at 0.03 and median of 0.00. The OI shows us how varied the energy consumption in Transport sector is. For a high TL, it would be more secure to have a high OI. However, only 10% of the countries have a OI > 0.12, and the high OI is attributed to the dependency of import crude oil and import oil product as well as natural gas. Perhaps, having a OI value slightly greater than 0 is much more secure than greater than 0.12.

Figure 4-9 Transportation Sector Trophic Level and Omnivory Index



Note: o Africa, o Asia (including Oceana), o Europe, o North America, o South America

We can see that almost 60% of TR_OI assumes the value of 0. This means that TR sectors generally consume energy at a TL immediately below, i.e. TL 2 to 3. This is attributed to a characteristic of TR sector reliant on OI, which needs to be processed from CR or imported. In fact, among the sectors studied, TR has the lowest energy consumption variance. This is further explained in the discussion section.

Figure 4-10 Transportation Sector Energy Source Diversity

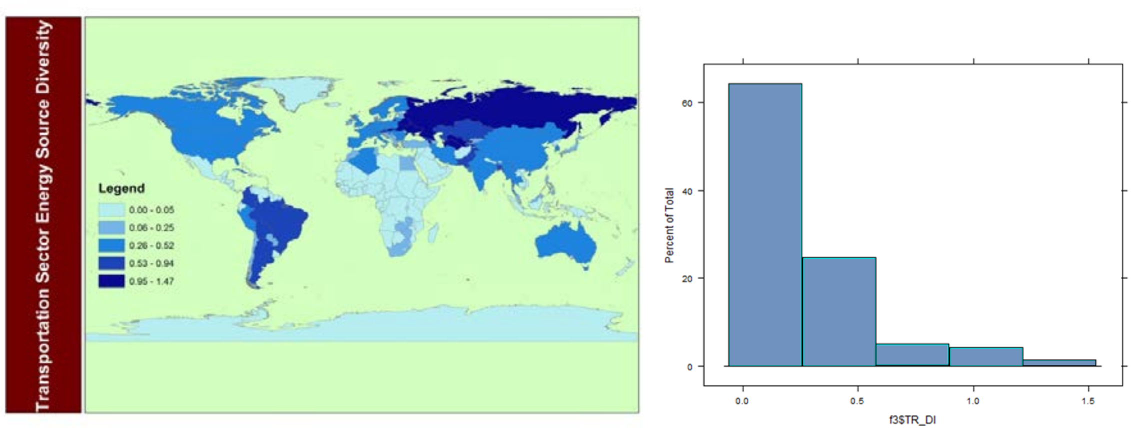


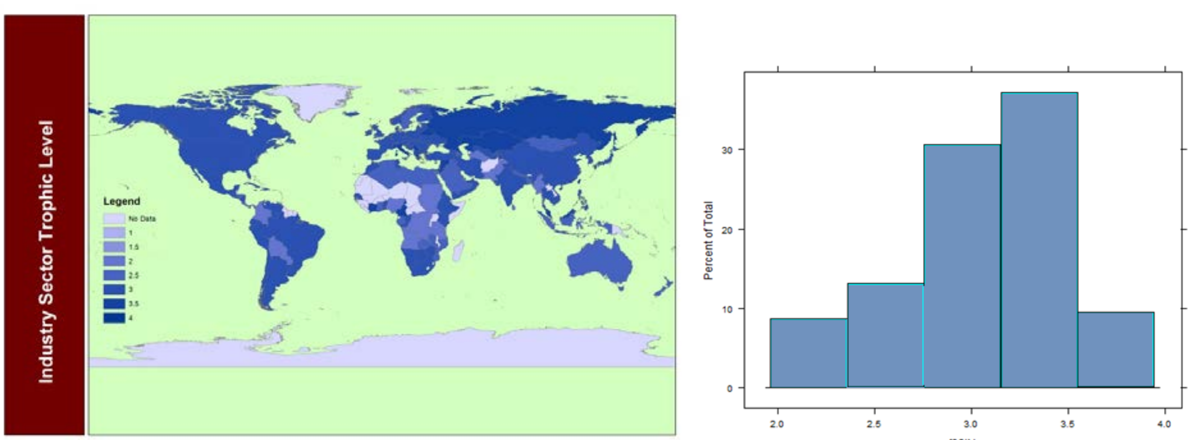
Figure 4-10 shows a diversity of Transportation energy sources, generally, TR sector has the lowest diversity among all other sectors, 40% of TR_DI has a value of 0. It is further explained by T-test matrix in Discussion section.

4.4.2 Industry sector

Industry sector insecurity is caused by insecurity of import, primary and secondary energy sources. Unlike Transportation sector, in which the sources are mainly oil, gas and some electricity, Industry sector derive its energy from a variety of sources such as Coal, Gas, Biofuel (primary) and Oil, Electricity, Heat (secondary). Thus, the main indicators of consumption variation (OI) and diversity (DI) is expected to be higher than that of transportation. In fact, the student t-tests accept this hypothesis with high confidence.

The minimum value of IN_TL is 2.04 and the maximum is 3.87 with the average being 3.07 and median of 3.13. These numbers indicate that Industry sector is at least 2 degree away from the original source. NA from Africa is the country with smallest TL of 2.04, this is due to NA's simple national energy structure, which consists of small import product oil, and electricity to supply industry sector. IL in Asia is the country with highest TL, due to the non-diverse propagation of energy, from import Crude oil (TL=1) to Crude oil (TL=2) to oil product (TL=3) and energy from electricity (TL=3) and finally to IN (TL=4).

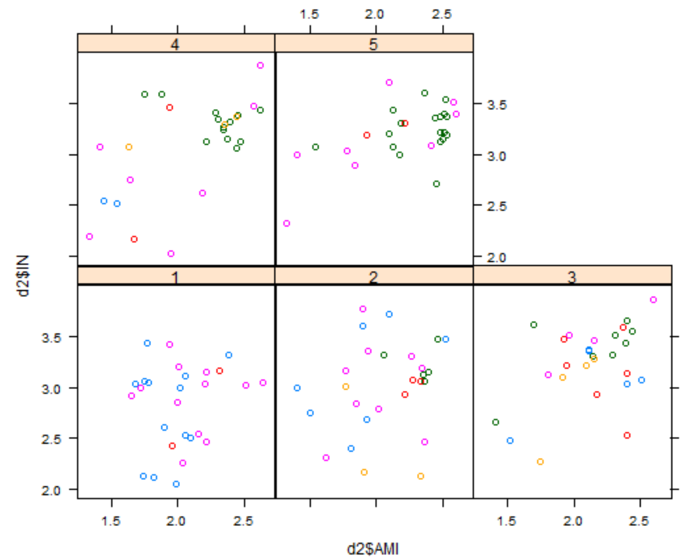
Figure 4-11 Industry Sector Trophic Level



IN_TL follows a normal curve, with the average of 3.2. We can see that IN sector energy quality is lower than most sectors except RE. There is no clear pattern of IN_TL spatially.

The next relationship worth exploring is between TL and GDPpc and DR, AMI. The analysis of variance revealed that among the three factors, TL depends most on AMI or system's redundancy.

Table 4-6 Industry Sector Trophic Level and Average Mutual Information

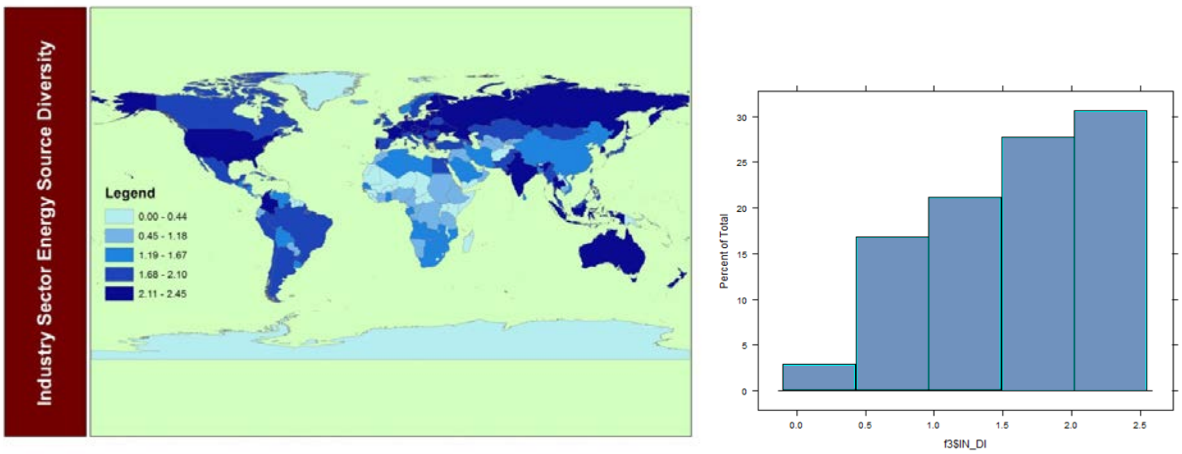


Cont.	Corr.	p-val	Signif
1st	0.150	0.454	
2nd	0.214	0.283	
3rd	0.466	0.014	*
4th	0.604	0.001	***
5th	0.553	0.002	**
All	0.434	0.000	***

Note: o Africa, o Asia (including Oceana), o Europe, o North America, o South America

The correlation shows that the highest and most significant positive correlation is in the 4th and 5th quintile of GDPpc. This is congruent with the fact that as a country becomes more developed, the redundancy of their energy system (high AMI) reflects a more complexity of energy technologies, thus driving the end use sector's further from original sources.

