A Thesis

entitled

Diversity Analysis of Water System in the US

by

Sonia Barakoti

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Civil Engineering

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May, 2018

An Abstract of

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The concept of diversity has been used in many different fields with the basic idea that diversification can reduce risk and increase resilience. Yet, the use of diversity concepts in engineering infrastructure has been lacking. In particular, the water system has never been analyzed from a diversity perspective. In addition, the relation between diversity and efficiency is still debated in the literature. In this study, I addressed these literature gaps by conceptualizing and quantifying water diversity for the very first time. Data were collected from the United States Geological Survey and the Energy Information Administration. Diversity was calculated using the Shannon Weiner Index. I found the water use diversity to be 0.8 which is lower than the energy use diversity of 1.4. Water use diversity also fluctuated a lot; both temporally and across states, water diversity displayed much greater variation than energy diversity. The efficiency showed a positive correlation with diversity. This correlation was more evident for the energy system than for the water system.

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List of Abbreviations

ANOVA	Analysis Of Variance
EIO-LCA	Economic Input Output Life Cycle Assessment
GAL	Gallon
GIS	Geographic Information System
GDS	Gross Domestic Product of State
GNP	Gross National Product
GSP	Gross State Product
KWH	Kilo Watt Hour
MJ	Mega Joule
GJ	Giga Joule
MG	Million Gallon
NWIS	National Water Information System
OH	Ohio
SEDS	State Energy Data System
USEIA	United States Energy Information Administration
USEPA	United Stated Environmental Protection Agency
USGS	United States Geological Survey
US	United States

Chapter 1

Introduction

Diversity is an important concept for complex systems. Its calculation dates back to 1949 when Shannon published an electrical engineering book on the Mathematical Theory of Communication (Spellerberg et al., 2003)). Since then, the diversity index was picked up by ecologists who used Shannon's diversity index to calculate the diversity of species in ecosystems. Ecologists showed that species in an ecosystem provides diversity in the form of richness (number of species), abundance (number of individuals in each species), and evenness (distribution of species). Ecologists suggested that diversity enhances resistance to perturbations, increases recovery after perturbations and therefore creates resilience (Hughes et al, 2004, Reusch et al, 2005). They attributed this to the insurance effect provided by superfluous number of species. They suggested that redundancy provides more response options to perturbations in a system thereby increasing resiliency.

While diversity is most commonly used in ecology, it has also found many uses in other fields including finance, agriculture, software security, energy, economics (Reinmoeller, 2005; Ulanowicz et al, 2008; Gaudin et al, 2015; Safarzynska, 2017). In finance, it is common knowledge that one can reduce risk by diversifying assets. Increases in crop diversity, fuel sources, software diversity and even income diversity also suggest a decrease in risk and increase in resilience of various complex systems. Even in human population, diversity has been emphasized. It's been suggested that a society diverse in philosophy, method, and reaction can be a resilient society (Chuang et al, 2013).

While diversification is generally considered a good practice, it is not always prioritized in engineering design and in particular the design of infrastructure systems. Efficiency often takes center stage in infrastructure engineering leaving little room to include redundant nodes and processes and often resulting in larger and more centralized designs. A good example of this is the water system; both the water and wastewater are treated and managed at centralized treatment plants that have become increasingly larger as city populations grew. The economies of scale have been shown for these systems: the bigger the more efficient and more eco-efficient (Cornejo et al., 2016). Yet, if these systems fail, there is little resilience available for users. As recent examples, in Toledo and Flint, failures in water treatment and supply led large populations without useable water (Wynne et al., 2015; Butler et al., 2016)).

The relation between diversity and efficiency is an ongoing debate in the literature. In ecology this is still debated (Guderle et al, 2018). In engineering, a recent paper suggested that redundant nodes do not decrease eco-efficiency (Pizzol, 2015) suggesting that diversity can increase efficiency.

In this study, I had two goals. The first goal was to conceptualize and quantify the diversity in the water system. Energy diversity has been reported previously (Chuang et al, 2013; Kharrazi et al, 2015; Templet 1999; Xu et al. 2002)) but to my knowledge, no other study previously quantified water diversity. Lack of this knowledge can create a barrier as we move towards increasing resiliency in the water infrastructure. My second goal was to analyze the relation between diversity and efficiency. I hypothesized that diverse systems may create redundancy and therefore decrease efficiency. To address these goals, I collected and analyzed data from the US Geological Survey (USGS) (on water use and water source), Carnegie Mellon’s EIOLCA model (on water used by 426 sectors in the US economy), and FRED Economic Data (on the gross domestic product of states which was used for efficiency calculations). I also collected data from the Energy Information Administration on energy use and energy source to compare water diversity and efficiency to energy diversity and efficiency (USEIA). This was important so as to interpret water diversity in relation to another equally important system that is relatively better studied.

After outlining the methodology in Chapter 2, we present the main results of our analysis in Chapter 3 and then discuss the findings with the literature and wider sustainability implications in Chapter 4 and finally overall conclusion is provided in Chapter 5.

Chapter 2

Methodology

2.1. Calculation of Water Source and Water Use Diversity

Figure 2-1 shows the conceptual framework of my study. The right side of the figure shows the water system. Annual water source and water use data were collected from USGS for each state. USGS's National Water Information System (NWIS) reports these data every five years. I analyzed the data for 1995, 2000, 2005, and 2010. . The amount of water is provided in the form of source and use in one category which I separated into two categories – source and use. For example, value under NWIS category 'public supply deliveries groundwater withdrawals to domestic' is added as one of the source category in public supply groundwater and as a use category in domestic. I organized the water source (withdrawal) data into four categories: public-supply water from ground and surface, and self-supply water from ground and surface. In water use, I organized the data in eight categories; domestic, industrial, thermo-electrical, mining, livestock, aquaculture and irrigation. Water data is given in five years interval while energy data is provided annually but for comparison, we use 5 years interval for both energy and water. We obtained data from 1995 to 2010, so the analysis for diversity was done for 1995, 2000, 2005 and 2010.

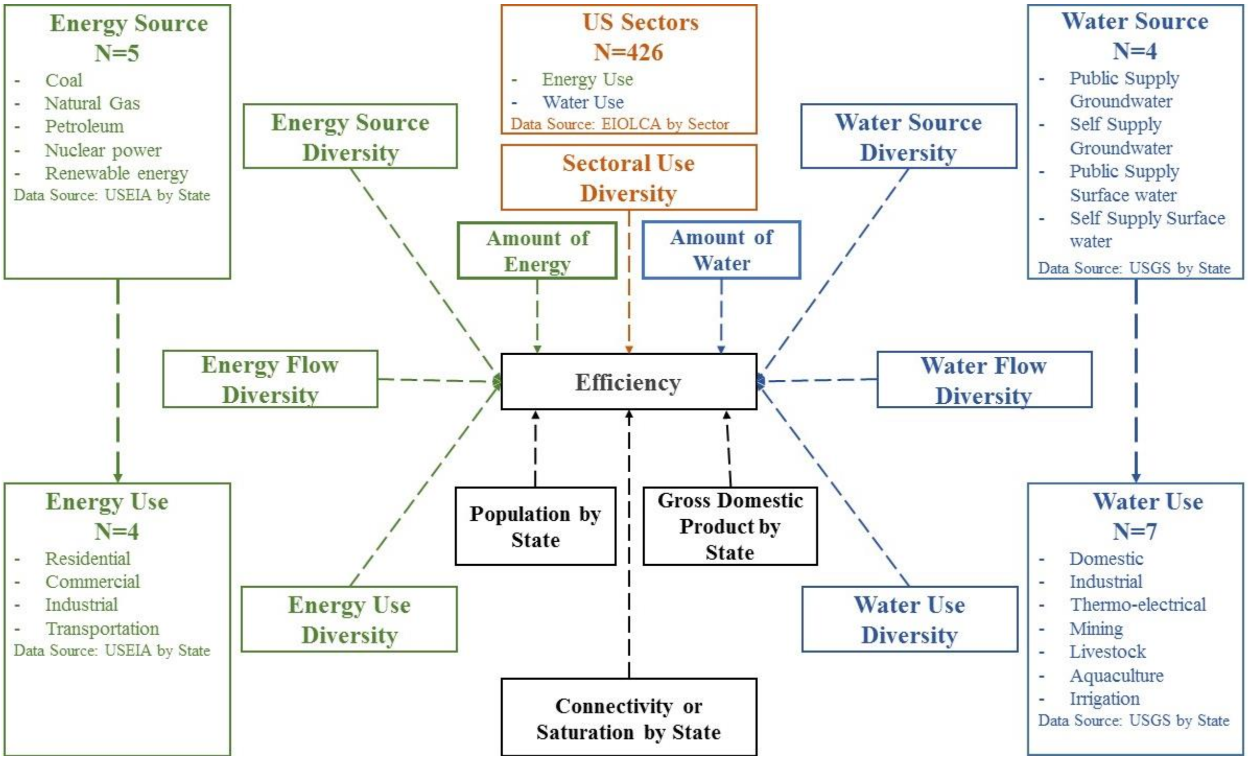


Figure 2-1: Framework of our study showing data source and methods used. (Green = energy system, blue = water system, orange = US economic sectors, black = S and N is the number of categories.)

Shannon Weiner’s Index (H) was used to calculate the diversity of water source and water use for each state:

$$H = -\sum_{i=1}^{N} p_i ln p_i$$

…Equation 1

Where, p_i is the fraction of water from various sources or the fraction of water use within a state.

N is the number of categories (N = 4 for water source and N = 7 for water use), and i is the categories from 1 to N. In other words, i can be related to ‘species’ in an ecosystem. The analogy here is that in the water infrastructure, there are four species that provide water and seven species that consume water. There are various diversity indices available in the literature but Shannon Weiner’s method is one of the most commonly used approach in economic and energy studies as it incorporates variety (number of entity) and balance (evenness) in the sampled population (Chuang et al 2013; Kharrazi et al. 2015; Molyneaux et al 2016; Safarzynska 2017; Paul H Templet 1999; Xu et al. 2002).