Figure 4-12 Industry Sector Energy Source Diversity



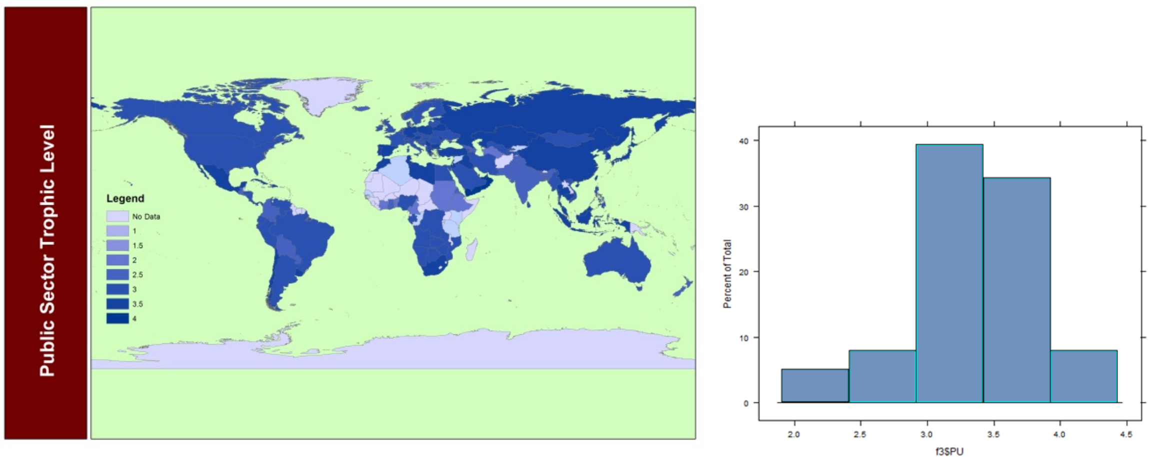
We can see that IN_DI has a log distribution, with the more high values than lower ones. Comparing to other DI, IN is the most divers sector.

According to regression analysis, there is no relationship between IN_DI and GDPpc. Due to the construction of the indicator, it is tautological to find a correlation between any diversity indicator with AMI or DR.

4.4.3 Public sector

Public sector has a minimum TL of 2.00, maximum of 4.34, median of 3.35 and mean of 3.32. The numbers tell us that the Public sector is at least 2 degree away from original energy source and could be as far as more than 4 degree away.

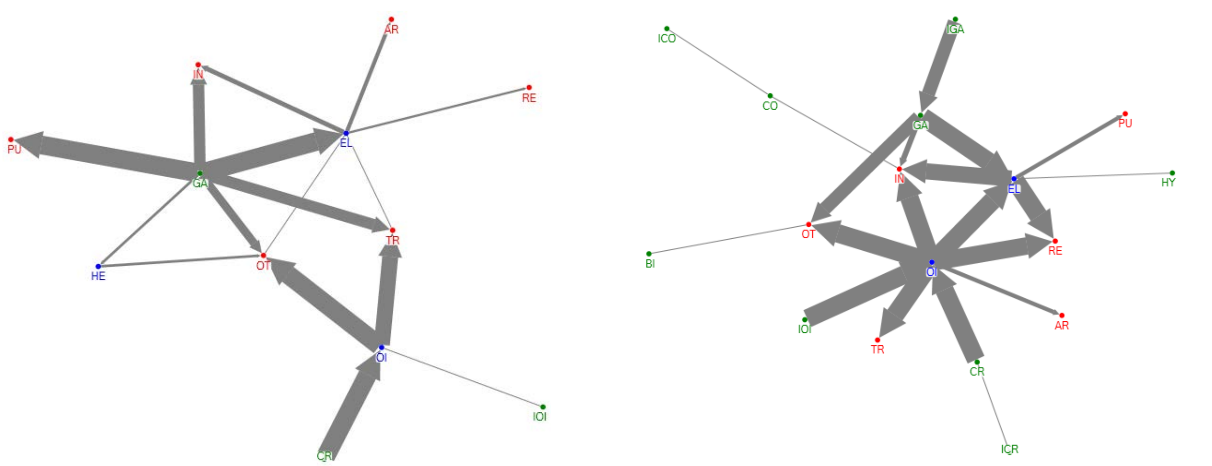
Figure 4-13 Public Sector Trophic Level



The figure shows PU has a very small standard deviation, with most of the countries having a similar value of 3.5.

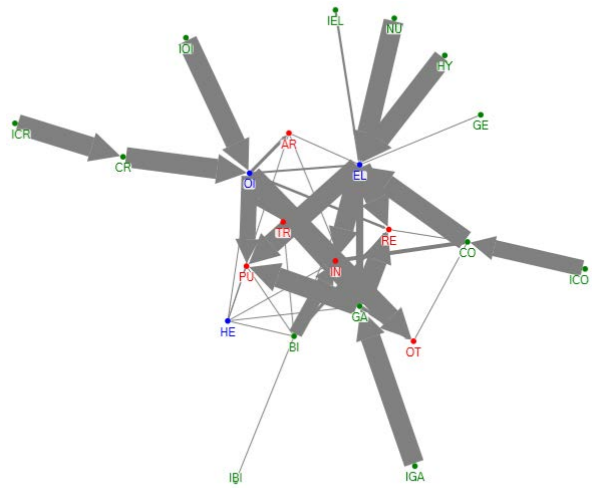
The smallest TL is TM, since their Public sector only use self-produced Natural gas (TL = 1). The highest TL is SY, which PU is fueled by GA (TL = 2.0), and EL (TL = 3.3), that uses imported Crude oil (TL = 2.0) and Product Oil (TL=2.6)

Figure 4-14 Example of four different energy systems

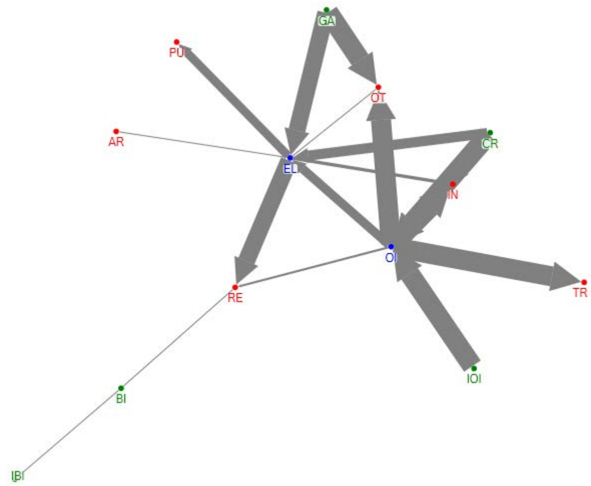


TM, PU_TL = 2, PU_OI = 0.0, PU_DI=0.0, AMI = 1.62, DR = 2.32, GDPpc = 4,000

SY, PU_TL = 4.3, PU_OI = 0.0, PU_DI=0.0, AMI = 1.90, DR = 2.88, GDPpc = 2,700



CA, PU_TL = 3.37, PU_OI = 0.1, PU_DI = 1.6, AMI = 1.93, DR = 3.28, GDPpc = 40,000

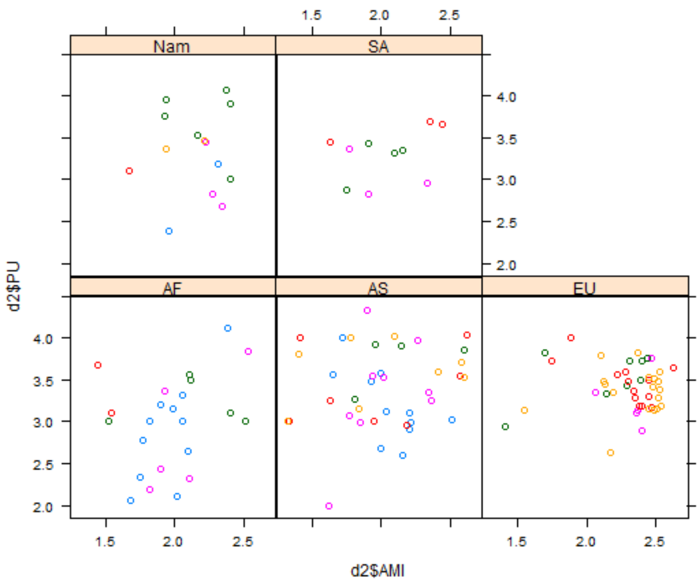


SA, PU_TL = 3.32, PU_OI = 0.0, PU_DI=0.0, AMI = 1.64, DR = 2.10, GDPpc = 14,000

As we can see, slightly similar value of TL can be found in completely different energy structure in the case of SA and CA. The common here is that in CA, PU consumes energy from EL (TL = 2.4), OI and GA (TL=2.0); and in SA, PU consumes energy from EL (TL=2.5).

The next relationship being explored is between TL and GDPpc (proxy for development) and DR or AMI (proxy for energy system structure). The analysis of variance revealed that among the factors, TL depends most on AMI or system's redundancy, which is similar to TR and IN.

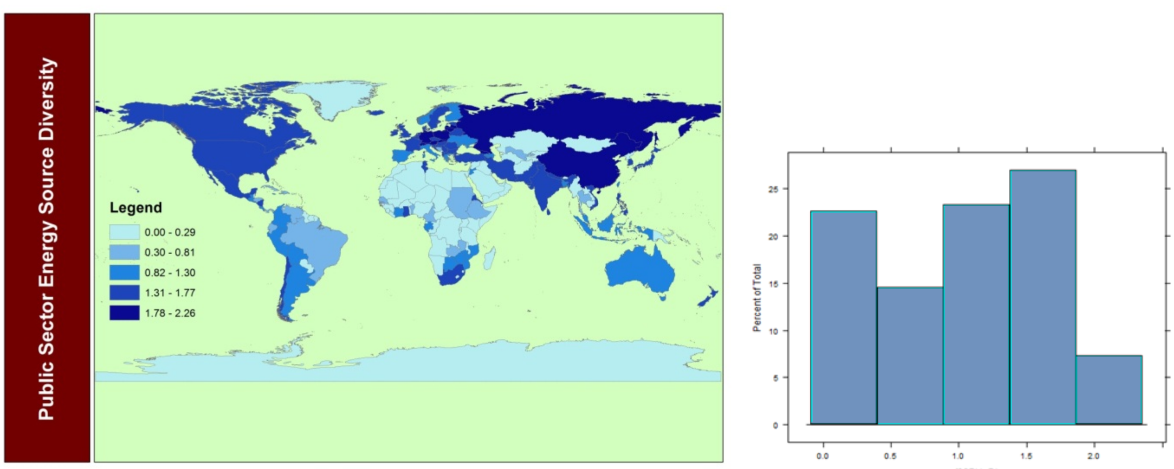
Table 4-7 Public Sector and Average Mutual Information



Cont.	Corr.	p-val	Signif
AF	0.320	0.136	
AS	0.131	0.426	
EU	-0.023	0.884	
Nam	0.058	0.843	
SA	0.334	0.345	
All	0.200	0.020	*

The coefficient shows very weak correlation (the highest was SA and AF at 0.3) and none was significant.

Figure 4-15 Public Sector Energy Source Diversity

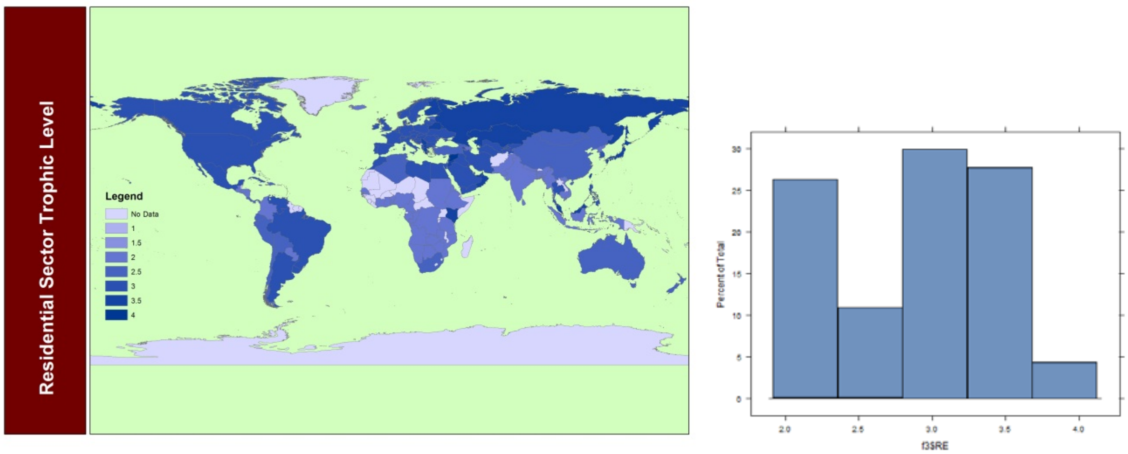


The figure show that there is not variation of PU_DI with 20% of the value are 0. The t-test reveals that energy diversity in PU is the second to lowest among sectors (only higher than TR_DI).

4.4.4 Residential sector

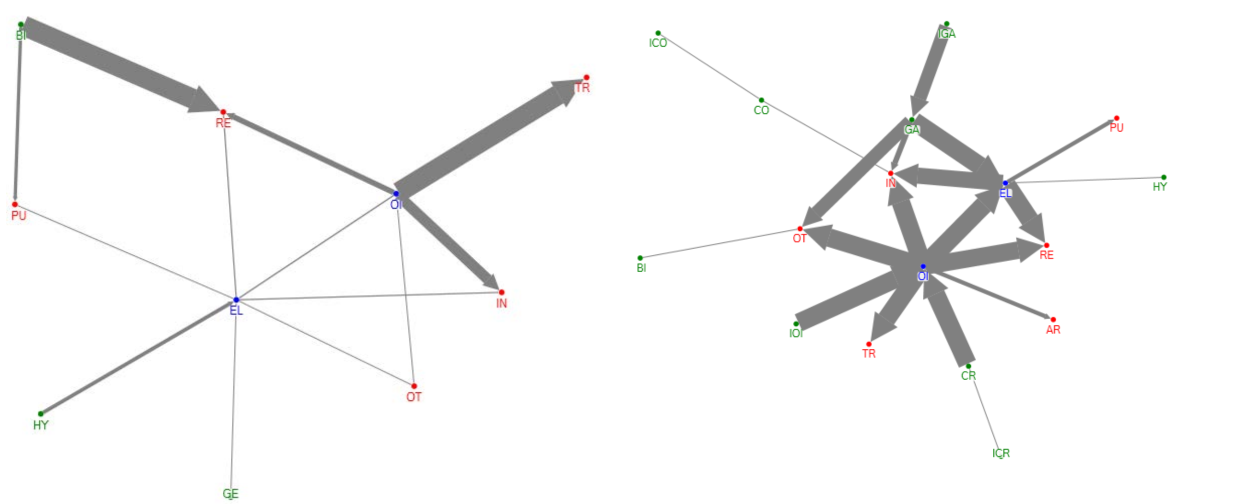
The residential sector TL has the lowest value of 2.0, highest of 4.0, mean of 2.9 and median of 3.0.

Figure 4-16 Residential Sector Trophic Level



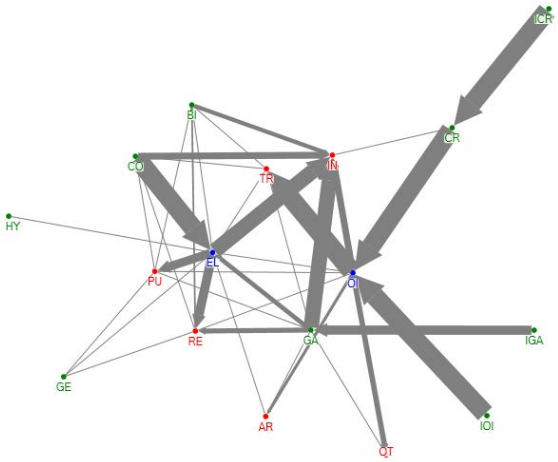
The RE also has the lowest average TL compare to all other sectors.