2.2. Calculation of Diversity

The source and use diversity of the water system would be considered as ‘structural diversity’, which can be useful in understanding how the water system functioning is affected by structural make up (Mouchet et al, 2010). In addition to structural diversity, I calculated flow diversity which is a measure of the diversity of water flow from source to use. The equivalent of this analysis in ecology is ‘functional diversity’ which is considered an essential trait in ecosystem functioning (Villeger et al, 2008) and gives a predictive measure of how functions are linked to ecosystem processes like productivity, reliability, rate of ecosystem process, resistance and resilience to perturbation (Mouchet et al, 2010; Mason et al, 2005). To calculate flow diversity, again Shannon Weiner’s index was used. With 4 water source categories and 7 water use categories, theoretically there are 28 flow categories that can be included in the Shannon Weiner’s index. However, not each source is connected to each use. Eleven categories had no water flows from source to use: public supplied surface water to domestic, industrial, thermoelectric, mining, irrigation, aquaculture, livestock and public supplied ground water to mining, irrigation, aquaculture and livestock. This left 17 flow categories that were modeled and these categories are shown in table 2-1 as tick mark.

Table 2-1: Water flow categories from four sources to seven uses ('×' shows value of zero)

Use Source	Domestic	Industrial	Thermo-electric	Mining	Irrigation	Aquaculture	Livestock
Public supply ground water	√	√	√	×	×	×	×
Public supply surface water	×	×	×	×	×	×	×
Self-supply ground water	√	√	√	√	√	√	√
Self-supply surface water	√	√	√	√	√	√	√

In 1995, the aquaculture use was included within commercial use and aquaculture became a separate category from 2000. Therefore, the value of aquaculture included within commercial category is high as it includes other uses such as motels, restaurants, office buildings, military and non-military uses.

2.3. Calculation of Sectoral Water Use Diversity

In addition to calculating water source, water use, and water flow diversity, data were collected from the EIOLCA online model to estimate the water use diversity based on a sectoral analysis (Green Design Institute, 2002). EIOLCA method was theorized and developed by economist Wassily Leontief in the 1970s. In the EIOLCA model, the US economy is divided into 426 sectors. The economic transactions among these sectors are tracked and input into a matrix within the model. Additionally, the environmental impacts (e.g. greenhouse gas emissions, water demand, energy demand) for each sector are separately collected and matched to the individual sector resulting in an economy wide analysis of environmental impacts throughout the supply chain that occurs across the 426 sectors. In this case, the analogy is that there are 426 species within the US economy.

Within the EIOLCA model, I used the US 2002 Benchmark Producer Price Model for my analysis. There are 28 broad sector group and each broad sector consists of detailed sectors that requires the input of both direct and indirect suppliers from 426 sectors. EIOLCA was run for 1 million $ for each of the 426 sectors. For each run, the model output the water use across the supply chain for that particular sector. These data were exported to excel and diversity of water use for that particular sector was calculated using the Shannon Weiner Index. The model was then again run for the second sector, third sector, and so on until it was run for all 426 sectors ultimately resulting in 426 diversity values to represent the water diversity for all sectors. With this approach, both the direct water demand of a sector and the indirect water demand of a sector were tracked and all of these flows were incorporated in the sectoral water diversity analysis. While I ran the model for 1 million dollars, I could have run it for any other value since the water amounts used in each sector are incorporated in the Shannon Weiner's index based on a fraction and not an absolute amount. The EIOLCA model is linear. Running it for two million dollars would produce twice the water demand from each sector but would results in the same diversity value.

2.4. Calculation of Water Efficiency

In the literature, prior studies reported energy intensity (Templet, 2001) which is a measure of energy needed for a dollar of economic output (MJ/$). Inverting this concept, one can analyze the economic output that can be achieved with a unit of energy input in the system ($/MJ). The higher the economic output per unit energy input in the system, the greater the efficiency of the system. In other words, the energy efficiency of economy can be calculated using MJ/$.

In this study, an analogy was made to water efficiency within the economy and the water source efficiency and water use efficiency of each state was calculated. To do this, the gross domestic product of the state was divided by the amount of total water withdrawn (for water source efficiency) or the total water used (for water use efficiency) for that given year for a particular state. This provided the water efficiency of the sector in terms of $/gal. A higher value of water efficiency indicates that greater economic output can be generated per each unit volume of water input into the system.

2.5. Diversity and efficiency calculations for the energy system

While the primary focus of this study was the water system, the energy system was also analyzed so as to provide a comparison. The exact same types of calculations were done for the energy system. The only difference was the source of data. While water data were obtained from the USGS, energy source and use data were obtained from EIA. For EIOLCA analysis, for the water system the model output was collected for the water demand of each of the 426 sectors. For the energy system, the model was again run for 1 million $ but the output was collected for energy demand for each sector. EIOLCA outputs various other environmental metrics as well. This analysis collected the data only for water and energy diversity within the 426 sectors but diversity of greenhouse gas emissions, toxicity, ozone depletion potential, PM emissions could also be easily calculated from EIOLCA model.

To calculate the energy efficiency of each state, the gross domestic product of each state was divided by the total energy withdrawn or used in the state resulting in an energy efficiency metric in terms of \$/MJ. The different units used in energy efficiency (\$/MJ) and water efficiency (\$/gal) prohibits the comparison of energy and water efficiencies. To circumvent this problem, we converted the water efficiency value from \$/gal to \$/MJ by assuming that 2100kWH of energy is needed to produce 1 million gal of water (Pabi et al., 2013). As an example of this conversion, assume the water efficiency for Alabama is = 41.66 \$/Mgal.

Water efficiency of Alabama (\$/MJ) = 41.66 \$/Mgal X 2100kWH of energy needed/Mgal of water produced X 3.6 MJ/kWh X 10^{-3} GJ/MJ = 5.51 \$/GJ

2.6. Calculation of connectivity

Connectivity or saturation was calculated as the actual number of connections divided by the total number of connections possible from source to use. This metric was used as a stability measure of the system. When the connectivity is high, it is supposed to be more stable then when the connectivity is low. Connectivity along with the strength of connections or flow diversity are the parameters that help to determine if a system is stable.

2.7. Linear Model

I used the linear model to understand the parameters that may affect diversity. Linear models were done using Data Desk software (student version 8.1). Linear model is a linear method used to represent the relationship between a dependent variable with one or more independent variables. Linear model utilizes linear regression, ANOVA, ANCOVA, logistic regression, etc. as a statistical method to analyze various types of data. Linear model utilizing simple linear regression gives an equation of the form:

$$Z = a + b X + c Y$$

where, a, b and c are the coefficients, and p-value for each variables X and Y shows significance of relation with the dependent variable Z.

Using linear model, flow diversity was correlated to source and use diversity with years. Also, diversity was related to, population, amount of resources, GDS and intensity, which is the amount of energy or water used per GDS (Gross Domestic Product by State). A low p-value (statistically significant) which is less than the common alpha level of 0.05 means that change in the predictor's (independent variable) value are related to changes in the response (dependent) variable. This method is used to study how various types of diversities, intensity and other factors are related as shown in figure 1. Equation of the form given by equation 2 is one of the equation we used in the linear model and is as:

Energy flow diversity (EFD) = Energy source diversity (ESD) + Energy use diversity (EUD) + year (Y) + (ESD × EUD) + (ESD × Y) + (EUD × Y) *.....Equation 2*

Chapter 3

Results

3.1. Water Use Categories

In the U.S., the greatest percentages of water are used in thermoelectric category (40.6% in 2010) followed by Irrigation category (39.9% in 2010) and domestic category (9.3 % in 2010) (Figure A-1 and Table 3-1). Livestock water use has the lowest percentage (0.7 % in 2010) and only several states (Iowa, Kansas, South Dakota, Oklahoma, and Wisconsin) visibly show livestock water use in Figure A-1. Mining also has a very low percentage use (0.8 % in 2010) and again, only several states (Arkansas, Nevada, Minnesota, and South Dakota) visibly show mining water use in Figure A-1.

Aquaculture data are the least reliable. In 1995, USGS had a category of 'commercial use' which was later discontinued in future years. Commercial use included aquaculture and other uses such as motels and restaurants water uses. From 2000, motels and office buildings, and military and non-military institutions uses were not collected and the commercial use category was renamed as 'aquaculture'.

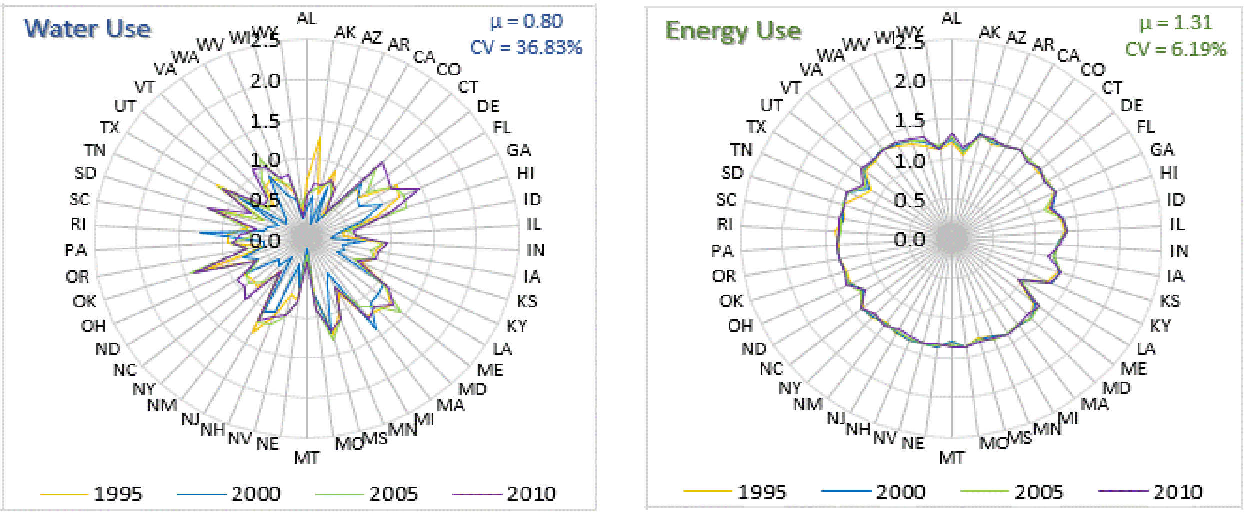
Table 3-1: Mean Water Use by Category with Coefficient of Variation (among 50 US States from 1995 to 2010).