Figure 4-17 Four example of energy systems

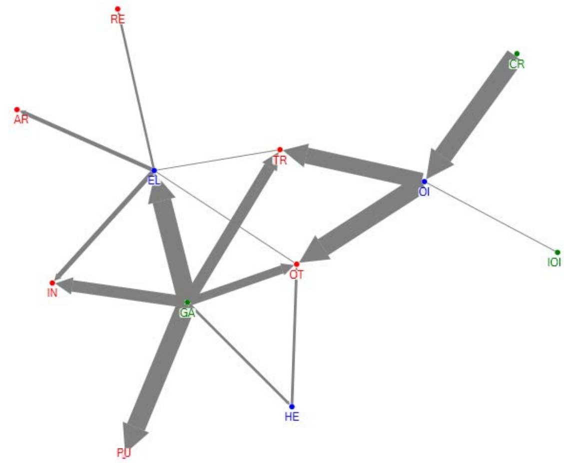


ET, RE_TL = 2.02, RE_OI = 0.02, RE_DI = 0.12, AMI = 1.71, DR = 0.22, GDPpc = 400

SY, RE_TL = 4.04, RE_OI = 0.11, RE_DI=1.0, AMI = 1.90, DR = 2.88, GDPpc = 2,700



AU, RE_TL = 2.94, RE_OI = 0.18, RE_DI = 1.69, AMI = 1.85, DR = 0.84, GDPpc = 45,500



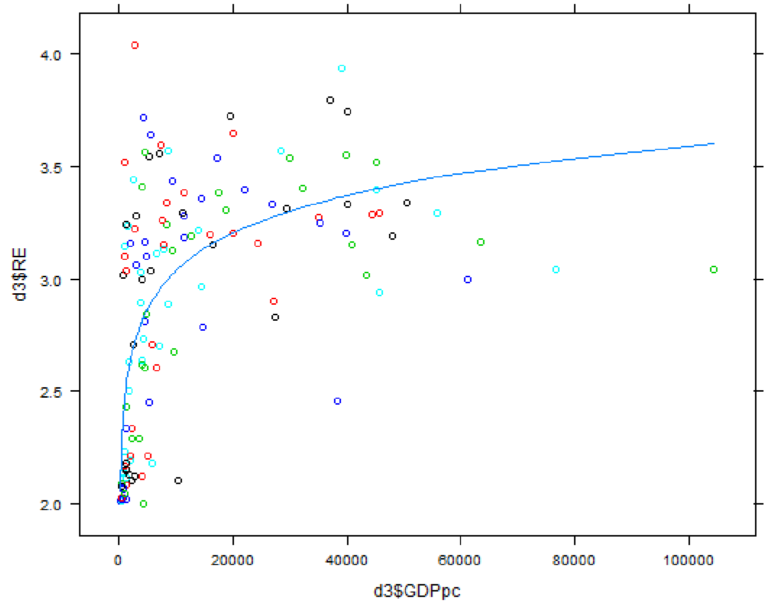
TM, RE_TL = 3.00, RE_OI = 0.00, RE_DI = 0.00, AMI = 1.62, DR = 0.70, GDPpc = 4,000

Similarly to other TL indicators, different systems can have similar TL. This means that there are different construction that could lead to high TL, thus high TL does not necessarily equate energy insecurity. To gauge the differences between these systems, we have to rely on the additional OI and DI's indicator. For example AU and TM has similar RE_TL, but completely different energy system's structure, only based on OI and DI that we are able to distinguish the two countries.

RE_TL's regressions against GDPpc, AMI or DR show that GDPpc plays a more central and more significant role in RE's variation (higher variance in analysis of variance).

We found that RE_TL has a significantly moderate correlation of 0.65 with log(GDPpc) and that the R-square fit is 0.47. This non-linear relationship tells us that Residential sector energy quality (EL_TL) increase sharply during the first quintile of GDPpc, i.e. poor countries are more prone to high EL_TL as the GDPpc increase. However, after a certain threshold in 2nd GDPpc quintile, the EL_TL only increases moderately as GDPpc changes

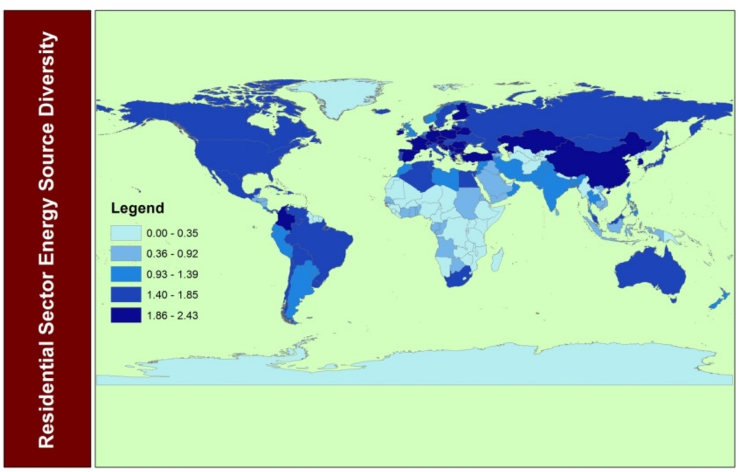
Figure 4-18 Residential Sector Trophic Level and GDP per capita

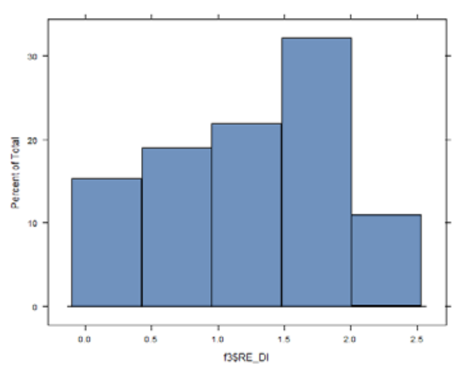


Note: o Africa, o Asia (including Oceana), o Europe, o North America, o South America

This trend is completely different from previous TL (EL, IN, TR and PU), reflecting that RE sector might be a decentralized sector, in which energy consumption pattern is personalized.

Figure 4-19 Residential Sector Energy Source Diversity



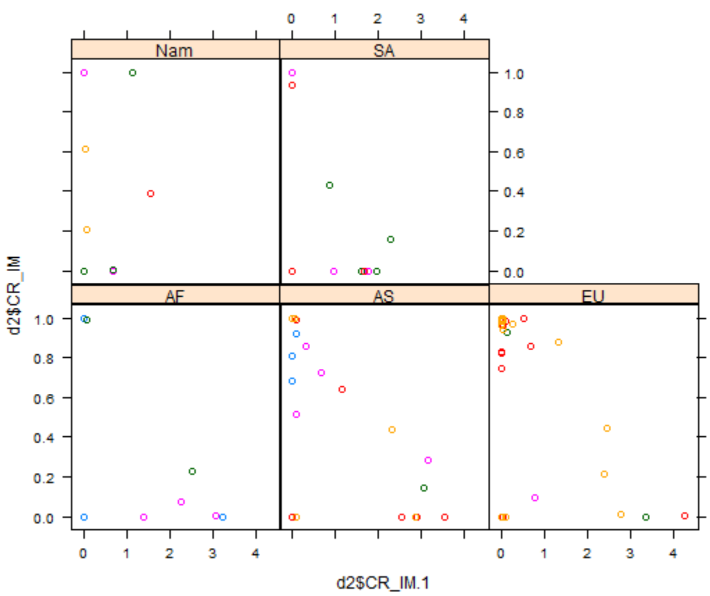


The figures show that there is an even distribution of RE_DI and there is a wide spatial distribution as well, showing that there is no discernible pattern in RE_DI.

4.5 International energy trade networks

4.5.1 Vulnerability of crude oil networks

Table 4-8 Crude Oil Import dependency and Crude Oil Omnivory Index



Cont.	Corr.	p-val	Signif
AF	-0.550	0.052	.
AS	-0.553	0.006	**
EU	-0.474	0.005	**
Nam	0.208	0.565	
SA	-0.654	0.040	*
All	-0.480	0.000	***

GDPpc	Corr.	p-val	Signif
1st	-0.311	0.279	
2nd	-0.415	0.097	.
3rd	-0.569	0.042	.
4th	-0.571	0.004	**
5th	-0.439	0.036	*

Normally we would expect countries to hedge their import dependency with import diversity, thus, having a positive correlation between the two indicators. However, this is not the observed trend in Crude oil, in fact, the overall correlation is -0.48 at a significant level with the trend most observed in Asia and Europe.

Another reasonable expectation in relation to supply security is that more developed countries are more equipped to diversity their source, however, this is not a trend in the data (the correlation between import dependency and diversity is still negative for all five income per capita groups).

Furthermore, there is no significant correlation between import dependency or import source diversity and GDPpc or continent.

Figure 4-20 Crude Oil Energy Source Diversity

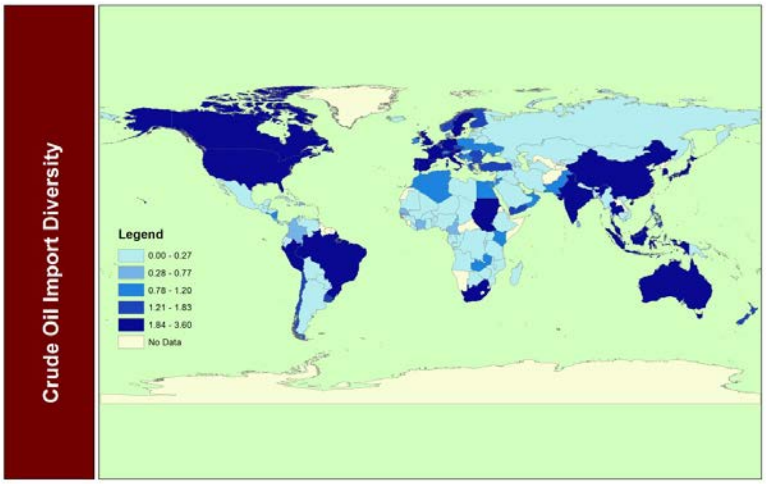
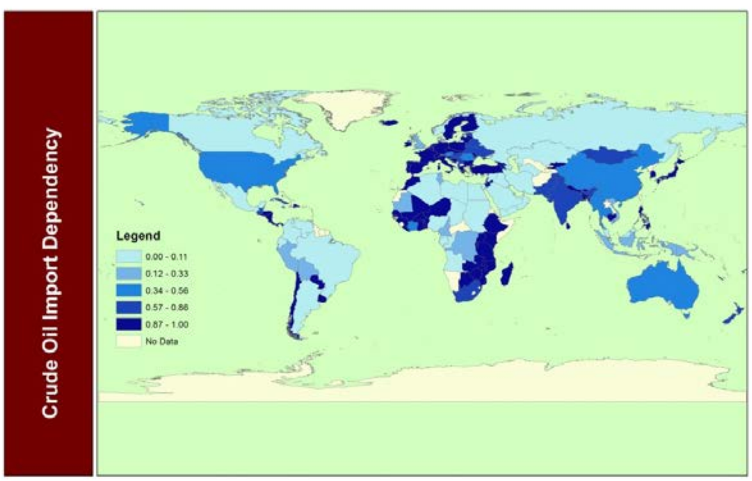


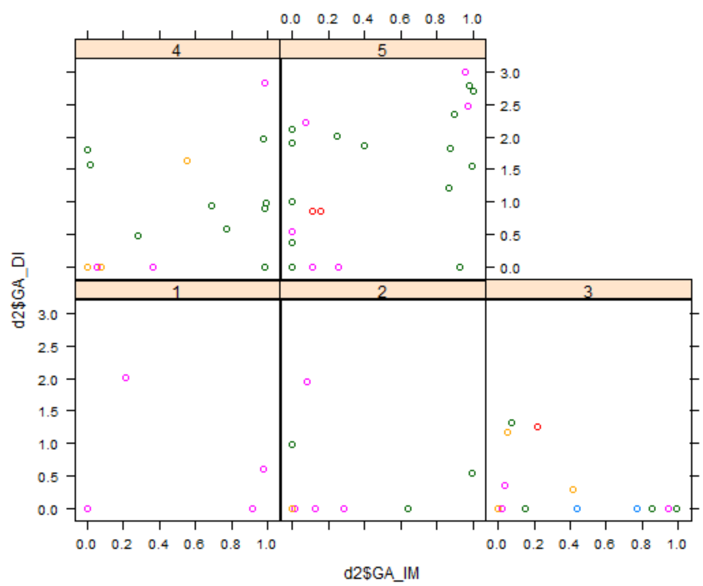
Figure 4-21 Crude Oil Import Dependency



4.5.2 Vulnerability of natural gas networks

Natural gas vulnerability is measured by Diversity of import source and Import dependency. The two indicators have a low (0.37) but significant positive correlation. Their correlation is further categorized into continent and GDPpc. We can see from the plot and the table that the correlation is highest significant in North America (close to 1), this high correlation should be ignored because of small sample size. However, the high (0.5) and significant correlation in the 4th and 5th quintile could be hypothesize on the fact that these rich European countries might be equipped with pipelines and LNG terminals so that the security of import dependency is reduced by the high import diversity

Table 4-9 Natural Gas Energy Source Diversity and Import Dependency



Cont.	Corr.	p-val	Signif
AF	NA	NA	
AS	0.484	0.012	*
EU	0.224	0.171	
Nam	0.983	0.003	**
SA	0.637	0.124	
All	0.372	0.000	***

GDPpc	Corr.	p-val	Signif
1st	0.116	0.805	
2nd	0.060	0.847	
3rd	-0.247	0.308	
4th	0.509	0.018	*
5th	0.553	0.005	**

Note: o Africa, o Asia (including Oceana), o Europe, o North America, o South America

The import dependency and import diversity indicators are then regressed against the energy system indicators (AMI and DR) to see if there is an pattern in the energy system that could have caused higher energy security (Table 4-5).

Table 4-10 Correlation coefficient of Import diversity (left) and Import dependency (right) against AMI and DR

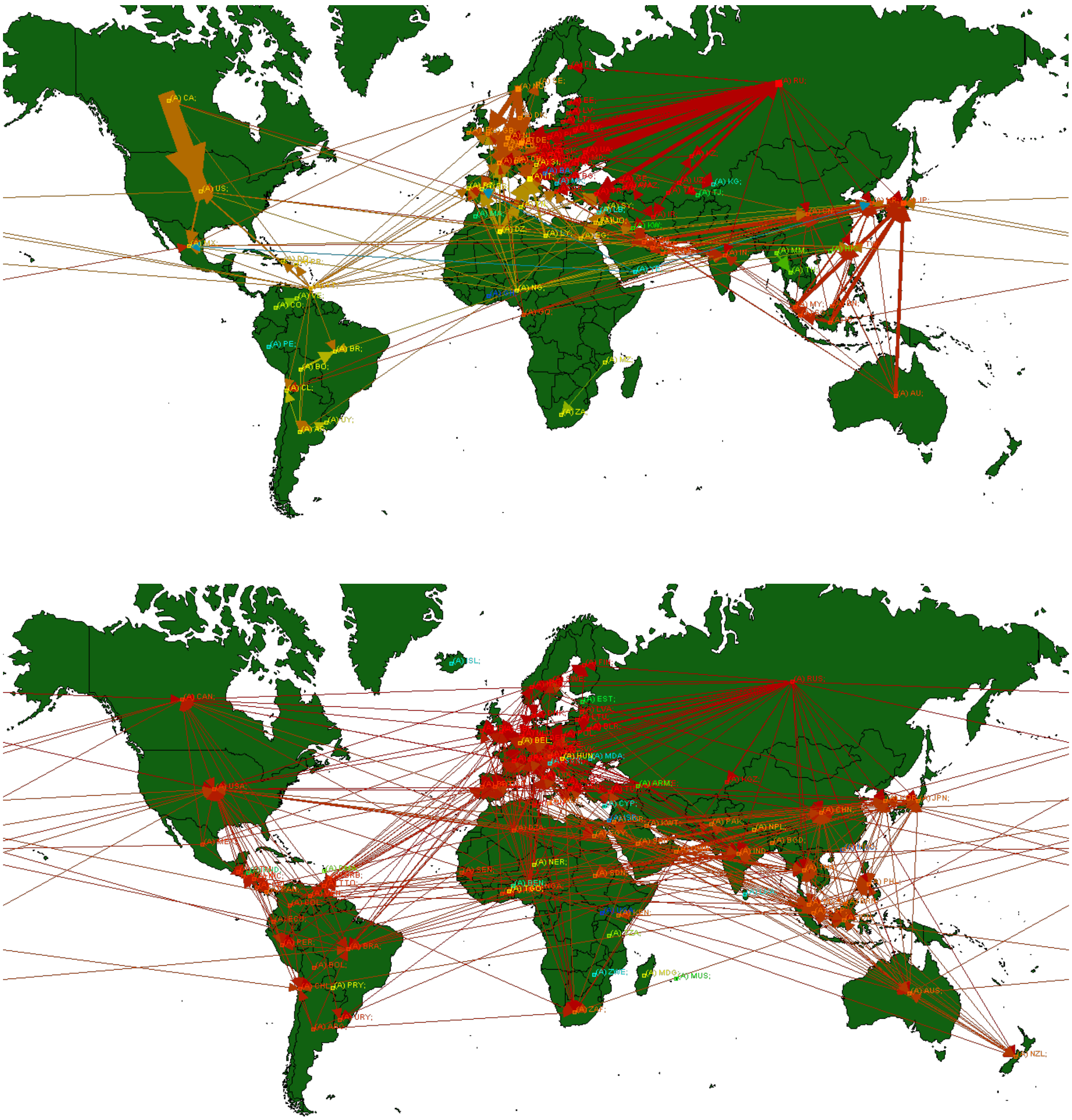
GDPpc.	AMI	Signif	DR	Signif
1st	0.259		0.840	*
2nd	0.242		0.264	
3rd	-0.424	.	0.241	
4th	0.413	.	0.460	*

GDPpc	AMI	Signif	DR	Signif
1st	0.707	**	0.137	
2nd	0.462	*	0.390	.
3rd	0.565	**	0.124	
4th	0.553	**	0.535	**

5th	0.458	*	0.155	5th	0.505	**	0.360	.

The correlation table shows that while import diversity does not have high correlation with either AMI and DR, Import dependency is moderately correlated with AMI. This correlation means that country with high energy flow efficiency is likely to have high import dependency.