Year		Domestic	Industrial	Thermoelectric	Mining	Irrigation	Aquaculture	Livestock
1995	Mean %	7.80	7.41	40.08	0.72	39.49	2.88	1.61
	CV	129.70	123.64	132.45	134.37	193.03	121.97	209.38
2000	Mean %	1.57	6.13	43.50	0.81	48.02	1.81	0.86
	CV	120.34	156.66	126.03	162.28	194.24	287.12	170.64
2005	Mean %	8.81	5.11	42.50	0.69	39.52	2.70	0.67
	CV	132.18	166.01	122.91	132.75	183.74	223.41	120.99
2010	Mean %	9.33	5.32	40.55	0.77	39.94	3.36	0.71
	CV	121.69	145.01	129.02	151.14	183.06	233.78	122.48

3.2. Comparison water use diversity to energy use diversity

The mean of water use diversity was 0.8 (Figure 3). Water use has higher (eight) number of categories than energy use (four), which would increase the diversity value. However, water use is much less evenly distributed than energy use resulting in the mean energy use diversity being much higher (1.31). The energy use diversity from my study is close to the energy use diversity values reported previously. Templet (2001) estimated the energy use diversity for all US states in 1995. The mean value calculated was 1.25, whereas the mean of energy use in my study for 1995 was 1.30. Lo (2011) reported 1.4 for energy use diversity in Japan for the period of 1987 to 2006. The energy use diversity from 1987 to 2006 for four Asian countries - Japan, Korea, Taiwan and Indonesia varied from 0.9 to 1.5 (Lo, 2011). Among these countries Indonesia changes from 0.9 to 1.5 while Korea (1.45) and Taiwan (1.3) don't vary much with years.

Water use diversity fluctuated a lot both temporally and across states (Compare figure 3-1.b to figure 3-1.a). This big contrast suggests that the energy use is much more stable than the water use system. In the U.S. most of the energy is used in secondary energy in the form of electricity with the exception of petroleum which is used primarily in transportation. The electrification and the nationwide electricity grid are possible reasons for energy diversity to not vary with time and across states. Electricity generation using variety of sources such as natural gas, oil, coal and nuclear as well as the fastest growing sources from renewable resources like solar and wind would bridge the gap created by the high and low fractional use of various resources. Also, as energy in the form of electricity can't be stored, they are produced and used as required by each state.



(a)

(b)

μ	0.84	0.63	0.86	0.89
CV	33.93	48.40	33.45	31.57

μ	1.30	1.31	1.32	1.32
CV	6.82	6.00	5.94	6.03

Figure 3-1: Water use diversity (a) and energy use diversity (b)

3.3. Temporal Variation of Water Use Diversity versus Intensity of Energy and Water

For many of the states the water use diversity increased from 2000 to 2010 (approx. 42% as mean of all states). The primary reason for the increase was the decrease in high use categories of thermoelectric and industrial and increase in low use categories of domestic and aquaculture. For example, the water use diversities in New York and North Carolina increased almost 130% from 2000 to 2010. During this period, thermoelectric use decreased from 88% to 59% of total water use in New York indicating more evenness of water use in various water use categories.

While the water use diversity increased in many states, there were several states that showed an opposite trend. Examples are Hawaii, Mississippi, South Carolina, Washington, Wyoming, etc. These are states that showed an increase in thermoelectric and irrigation use and a decrease in domestic and industrial use. For instance, the thermoelectric use in South Carolina increased from 3539 (79%) to 5504 (85%) MGD from 2005 to 2010. At the same time, the domestic and industrial use decreased from 418.7 MGD (9.3%) to 387.7 MGD (6%).

1995 is a peculiar year in the water use diversity analysis. Water use diversities of several states (more prominent in Florida and New Jersey) were quite higher in 1995 compared to 2010. In New Jersey, industrial water use decreased by 50%. Also, aquaculture was reported as commercial use in 1995 which included other commercial water uses such as motels, restaurants, offices, etc. making high water use. From 2000, commercial use included only aquaculture and was a separate category as aquaculture itself and had lower value and used in low proportion. Aquaculture use was approx. 0.5% of total water use, which makes the water use diversity lower from 2000 to 2010 compared to 1995. To clarify, in Ohio in 1995 commercial use was 423 MGD

(4% MGD) however, from 2000 it was reported as aquaculture and value is 1.4 (0.5%), 9.5 (0.1%), and 34.3 (0.4%) in 2000, 2005 and 2010 respectively.

3.4. Variation of Diversity among States

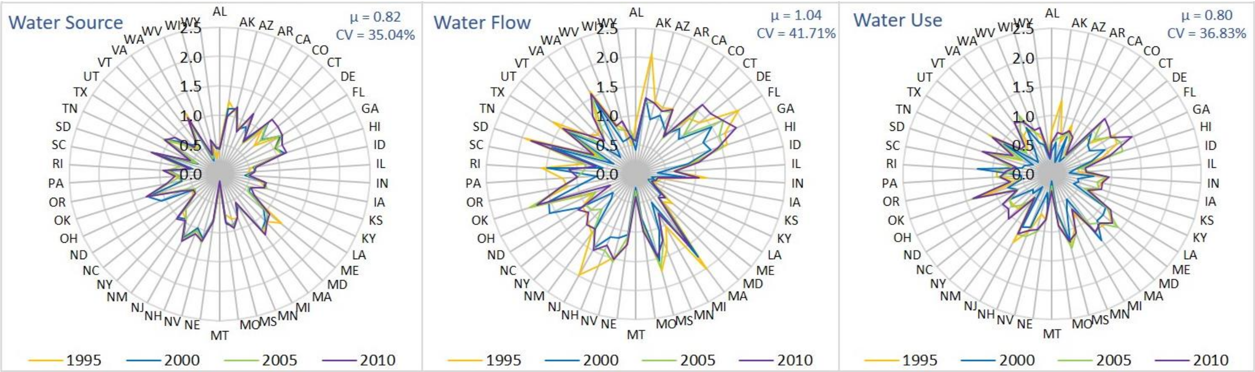
Water use diversity varied with a mean coefficient of variation of 33% across the states. To analyze the reasons behind the variation of diversity, I ran a linear model and included year and water use categories (domestic, industrial, thermoelectric, mining, irrigation, aquaculture, and livestock) on the diversity of water use (SI Table 25). I found that the major factor affecting the diversity of water use are domestic ($p<0.0001$), thermoelectric ($p<0.0001$) and irrigation ($p<0.0001$) categories. Based on the coefficients of the linear model, changes in domestic water (coefficient = 209) use increase and thermoelectric (coefficient = -49) and irrigation (Coefficient= -47) decrease the diversity. These effects are visible in Figure 2. For example in New Jersey, Maine, Massachusetts, and Maryland have high percentage of domestic water use and low percentage of thermoelectric water use resulting in water use diversity greater than one for these states. As a quantitative example, in 2010, the mean domestic water use was 9.3% and the mean thermoelectric water use was 40.6% for all states. The percentage of domestic water use is much higher in New Jersey (48 %), Massachusetts (55 %) and Maryland (50 %). The percentage of thermoelectric water use is much lower in New Jersey (37 %), Maine (8 %), Massachusetts (31 %), and Maryland (37 %). The effect of irrigation is best visible in Montana, Wyoming, Colorado and Idaho. In these states, the diversity value was less than 0.5 because the percentage of irrigation water use was very high (90% compared to 39.9% for all states).

3.5. Comparison of Water Use Diversity to Water Source Diversity

The primary water source in the U.S. is self-supplied surface water (66.9 % in 2010) followed by self-supplied ground water (19.7 % in 2010) (Figure 3-2 and Table 3-2). Public supply of surface water (8.4% in 2010) is greater than the public supplied ground water (5.1% in 2010). There were only four categories in water source which is fewer than the seven categories in the water use. Despite the lower number of categories, water source diversity (0.82) was similar to water use diversity (0.80) (Figure 3-2). The fewer number of categories that would have decreased diversity is counterbalanced by more evenness of these categories that resulted in very similar diversity values for both use and source.

Table 3-2: Mean Water Use by Category with Coefficient of Variation among 50 US States from 1995 to 2010.

Year		Public supplied Ground Water	Public supplied Surface Water	Self-supplied Ground Water	Self-supplied Surface Water
1995	Mean %	4.45	7.39	18.14	70.02
	CV	154.24	122.42	176.23	96.04
2000	Mean %	4.70	7.94	20.00	67.36
	CV	155.56	125.12	176.44	98.16
2005	Mean %	4.18	8.36	19.25	68.21
	CV	127.46	156.85	170.75	92.01
2010	Mean %	5.10	8.39	19.65	66.86
	CV	152.86	127.95	160.95	94.66



Water Source	1995	2000	2005	2010	Water Flow	1995	2000	2005	2010	Water Use	1995	2000	2005	2010
Mean	0.8	0.81	0.81	0.85	**Mean**	1.16	0.9	1.03	1.08	**Mean**	0.84	0.63	0.86	0.89
CV	36.51	34.46	34.69	34.51	**CV**	40.87	46.97	39.80	39.19	**CV**	33.93	48.4	33.45	31.57

Figure 3-2: Diversity of water source (a), flow (b), and use (c)

Water use was highly correlated with water source ($p<0.0001$ with $R^2 = 32.9\%$) (A-C, Table 13). As some examples, Nebraska has a low water use diversity (0.80) and water source diversity (0.75) while Oklahoma has high water use diversity (1.39) and high water source diversity (1.06). Similarly, Florida have high water use diversity (1.17) and water source diversity (1.09).