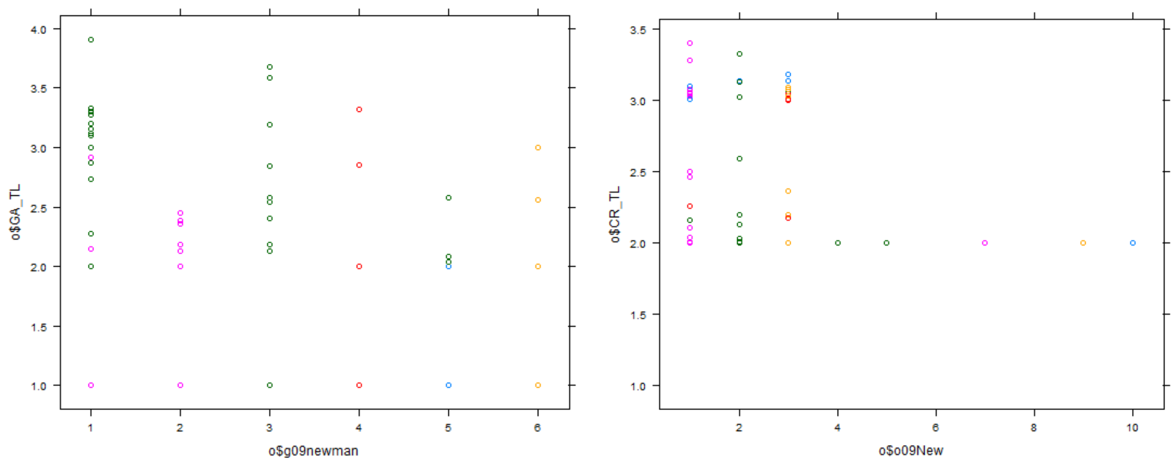
Figure 4-22 Global Natural Gas Trade Network



Note: The size of the links represent the relative amount of gas trade flow. The color of the nodes represent different roles the country were playing in the trade network. Natural gas data from BP (2010) Crude oil data from UNComTrade (2011) graphic from ORA (citation)

The calculated trophic levels are graphed against the Newman method of finding community.

Table 4-11 Trophic Level and Structural Role for natural gas (left) and oil (right)



Note: o Africa, o Asia (including Oceana), o Europe, o North America, o South America

There is no discernible correlation between the two equivalence methods, deriving to a conclusion that due to methodological challenges, TL is not the most appropriate indicator to use at international level.

5 Discussion

5.1 National energy system security

The national system energy indicators used here are AMI, and DR. Both indicators serve the purpose of reflecting energy concerns based on the configuration of energy system.

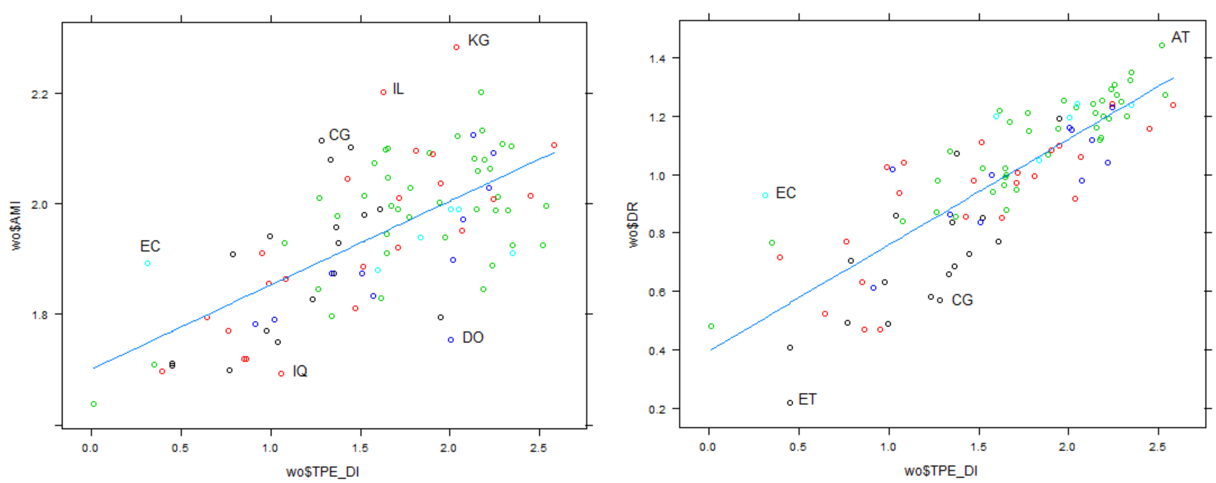
The indicators intuitively gauge the different aspects of energy security: robustness (AMI) and resilience (DR), similarly to ecological network. To further understand their application in energy security, the indicators are compared against a typical indicator of Total primary energy supply diversity (citation) TPE_DI

$$TPE\_DI \ = \ \sum_{i}^{n} -p_i \cdot log(p_i)$$

p_i is the percentage of energy use from one type of primary fuel.

We can see that there is a high correlation between TPES_DI and DR, AMI:

Figure 5-1 Average Mutual Information and Conditional Uncertainty v.s. Primary Energy Diversity



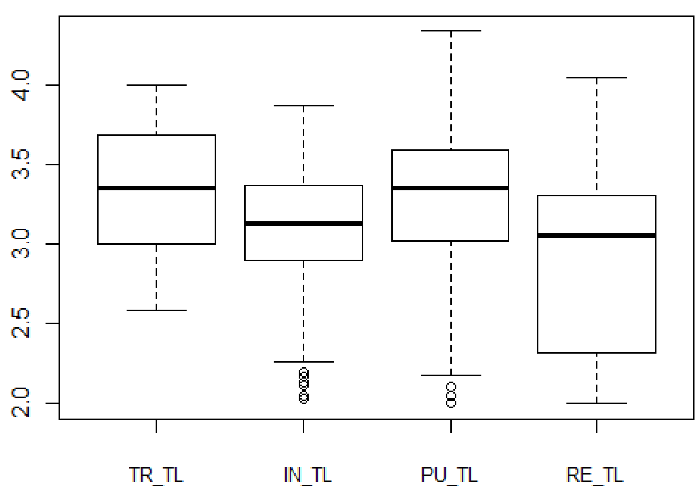
.AMI	corr	p-val	signif
AF	0.554	0.021	*
AS	0.767	0.000	***
EU	0.606	0.000	***
NAm	0.713	0.014	*
SA	0.490	0.324	
All	0.654	0.000	***
.AMI	corr	p-val	signif
1st	0.808	0.000	***
2nd	0.120	0.624	
3rd	0.504	0.028	*
4th	0.802	0.000	***
5th	0.482	0.032	*

.DR	corr	p-val	signif
AF	0.798	0.000	***
AS	0.782	0.000	***
EU	0.901	0.000	***
NAm	0.770	0.006	**
SA	0.863	0.027	*
All	0.830	0.000	***
.DR	corr	p-val	signif
1st	0.780	0.000	***
2nd	0.548	0.015	*
3rd	0.780	0.000	***
4th	0.895	0.000	***
5th	0.946	0.000	***

We can see that the high correlation between AMI and TPES and the correlation between DR and TPES tells us that while AMI and DR conveys similar notions on energy security, the two indicators give us more information on the structure of the system than the simple TPE_DI.

5.2 Sectoral energy system security

Table 5-1 End Use Sector Energy Quality

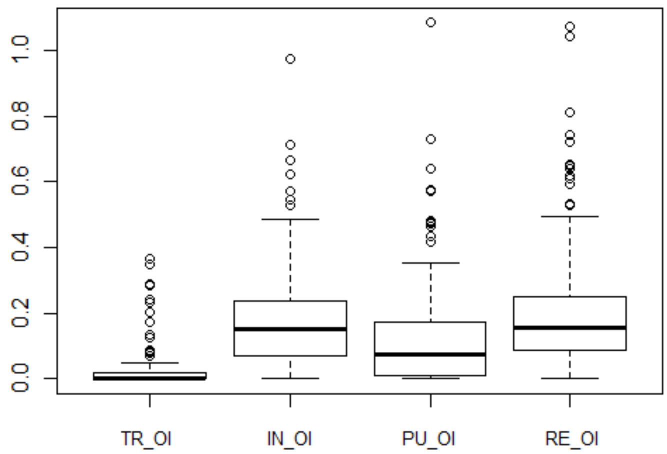


	TR	IN	PU	RE
TR	3.35	3.07	3.32	2.9
IN	H		H	L
PU		L		L
RE	H	H	H	

Note: The first line shows the average value of TL of each sector. The student t-test shows the comparison between column values and row values, L stands for Lower, H stands for higher. All of the result here are high significance excepts TR-PU, of which the p-value is 0.5.

The student t-test showed that while the pattern for other sectors are not discernible, there is a clear lower value of RE_TL, setting the sector apart from others.

Table 5-2 End Use Sector Consumption Variance

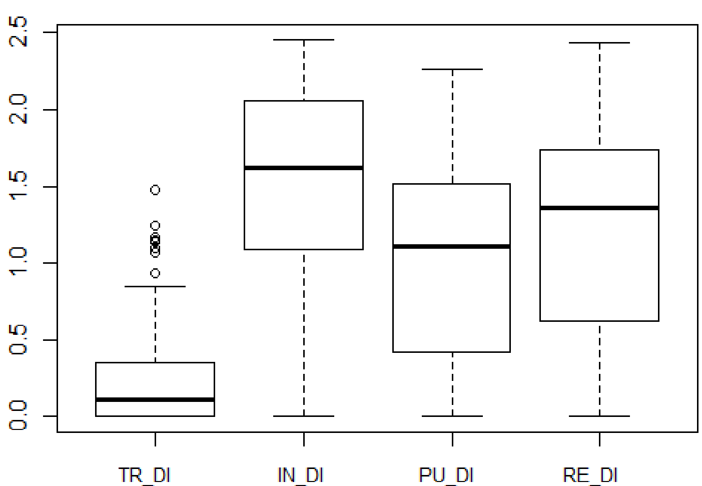


	TR	IN	PU	RE
TR	0.03	0.19	0.13	0.22
IN	L		H	H
PU	L	L		H
RE	L		L	

Note: The first line shows the average value of OI of each sector. The student t-test shows the comparison between column values and row values, L stands for Lower. All of the result here are high significance with p-value < 0.0001 except for IN and RE.

The student t-test showed that TR sector has the lowest consumption variance, followed by PU sector, then IN sector and then RE sector. This is also congruent with findings using Diversity indicator.

Table 5-3 End Use Sector Diversity



	TR	IN	PU	RE
TR	0.23	1.57	0.98	1.23
IN	L			
PU	L	L		
RE	L	L	L	

Note: The first line shows the average value of DI of each sector. The student t-test shows the comparison between column values and row values, L stands for Lower. All of the result here are high significance with p-value < 0.0001.

5.3 Future research agenda

5.3.1 National energy system analysis

TL indicator is a difficult concept that reflects the "quality" of the energy sources each sector is consume. This quality is quantified by the distance from original energy source and the percentage of consumption. However, due to construction, production is not taken into consideration, thus, distorting the indicators. Originally, the formula for TL is

$$TL_j = 1 + \sum_{i=1}^{n} \frac{T_{ij}}{T_{j.}} \cdot TL_i$$

However, in application to energy security, it might be more beneficial to calculated as

$$TL_j = \frac{T_{ij}}{T_{j.}} \cdot TL_j + \sum_{i=0}^{n} \frac{T_{ij}}{T_{j.}} \cdot TL_i$$

The new formula does not follow the biological concept of trophic level anymore but carries a closer reflection to anthropological network

5.3.2 International energy system analysis

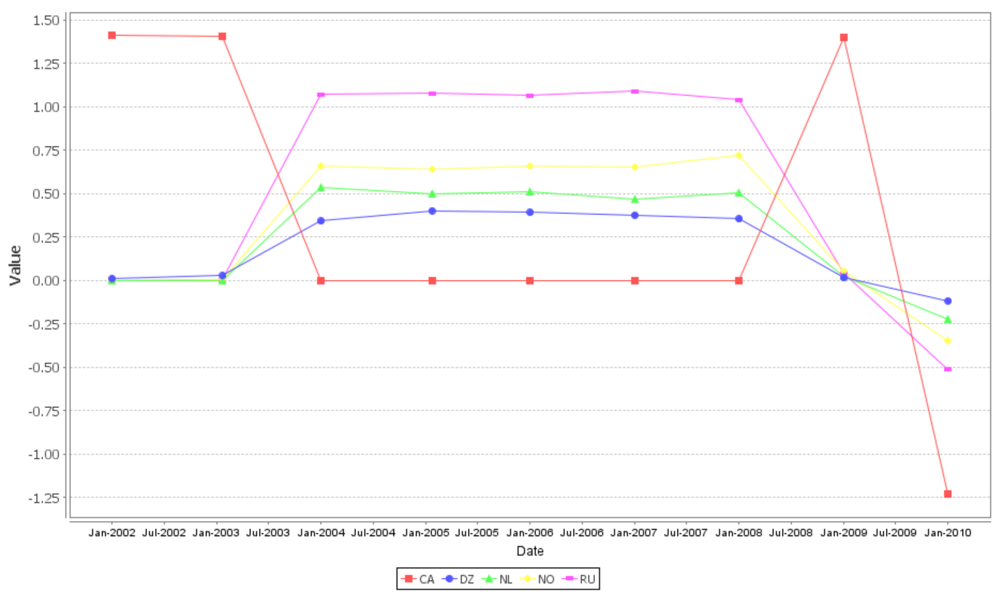
Similarly to national energy system analysis, the application of TL is problematic since TL does not reflect either production or export. Furthermore, the generalized reverse matrix used in TL calculation distorts the final result, giving not the most accurate numbers but the minimum least square numbers. This problem is not observed in national energy system analysis since that system assumes no export (it is rather difficult to quantify the amount of energy export in end-use sectors, an expansive energy-footprint of traded commodities has to be carried out in order to gauge this quantity).

5.3.3 Other improvements

A possible direction for future study is the analysis of dynamic networks both for national energy system and international energy trade network based on the result of this study. Considering 2008 marks the first setback of the global financial collapse, such analysis will not only have an environment but also economic value.

From preliminary study of international gas trade based on BP data (2002 – 2010), the network analysis showed that while there is a 30% increase in numbers of nodes (more countries reported trading after 2008) but the density of the network (the amount of existing links compare to the amount of possible links) is reduced after 2008.

Figure 5-2 Importer hub



The network configuration changed making the position of major importer as hub changed.

Thus, if similar analysis can be done for a long period of time, we can see the robustness of each country's role in the network.

6 Conclusions

The aim of this thesis was to explore the applicability of network analysis, especially food web analysis to energy security assessment. It is motivated by the fact that while there are many similarities between energy systems and ecological networks, the dialogue between the two areas of studies has remained very limited. The first objective of the thesis was to identify concepts and methods in network science which could be used in energy security assessment. The literature review (Chapter 2) explained similarities between energy systems and other networks, particularly food webs. It also identified several indicators previously used for the analysis of stability of food webs at the system level (AMI and DR) and the local level (TL and OI). Finally the literature review summarized concepts from social network theory (such as centrality and role hierarchy) which can be potentially applicable to the analysis of energy security.

The second objective of the thesis was to develop energy security metrics based on concepts and approaches from food web analysis and social network analysis. Such metrics (indicators) were systematically identified in Chapter 3 (Methodology). These indicators the measure of system's effectiveness (AMI), the measure of system's redundancy (DR), the trophic level (TL) and the omnivory index (OI).

The third objective was to evaluate national energy systems using the proposed indicators. The results of this evaluation for 87 countries are reported in Chapter 4 (Results) and summarized in Chapter 5 (Discussions). Two of the proposed indicators: AMI and DR meaningfully describe energy security of national energy systems. It can be hypothesized that AMI reflects exposure to risks and thus its higher value means lower energy security, whereas DR reflects redundancy and thus resilience of the system.

Both indicators highly correlate with one of the most common measures of energy security: diversity of primary energy sources. While the correlation of DR with diversity is expected: the higher values of both indicators signal enhanced energy security; the correlation of AMI with diversity shows something completely different: it means that higher diversity can in some situations lead to higher vulnerability. If correct, this hypothesis may revolutionize energy security studies.

The other two indicators: TL and OI were applied to essential energy sectors: transport, industry, electricity, public and residential consumption in 137 countries. This thesis did not identify meaningful interpretation of these "local" indicators in terms of energy security. Finally, the thesis explored the application of social network concepts such as degree centrality, betweeness centrality, clustering coefficient and hierarchical community clusters to international gas and oil trade networks. At this stage no meaningful interpretation of these concepts has been found.

The fourth and final objective of the thesis was to identify correlation between the identified indicators, other indicators of energy security and socio-economic and geographic characteristics of the countries. The 'meaningful' indicators – AMI and DR – did not correlate with the level of economic development but significantly correlated with the geographic location (the continent) of the countries concerned.

In summary, this thesis shows that concepts and indicators from food web and social network analysis are potentially able to provide new and unique insights into energy security of individual countries and global energy systems. Further work will be needed to explore the relationship between the trophic role of a sector or a country and its vulnerability. Adjustments to TL can be made to increase the utility of that indicator and dynamic network analysis can be introduced as explained in the Discussion section.

References

Blyth, W., Lefevre, N., 2004. Energy Security and Climate Change. *International Energy Agency Information Paper.*

Briand F. and J.E. Cohen, 1984. Community food webs have scale invariant structure. *Nature* 307:264-266.