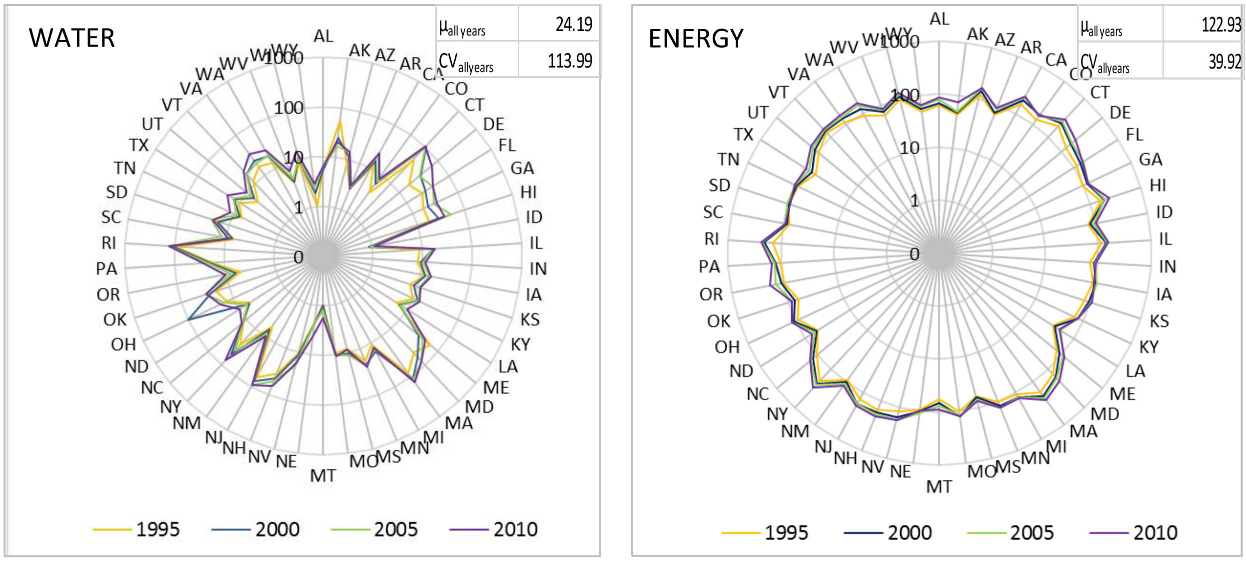
The relation between water use and water flow is further supported by the water flow diversity analysis. The linear model of water flow diversity with a water source, water use diversity shows the significant relation of water flow with a water source and use diversity ($R^2 = 57\%$) (A-C SI Table 9, 11, 12). There are a total of 28 categories that connect water use to water flow. Increase in flow diversity is directly related to the increase in source and use diversity as flow diversity comes from source to use. These higher number of categories can increase the diversity but since the flow is uneven, this decreases the diversity. The mean value of water flow diversity was 1.04 which is higher than the diversity of the source (0.80) or the use (0.82) for most of the states. This trend is however not followed by states such as Iowa, Kansas, Kentucky, Louisiana, Maine and Maryland because these states have uneven flow from source to use (A-C SI Table 1 & 2). Almost 50 to 80% of water flow is from self-supplied water sources to thermoelectric water use. The unevenness play a significant role to bring down the flow diversity in these five states although there are up to 28 possible flows from four sources to seven uses.

3.6. Comparison of Water Efficiency to Energy Efficiency

The mean water efficiency was $182.8/Mgal of water indicating that 182.4 $ of economic output can be generated for every million gallon of water used within the economy. Blackhurst (2010) reported a water intensity value of 1071 L/dollar (i.e. 283 Mgal/$). Inverting this value, I get 3533.6 $/Gal. Blackhurst's water efficiency value is higher than the value calculated in my study.

Assuming 2100kWh is needed to produce 1Mgal, the water efficiency expressed in terms of energy is $24.2/GJ from my study and $467.4/GJ from Blackhurst (2010). In other words, based on my analysis, 24.2 $ worth of economic output can be generated for every 1 GJ of energy that is used in producing water. A higher value of water efficiency indicates a higher economic output per unit of resource invested in water.

The water efficiency of $24.2/GJ was about 5 times lower than the energy efficiency $122.9/GJ. This could be attributed to higher losses in water use throughout the economy. For example, the energy loss in transmission and distribution is 5 % (USEIA). In contrast much higher losses are expected in irrigation and thermoelectric water use in which higher percentage of water are evaporated or infiltrated without benefiting the end product.



μ	100.48	119.61	130.96	140.67
CV	37.35	40.23	39.62	42.49

μ	24.19	24.48	25.47	28.66
CV	113.99	119.46	114.93	110.01

Figure 3-3: Energy and Water Efficiency ($/GJ)

Both the water and energy efficiency increased over years (figure 3-3). USGS has long documented that the US has become more efficient in its water use. In the U.S. total withdrawals have not changed much since 1980s while the population and economic output increased. This effect is also visible in my water efficiency calculation in which the water efficiency increased about 20 % from 1995 to 2010. The energy efficiency increased even more (40 %) during this period.

As in the diversity analysis, the efficiency analysis also showed a larger variation within water than in energy with CV (110 to 114 %) of water being more than twice as high as that of energy (37 to 43 %). Due to additional variability introduced from gross domestic product, the CV of water efficiency was also higher than that of CV of water use diversity (33%).

3.7. Water Efficient and Inefficient States

States like Idaho and Montana have lower water efficiency compared to other states because almost 85% and 97% of water is used in irrigation in Idaho and Montana respectively with lower economic output.

Water efficiency is the highest in Massachusetts ($136.42/GJ in 2010) and states like New Jersey ($90.9/GJ in 2010) and Rhode Island ($131.5/GJ in 2010) also have high water efficiency because of they use less water to produce same economic output.

3.8. Relation between Diversity and Efficiency

From figure 3-4 it is visible that water efficiency measured as $/GJ increases with increase in water use diversity. The R2 for the plot of water use diversity vs water efficiency is the highest in 2000 (0.35). Increase in diversity shows increase in efficiency except states such as Mississippi which has high water use diversity (1.19) in 2010 with low water efficiency ($8.86/GJ) when the mean water efficiency in 2010 for all states is $28.7/GJ. Besides, water use diversity, water source diversity also increases water efficiency (R2 = 0.27). Water system efficiency therefore is positively related to both water source and water use diversity.

In the energy system, energy use diversity has more impact on the energy efficiency (R^2 = 0.36) as seen from the figure 3-4. Increase in diversity in energy use categories increases the economic output as dollar per gigajoules of energy use. Energy source diversity show increasing energy efficiency with R^2 = 0.18 as of 1995.

The bottom figures of figure 3-4 shows sector energy use diversity vs energy efficiency and sector water use diversity vs water efficiency. Both energy and water use diversity in the sectors of US increase with efficiency ($R^2 = 0.45$ for energy system and $R^2 = 0.30$ for water system).

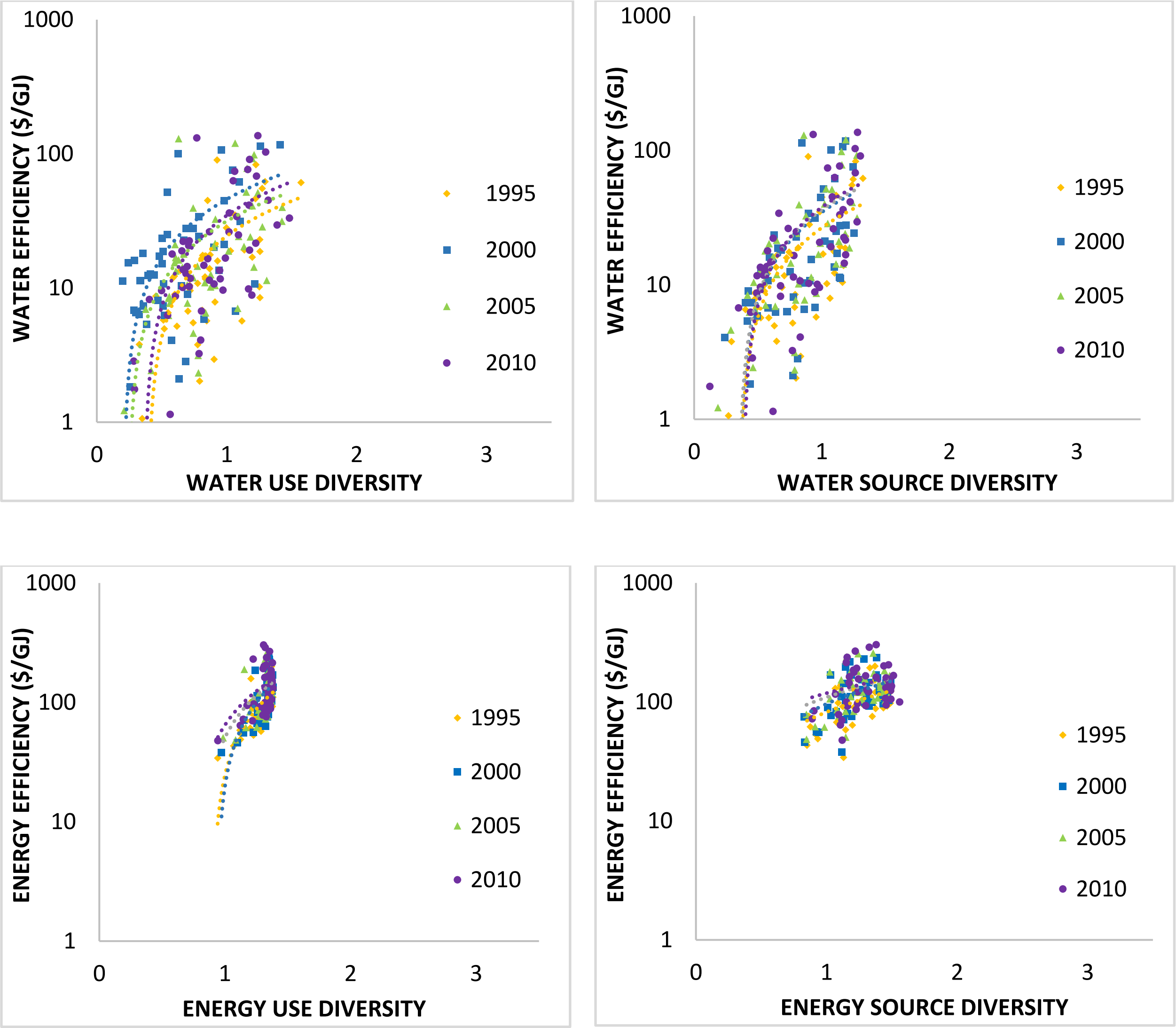


Figure 3-4: Relationship between Efficiency and Diversity of Water and Energy System in the US States.

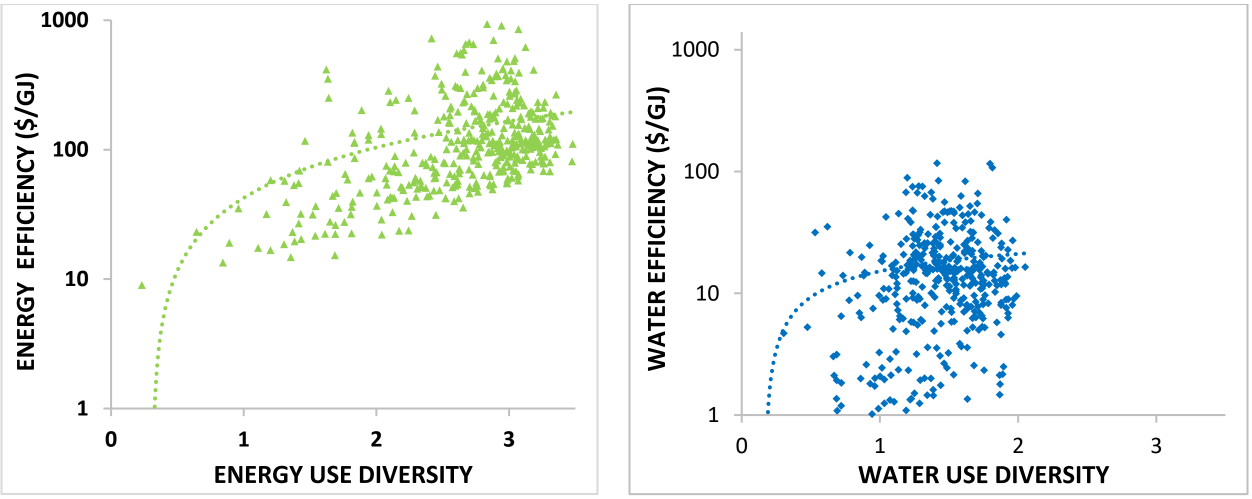


Figure 3-5: Relationship between Efficiency and Diversity of Water and Energy System of the US Sectors.

Chapter 4

Conclusion

For the first time, this study conceptualized and quantified the diversity of the water system in the U.S. The water use diversity (0.8) was found to be much lower than the energy use diversity (1.31). This is due to the uneven use of water across categories with thermoelectric (40.6% in 2010) and irrigation (39.9 % in 2010) dominating water use, followed by domestic water use (9.3 % in 2010) whereas other use categories of aquaculture, mining, livestock are relatively low (< 5 %). Water diversity fluctuated considerably both temporally and across states. This fluctuation is in big contrast to energy use that did not vary much temporally and across states. Based on the linear model, the differences in use of water in domestic, thermoelectric and irrigation categories are the primary reason for variation across states. Higher values of domestic and lower values of thermoelectric and irrigation even out the water use increasing diversity. The other use categories such as mining, industrial, aquaculture and livestock had minor impacts on water use diversity.

I found that the diversity in water system led to increase in water efficiency. Water use diversity (R^2 = 0.35) and water source diversity (R^2 = 0.27) were found to increase efficiency. States like Massachusetts have high water use diversity (1.24 in 2010), high water source diversity (1.30 in 2010) and therefore, the highest water efficiency ($136.42/GJ in 2010). Despite higher water use diversity, states such as Mississippi have lower water efficiency. This was because these states have low GDS than other states for the same amount of water used and although they have high water use diversity, water efficiency is low. Sectoral water use diversity was also seen to increase in water efficiency with $R^2 = 0.30$.

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Appendix A

Source and Use of Water in percentage

A.1 Water Use

Figure A-1: Water Use Percentages within the 50 US States from 1995 to 2010.

A.2 Water Use

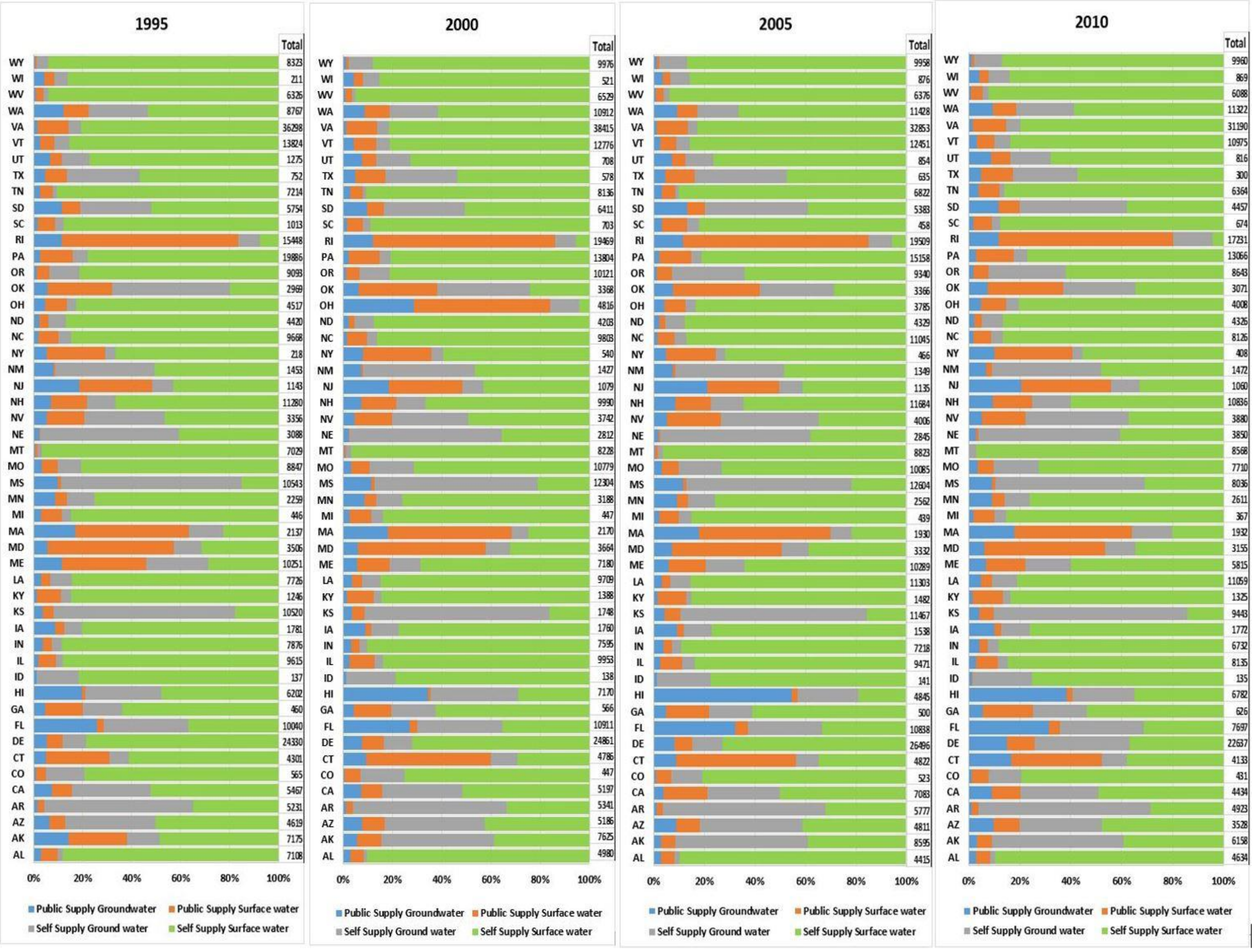


Figure A-2: Water source percentages of the states from 1995 to 2010

Appendix B

Change in diversity from 1995 to 2010

B.1. Water Footprint

Figure B-1 shows that water demand diversity has higher diversity in 1995 than in 2010 and water source diversity is almost equal in 1995 and 2010. Energy source diversity also has higher diversity in 2010 than 1995 while energy demand diversity also doesn't show much change from 1995 to 2010.

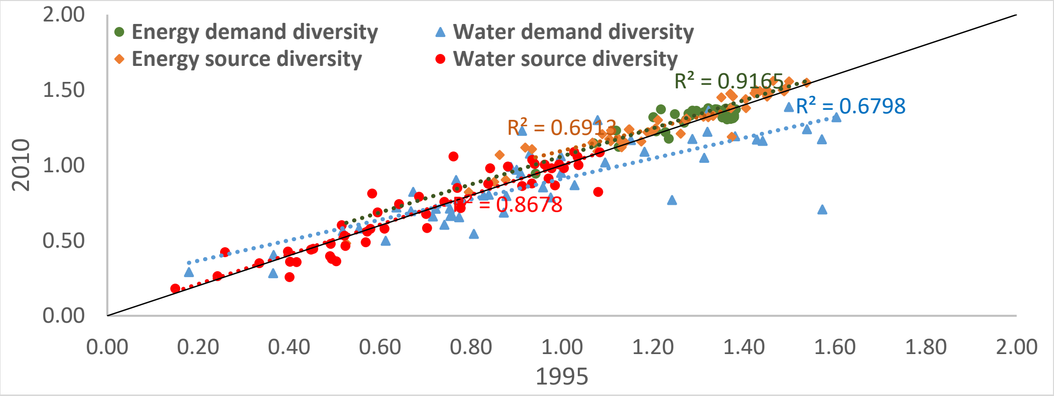


Figure B-1. Diversity comparison between 1995 and 2010

The states that showed very less diversity value are selected for further analysis as shown in table 2. The percentage change in diversity (H), energy use (E), energy intensity (I) has been calculated for two decades. During the decade of 1995 to 2005, there is a negative or very low increase in H (except Texas) with a decrease in energy consumption (except Louisiana). Louisiana shows an increase in both diversity and energy consumption and increased GSP. Other states had increased H and decreased me except for Hawaii which had a significant decrease in me despite a decrease in H. During the decade of 2005 to 2015, H increased for 3 states and decreased for 4 states. The negative value of E and I show that energy use and intensity decreased when % change in H was positive and vice-versa except for Texas where both H and E increase by slight % from 2005 to 2015. GSP was positive in all the states from 2005 to 2015 although the GSP values are expressed as current dollars. The US, as a nation, had slight (1.8 & 0.19) increase in H and GNP and high (35%) decrease in me over both the decades. The value of E was found to increase from 1995 to 2005 and decrease for 2005 to 2015. Even smaller percentage increase or decrease in the value of H, I, E and GNP produce significant absolute value and needs to be considered. GSP for states rose for all the states that increased or decreased their energy consumption. However, a decrease in energy use was related to GNP to rise more slowly over years (Templet, 2001). For bigger states, change in H was higher compared to an average of the change in H and change in E was smaller compared to the average change in E. This held true for both decades, however, was not followed by Texas for change in H in the decade of 2005 to 2015. This finding is similar to the analysis done by previous papers for developed and developing countries (Templet, 2001).

Table B-1. Changes in diversity, energy consumption and intensity by decade for selected states

State	% change from 1995 – 2005				% change from 2005-2015			
	H	E	I	GSP	H	E	I	GSP
Alaska	1.47	-13.28	-31.24	64.74	4.10	-22.30	-41.97	33.89
Hawaii	-4.40	9.29	-24.18	44.15	4.48	-13.03	-42.04	50.06
Iowa	-0.67	-14.80	-27.53	58.40	-5.48	18.92	-22.69	53.83
Louisiana	4.68	4.19	-34.26	45.75	-6.50	5.59	-26.24	43.15

North Dakota	2.10	-16.76	-28.79	63.95	-4.28	48.79	-35.68	131.31
Texas	7.21	-7.15	-43.78	90.60	1.30	8.32	-33.96	64.00
Wyoming	3.68	-13.06	-35.28	74.70	-4.80	14.84	-20.10	43.73

Table B-1 shows the value of diversity of energy and water in each state for the year 1995 and 2010. The change in the energy diversity in the fifteen-year period is almost negligible and there is no increasing or decreasing trend. The diversity values of water diversity are seen to be slightly lower (12%) than water diversity. The states such as Alaska, Maine, North Dakota, West Virginia and Wyoming have diversity index less than 1 and those states have higher energy intensity (more than average of all states i.e. 15.26 for 1995 and 9.44 for 2005). Hawaii and Rhode Island have low diversity index but have less energy intensity indicating that they are the most energy-efficient states. Both Hawaii and Rhode Island have least industrial energy use, Hawaii being a tourist attraction and not energy intensive, and 75% of the GSP in Rhode Island coming from service industries. Hawaii has also become the first state to set a deadline to make renewable sources as the only electricity producing source (U.S. EIA). Renewable energy as an alternative to conventional energy makes a system more diverse as it increases supply diversity (Lo, 2011). The main aim for the energy diversification is to achieve energy security, economic growth, and environmental protection in an integrated way and is considered by Li (2005) & Lo (2011) as the only feasible way for sustainable.