British Petroleum (BP). 2010. BP Statistical Review of World Energy June 2010.

British Petroleum (BP). 2011. BP Statistical Review of World Energy June 2011.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., Havlin, S. 2010. Catastrophic cascade of failures in interdependent networks. *Nature* 464: 1025-1028.

Cherp, A. and Jewell, J. 2011. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. *Current Opinion in Environmental Sustainability* (3):1–11.

Cherp, A., 2012a. Defining energy security takes more than asking around. *Energy Policy*, doi:10.1016/j.enpol.2012.02.016

Cherp, A., 2012b. " Energy and Security". In *The Global Energy Assessment: Toward a More Sustainable Future.* International Institute for Applied Systems Analysis. Cambridge University Press, Laxenburg, Austria.

Cherp, A., and J. Jewell. 2010. "Measuring energy security: from universal indicators to contextualized frameworks." In The *Routledge Handbook of Energy Security*, edited by B. K. Sovacool, 330-355. London and New York: Routledge.

Chester, L. 2010. Conceptualising energy security and making explicit its polysemic nature. *Energy Policy* 38(2): 887- 895.

Cohen, J. E., and Z. J. Palka. 1990. A Stochastic Theory of Community Food Webs: V. Intervality and Triangulation in the Trophic Niche Overlap Graph. *American Nature* 135:435–463.

Dassisti, M., Carnimeo, L. 2012. Net modelling of energy mix among European Countries: A proposal for ruling new scenarios. *Energy* 39:100-111.

Dunne, J.A. 2006. The network structure of food webs. Pages 27-86 in *Ecological Networks: Linking Structure to Dynamics in Food Webs*. M. Pascual and J.A. Dunne, eds. Oxford University Press.

European Commission (EC). 2009a. The January 2009 gas supply disruption to the EU: an assessment", Commission Staff Working Document, SEC 977. Brussels.

European Commission (EC). 2009b. The Commission adopts new rules to prevent and deal with gas supply crises, press release IP/09/1153, Brussels.

Farrell, A. E., Zerriffi, H., Dowlatabadi, H. 2004. Energy Infrastructure and security. *Annual Review of Environmental Resource* 29:421-469.

Fiscus, D.A., 2002. The ecosystemic life hypothesis. II. Four connected concepts. *ESA Bull.* 83, 94–96. Cited in Ulanowicz, R. E. 2004. Quantitative methods for ecological network analysis. *Computational Biology Chemistry* 28: 321–329.

Gnansounou, E. 2008. Assessing the energy vulnerability: Case of industrialised countries. *Energy Policy* 36: 3734–3744.

Gupta , E. , 2008 : Oil Vulnerability Index of Oil-importing Countries. *Energy Policy* , 36 (3): 1195 – 1211 .

Holling, C.S.1959. Some characteristics of simple types of predation and parasitism. *Canadian Entomologist* 91: 385-398.

IEA. 2012a. Energy Security. International Energy Agency: Energy Security. URL:http://www.iea.org/Textbase/subjectqueries/keyresult.asp?KEYWORD_ID=4103. [consulted February 27 2012]

IEA. 2012b. Balances. International Energy Agency: Statistics. URL:http://www.iea.org/Textbase/stats/prodresult.asp?PRODUCT=Balances. [consulted February 27 2012]

Jackson, M. O. 2009. *Social and economic networks*. Princeton University Press.

Jewell, J. 2011. The IEA Model of Short-term Energy Security (MOSES) Primary Energy Sources and Secondary Fuels. International Energy Agency, Paris, France.

Jordan, F., Scheuring, 2004. I. Network ecology: topological constraints on ecosystem dynamics. *Physics of Life Reviews* 1:139–172.

Kones, J.K., Soetaert, K., van Oevelen, D. and J.Owino. 2009. Are network indices robust indicators of food web functioning? a Monte Carlo approach. *Ecological Modeling* 220: 370-382

Le Coq, C., Paltseva, E. 2009. Measuring the security of external energy supply in the European Union. *Energy Policy* 37(11): 4474–4481

Leibold M.A., Holyoak M., Mouquet N., Amarasekare P., Chase J., Hoopes M., Holt R., Shurin J.B., Law R., Tilman D., Loreau M., and Gonzalez A. 2004. The metacommunity concept: A framework for multi-scale community ecology. *Ecology letters*, 7, 601-613.

Lotka, A. J. 1925. *Elements of physical biology*. Baltimore: Williams & Wilkins Co.

Luczkovich, J.J., Borgatti, S. P., Johnson, J. C., Everett, M. G. 2003. Defining and Measuring Trophic Role Similarity in Food Webs Using Regular Equivalence. *Journal of Theoretical Biology*. 220: 303-321.

MacArthur, R.. 1955. Fluctuations of animal populations, and a measure of community stability. *Ecology* 36, 533–536.

May, R.M., 1972. Will a large complex system be stable? Nature 238, 413–414. Cited in Ulanowicz, R. E., Goerner, S. J., Lietaer, B. Gomez, R. 2009. Quantifying sustainability: Resilience, efficiency and the return of information theory. *Ecological Complexity* 6: 27-36.

McCann, K. Hastings, A. Huxel. G.R. 1998. Weak trophic interactions and the balance of nature. *Nature*, 395: 794–798.

Meadows, D. 2008. *Thinking in systems : a primer*. Chelsea Green Publishing, Vermont

Nakicenovic, N., Alcamo, J., Davis, G., De Vries, B., Fenhamm, J., Gaffin, S., Gregory, K., Gruebler, A., Jung, T.Y., Kram, T., Lebre La Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., Van Rooyen, S., Victor, N., Zhou, D., 2000b. IPCC Special Report on Emissions Scenarios. Cambridge University Press, Cambridge.

Newman, M. E. J., 2004. Analysis of weighted networks. *Physical Review* 70, 056-131.

Newman, M., Barabási, A. and Watts, D. J. 2006. *The Structure and Dynamics of Networks*. Princeton, NJ: Princeton University Press.

Nordlund, C. 2010. *Social Ecography: International Trade, Network Analysis and an Emmanuelian Conceptualization of Ecological Unequal Exchange*. Lund University Press.

Pimm, S. L., and J. H. Lawton. 1980. Are Food Webs Divided into Compartments? *Journal of Animal Ecology* 49:879–898.

Riahi, K., Dentener, F. , Gielen, D. , Grubler, A. , Jewell, J. , Klimont, Z. , Krey, V. , McCollum, D.L. , Pachauri, S. , Rao, S. , van Ruijven, B. , van Vuuren, D.P. , Wilson, C. 2012. "Energy pathways for sustainable development" in *The Global Energy Assessment: Toward a More Sustainable Future* Gomez-Echeverri L. , Nakicenovic, TBJ, N. , Patwardhan A. (Eds.). Cambridge University Press, Laxenburg, Austria.

Scotti, M., Vedres, B. 2012. Supply security in the European natural gas pipeline network. *Networks in Social Policy Problems*. Cambridge University Press.

Sovacool, B. J. 2010. Evaluating energy security in the Asia pacific: Towards a more comprehensive approach. *Energy Policy*, doi:10.1016/j.enpol.2010.10.008.

Stirling, A. 1994. Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. *Energy Policy* 22(3).

Stirling, A. 2007. A general framework for analysing diversity in science, technology and society *Journal of The Royal Society Interface*, 4(15), 707–719

Stirling, A. 2010. Multicriteria diversity analysis: A novel heuristic framework for appraising energy portfolios. *Energy Policy* 38(4): 1622-1634

Ulanowicz, R. E. 2003. Some steps toward a central theory of ecosystem dynamics. *Computational Biology and Chemistry* 27: 523–530.

Ulanowicz, R. E. 2004. Quantitative methods for ecological network analysis. *Computational Biology Chemistry* 28: 321–329

Ulanowicz, R. E., Goerner, S. J., Lietaer, B. Gomez, R. 2009. Quantifying sustainability: Resilience, efficiency and the return of information theory. *Ecological Complexity* 6: 27-36.

Ulanowicz, R.E., 2002. Information theory in ecology. *Computational Chemistry* 25: 393–399.

Watts, D. J., Strogatz, S. H., 1998. Collective dynamics of "small-world" networks. *Nature* 393: 440-442.

White, D. R., Reitz, K.P. 1983. "Graph and Semigroup Homomorphisms on Networks of Relations." *Social Networks*. 5: 193-234. Cited in Nordlund, C. 2010. Social Ecography: International Trade, Network Analysis and an Emmanuelian Conceptualization of Ecological Unequal Exchange. Lund University Press.

Yergin, D. 2006. The New Energy Security Paradigm. *World Economic Forum*. Geneva, Switzerland.

Zorach, A.C, Ulanowicz, R. E. 2003. Quantifying the complexity of flow networks: how many roles are there? *Complexity* 8 (3): 68–76.