Table B-2. Energy and water source diversity of US states

STATE	ENERGY DIVERSITY		WATER DIVERSITY			STATE	ENERGY DIVERSITY		WATER DIVERSITY	
	1995	2010	1995	2010			1995	2010	1995	2010
Alabama	1.50	1.56	0.40	0.26		*Montana*	1.32	1.32	0.15	0.18
Alaska	0.85	0.89	0.98	0.87		*Nebraska*	1.46	1.56	0.78	0.75
Arizona	1.49	1.51	0.96	1.00		*Nevada*	1.26	1.21	1.04	1.00
Arkansas	1.54	1.55	0.78	0.71		*New Hampshire*	1.37	1.48	0.84	0.88

California	1.17	1.16	0.98	0.98	*New Jersey*	1.11	1.23	0.94	1.01
Colorado	1.21	1.24	0.61	0.58	*New Mexico*	1.15	1.24	0.91	0.86
Connecticut	1.33	1.33	0.84	0.98	*New York*	1.37	1.38	0.74	0.76
Delaware	1.07	1.15	0.76	1.06	*North Carolina*	1.45	1.48	0.50	0.36
Florida	1.37	1.19	1.08	1.09	*North Dakota*	0.92	1.12	0.45	0.45
Georgia	1.49	1.49	0.88	0.99	*Ohio*	1.31	1.32	0.52	0.46
Hawaii	0.53	0.48	1.03	1.09	*Oklahoma*	1.20	1.23	1.03	1.06
Idaho	1.14	1.15	0.52	0.60	*Oregon*	1.09	1.21	0.58	0.81
Illinois	1.46	1.48	0.40	0.43	*Pennsylvania*	1.42	1.48	0.57	0.49
Indiana	1.11	1.16	0.40	0.36	*Rhode Island*	0.79	0.82	0.64	0.74
Iowa	1.38	1.46	0.58	0.58	*South Carolina*	1.49	1.50	0.42	0.36
Kansas	1.35	1.45	0.70	0.68	*South Dakota*	1.27	1.30	1.00	0.98
Kentucky	1.08	1.09	0.49	0.38	*Tennessee*	1.44	1.49	0.33	0.35
Louisiana	1.13	1.12	0.52	0.53	*Texas*	1.15	1.24	0.93	0.88
Maine	0.86	1.07	1.08	0.82	*Utah*	1.13	1.17	0.69	0.79
Maryland	1.40	1.44	0.99	1.01	*Vermont*	1.10	1.18	0.49	0.48
Massachusetts	1.19	1.22	0.93	1.04	*Virginia*	1.45	1.46	0.57	0.56
Michigan	1.33	1.33	0.49	0.40	*Washington*	1.21	1.30	0.97	0.91
Minnesota	1.43	1.50	0.70	0.58	*West Virginia*	0.88	0.90	0.24	0.26
Mississippi	1.40	1.38	0.77	0.85	*Wisconsin*	1.45	1.49	0.45	0.44
Missouri	1.27	1.31	0.59	0.69	*Wyoming*	0.93	1.11	0.26	0.42

The water source diversity is seen to be decreasing in all the states from 1995 to 2005 except Connecticut, Hawaii, Idaho, Maine, North Dakota, Rhode Island, West Virginia and Wyoming. These are also the states with energy source diversity less than 1. The highest water diversity is seen in Louisiana (2.22 in 1995) and Oklahoma (1.86 in 2005). The diversity in Louisiana decreased to .95 (highest decrease among all states). This is because there are public supply deliveries for domestic, commercial and industrial sectors in 1995 but only for domestic sector in 2005 and no self-supply deliveries for the commercial sector in 2005. This is the reason why most of the states decreased diversity in 2005. Montana had the least diversity in both year 1995 and 2005. More than 95% of the total water withdrawal is from the self-supply deliveries used for irrigation. The water sources from diverse sources allow supply security and hence increase water productivity such that there is no limit in technological improvements and future strategies for reducing water use.

Table B-3. Energy and water demand diversity of US states

STATE	ENERGY DIVERSITY		WATER DIVERSITY	
	1995	2010	1995	2010
Alabama	1.20	1.32	0.81	0.54
Alaska	1.07	1.15	1.57	0.71
Arizona	1.36	1.35	0.67	0.69
Arkansas	1.28	1.34	0.98	0.79
California	1.33	1.33	0.72	0.71
Colorado	1.38	1.37	0.37	0.40
Connecticut	1.36	1.32	1.08	1.30
Delaware	1.32	1.38	0.91	1.23
Florida	1.35	1.32	1.43	1.17
Georgia	1.34	1.37	1.32	1.36
Hawaii	1.21	1.23	1.09	1.02
Idaho	1.33	1.35	0.52	0.56
Illinois	1.36	1.37	0.55	0.58
Indiana	1.27	1.28	1.00	0.95
Iowa	1.23	1.18	0.96	0.85
Kansas	1.34	1.37	0.88	0.80
Kentucky	1.27	1.30	0.76	0.67
Louisiana	0.94	0.94	1.15	1.17
Maine	1.25	1.34	1.60	1.32
Maryland	1.38	1.31	1.44	1.16
Massachusetts	1.36	1.35	1.54	1.24
Michigan	1.37	1.38	0.87	0.69
Minnesota	1.33	1.36	1.18	1.09
Mississippi	1.28	1.33	1.38	1.19
Missouri	1.37	1.37	0.77	0.90
Montana	1.29	1.36	0.18	0.29
Nebraska	1.38	1.32	0.83	0.80
Nevada	1.36	1.37	0.89	0.99
New Hampshire	1.37	1.33	1.31	1.05
New Jersey	1.36	1.30	1.57	1.17
New Mexico	1.31	1.35	0.61	0.50
New York	1.37	1.31	1.00	1.06
North Carolina	1.36	1.38	0.91	0.95
North Dakota	1.23	1.22	0.90	0.97
Ohio	1.33	1.37	0.77	0.65
Oklahoma	1.31	1.34	1.50	1.39
Oregon	1.36	1.37	0.75	0.71
Pennsylvania	1.34	1.37	1.03	0.87
Rhode Island	1.38	1.33	1.24	0.77
South Carolina	1.30	1.36	0.74	0.60
South Dakota	1.36	1.33	1.32	1.22
Tennessee	1.22	1.37	0.64	0.72
Texas	1.12	1.23	1.29	1.18
Utah	1.32	1.37	0.72	0.66
Vermont	1.33	1.35	0.75	0.66
Virginia	1.38	1.37	0.93	1.08
Washington	1.34	1.37	0.99	1.02
West Virginia	1.28	1.34	0.84	0.80
Wisconsin	1.20	1.32	0.67	0.82
Wyoming	1.12	1.12	0.36	0.28

B.1. Water and Energy Use

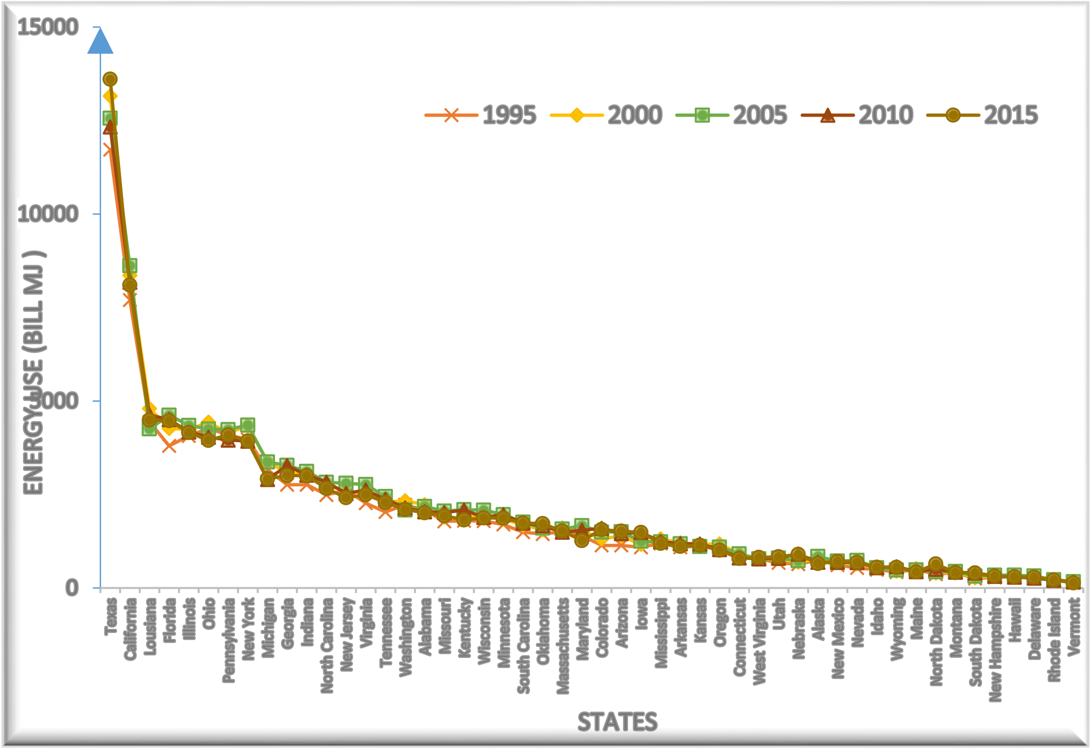


Figure B-2. Total energy use by US states over time (1995-2015)

The value of total energy use is the total energy coming from all the energy sources and which is also equal to the total energy used in all the US sectors. The data for this study is from the U.S. EIA which provides data as four main sectors as residential, commercial, industrial, and transportation. Total energy seem to be almost constant or fluctuating for most states except some which continually increased (Iowa, North Dakota, Oklahoma, South Dakota, Energy use increased from 1995 to 2005 for 47 states (decrease in Hawaii by 8%, Rhode Island by 11%) remained almost same or increased for all states from 2000 to 2005 except few states decreased (Louisiana by 11%, Washington by 11%). There was a decrease in energy use for most of the states from 2005 to 2010 (increase in North Dakota by 16%, Iowa by 18%, Nebraska by 24%, South Dakota by 25%) and 2010 to 2015(increase in Texas by 10% and North Dakota by 27%).California, Texas, and

Louisiana together accounted for 25% of total energy use in the US in all years under study. Total energy use in the US increased till 2005 then started to decrease till 2015 with a total of 7% increase from 1995 to 2015. Texas consumes more energy than any states for all the years since 3/10th of crude oil refining capacity and 1/4th of natural gas reserves of US is located in Texas. California, second largest energy consumer ranks third in petroleum refining capacity with least energy use per capita after Hawaii. The highest energy-consuming sector in Texas and California are industrial and transportation respectively. Both states have their energy coming from natural gas and petroleum (more than 80%) as seen in figure 3. Other bigger states such as Louisiana, Florida, Illinois, Ohio, Pennsylvania and New York have higher energy use. Most of these states have their highest fraction of energy coming from natural gas and petroleum and used highest in the industrial sector for most of the states.

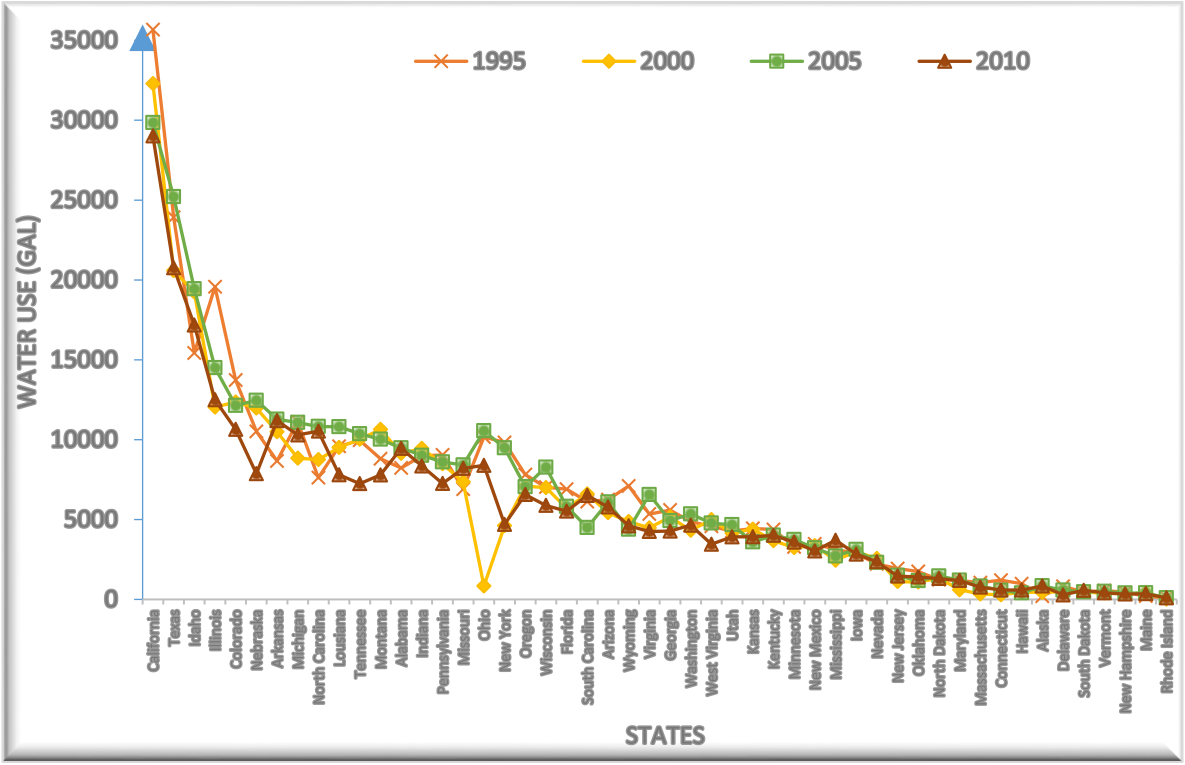


Figure B-3. Total energy use by US states over time (1995-2015)

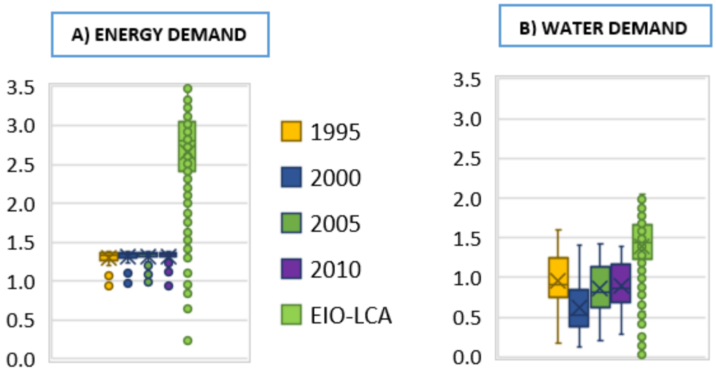


Figure B-4. Comparison of energy and water demand diversity of the 50 US states (1995 – 2010) and 426 US sectors of EIO-LCA

Figure B-5 shows US energy sources from five major categories for 50 states for the year 1995 and 2005. For most of the states, the energy comes from coal, natural gas, and petroleum and accounts for almost 80% of the total energy. States like Idaho, Maine, Oregon, South Dakota and Washington has more than 40% of energy coming from the renewables. The hydroelectric facility in Idaho provided by Hells Canyon dam system, hydroelectric dams, and wood biomass in Maine, hydroelectric power in Oregon and Washington, and wind and hydroelectric power in South Dakota provide around four-fifths of the renewables in the US (US EIA). Figure 3 doesn't show much difference between the energy use of 1995 and 2005.

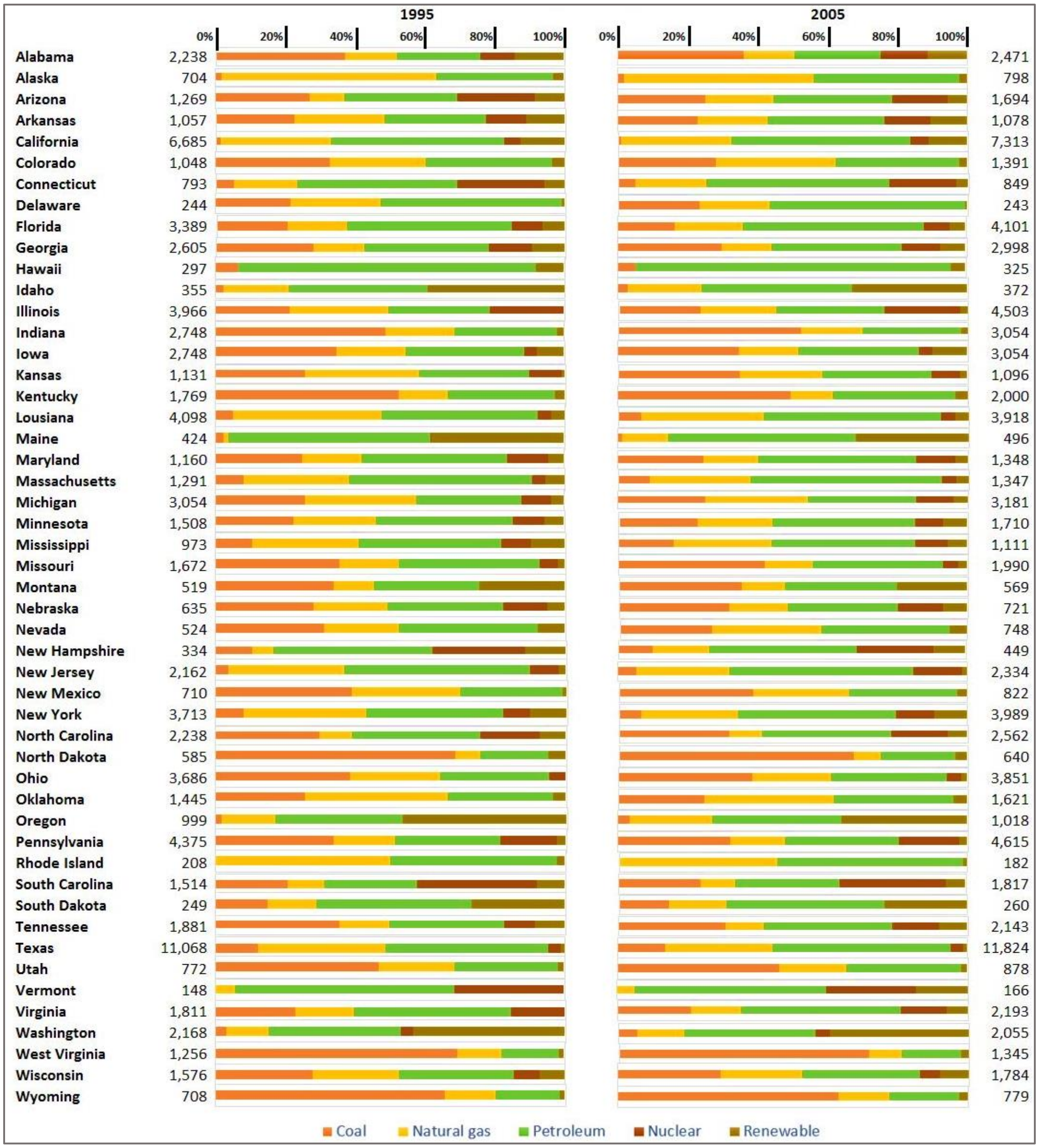


Figure B-5. Total energy use by sources of the US states over time (1995-2015)

Appendix C

Results of Linear Modeling Analysis

1. Water Flow Diversity = Energy Flow Diversity + Year

Table SI 1. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	216.924	216.924	1313.8	< 0.0001
EFw	1	5.3161	5.3161	32.197	< 0.0001
Yr	3	2.27808	0.75936	4.5991	0.0039
Error	195	32.1966	0.165111		
Total	199	39.3497			
R squared = 18.2% R squared (adjusted) = 17.8%					
s = 0.1719 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	1.30029	1	1.30029	44	< 0.0001
Residual	5.85275	198	0.0295593		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	0.852134	0.03103	27.5	< 0.0001	
WaterFlow	0.181781	0.02741	6.63	< 0.0001	

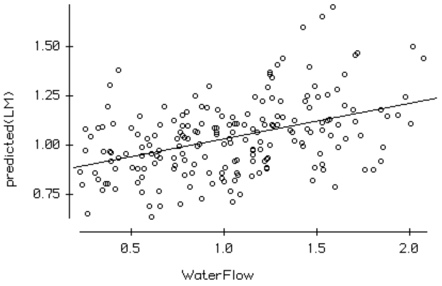


Fig SI 1 Actual value vs predicted values

2. Water Source Diversity = Energy Source Diversity + Year

Table SI 2. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	133.727	133.727	1602.1	< 0.0001
EnS	1	0.133648	0.133648	1.6012	0.2072
Yr	3	0.102972	0.0343241	0.41123	0.7451
Error	195	16.2761	0.0834673		
Total	199	16.4941			
R squared = 1.3% R squared (adjusted) = 0.8%					
s = 0.03296 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	0.00288153	1	0.00288153	2.65	0.105
Residual	0.215128	198	0.00108651		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	0.105
Intercept	0.806892	0.007034	115	< 0.0001	
WaterSource	0.0132174	0.008116	1.63	0.105	

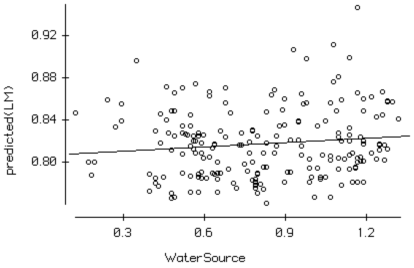


Fig SI 2 Actual value vs predicted values

3. Water Use Diversity = Energy Use Diversity + Year

Table SI 3. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	128.801	128.801	1512.5	< 0.0001
Enr	1	0.100822	0.100822	1.1839	0.2779
Yr	3	2.11256	0.704186	8.2691	< 0.0001
Error	195	16.606	0.085159		
Total	199	18.8151			
R squared = 11.7% R squared (adjusted) = 11.3%					
s = 0.09923 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	0.259382	1	0.259382	26.3	< 0.0001
Residual	1.94976	198	0.00984728		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	0.708276	0.01965	36	< 0.0001	
WaterUse	0.117413	0.02288	5.13	< 0.0001	

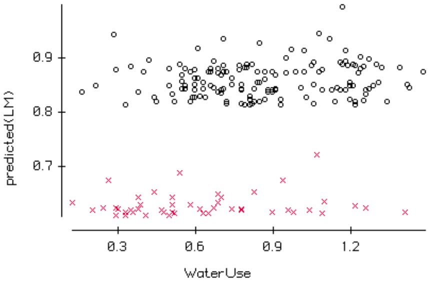


Fig SI 3 Actual value vs predicted values

4. Energy Flow Diversity = Energy Source Diversity + Energy Use Diversity + Year

Table SI 4. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	544.83	544.83	13318	< 0.0001
ESH	1	1.10862	1.10862	27.099	< 0.0001
EsH	1	0.0434614	0.0434614	1.0624	0.304
Yr	3	0.294895	0.0982984	2.4028	0.0689
Error	194	7.93642	0.0409094		
Total	199	9.70955			
R squared = 18.3% R squared (adjusted) = 17.8%					
s = 0.08556 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	0.323804	1	0.323804	44.2	< 0.0001
Residual	1.44933	198	0.00731983		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	1.34909	0.04572	29.5	< 0.0001	
EFlowH	0.182617	0.02746	6.65	< 0.0001	

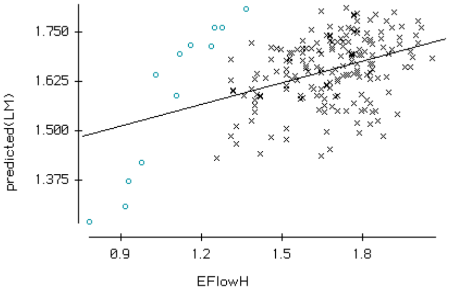


Fig SI 4 Actual value vs predicted values

5. Energy Source Diversity = Energy Use Diversity + Year

Table SI 5. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	309.532	309.532	7584.9	< 0.0001
EsH	1	1.36604	1.36604	33.474	< 0.0001
Yr	3	0.0697781	0.0232594	0.56996	0.6354
Error	195	7.95777	0.0408091		
Total	199	9.40462			
R squared = 15.4% R squared (adjusted) = 15.0%					
s = 0.07863 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	0.222589	1	0.222589	36	< 0.0001
Residual	1.22426	198	0.00618312		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	1.05266	0.03238	32.5	< 0.0001	
ESourceH	0.153844	0.02564	6	< 0.0001	

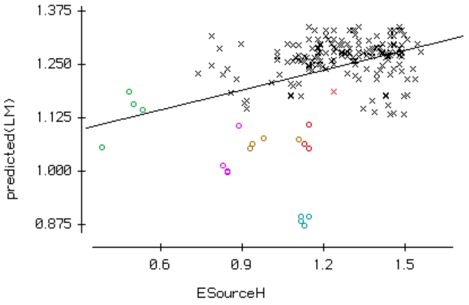
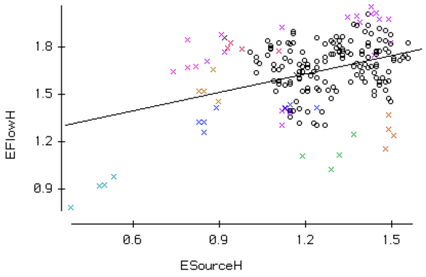


Fig SI 5 Actual value vs predicted values

6. Energy Flow Diversity VS Energy Source Diversity

Table SI 6. Result of linear model represented by equation 1

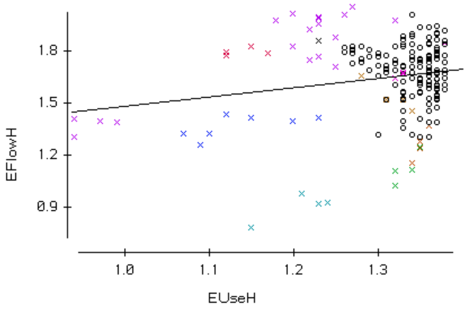


R squared = 14.9% R squared (adjusted) = 14.5%					
s = 0.2042 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	1.44993	1	1.44993	34.8	< 0.0001
Residual	8.25962	198	0.0417153		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	1.16203	0.0841	13.8	< 0.0001	
ESourceH	0.392647	0.0666	5.9	< 0.0001	

Fig SI 6 Actual value vs predicted values

7. Energy Flow Diversity VS Energy Use Diversity

Table SI 7. Result of linear model represented by equation 1

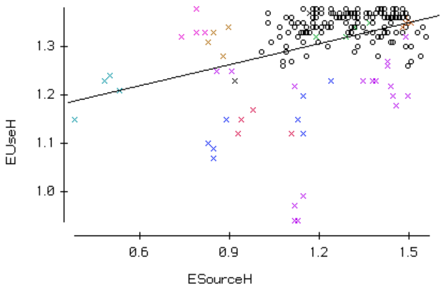


R squared = 3.9% R squared (adjusted) = 3.4%					
s = 0.2171 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Square	df	Mean Square	F-ratio	p-value
Regression	0.379718	1	0.379718	8.06	0.005
Residual	9.32983	198	0.0471204		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	0.005
Intercept	0.951013	0.2469	3.85	0.0002	
EUseH	0.53278	0.1877	2.84	0.005	

Fig SI 7 Actual value vs predicted values

8. Energy Source Diversity VS Energy Use Diversity

Table SI 8. Result of linear model represented by equation 1



R squared = 14.6% R squared (adjusted) = 14.2%					
s = 0.07594 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Square	df	Mean Square	F-ratio	p-value
Regression	0.195875	1	0.195875	34	< 0.0001
Residual	1.14184	198	0.00576688		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	1.13336	0.03127	36.2	< 0.0001	
ESourceH	0.144317	0.02476	5.83	< 0.0001	

Fig SI 8 Actual value vs predicted values

9. Water Flow Diversity = Water Source Diversity + Water Use Diversity + Year

Table SI 9. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	216.924	216.924	2479.1	< 0.0001
WSH	1	7.84218	7.84218	89.625	< 0.0001
WsH	1	1.31085	1.31085	14.981	0.0001
Yr	3	1.13021	0.376735	4.3055	0.0058
Error	194	16.975	0.0875002		
Total	199	39.3497			
R squared = 56.9% R squared (adjusted) = 56.6%					
s = 0.2208 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Square	df	Mean Square	F-ratio	p-value
Regression	12.7225	1	12.7225	261	< 0.0001
Residual	9.65218	198	0.0487484		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	4.49E-01	0.03984	1.13E+01	< 0.0001	
WFlowH	0.568611	0.0352	16.2	< 0.0001	

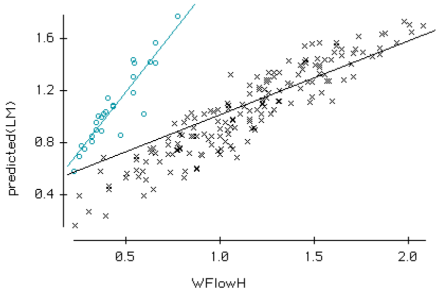


Fig SI 9 Actual value vs predicted values

10. Water Source Diversity = Water Use Diversity + Year

Table SI 10. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	133.727	133.727	2504.7	< 0.0001
WsH	1	5.99866	5.99866	112.35	< 0.0001
Yr	3	0.597749	0.19925	3.7319	0.0122
Error	195	10.4111	0.0533903		
Total	199	16.4941			
R squared = 36.9% R squared (adjusted) = 36.6%					
s = 0.1393 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	2.24341	1	2.24341	116	< 0.0001
Residual	3.83961	198	0.019392		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	0.516133	0.02972	17.4	< 0.0001	
WSourceH	0.368799	0.03429	10.8	< 0.0001	

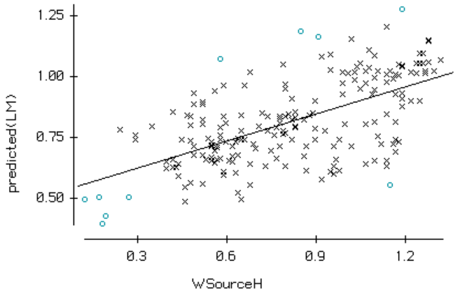
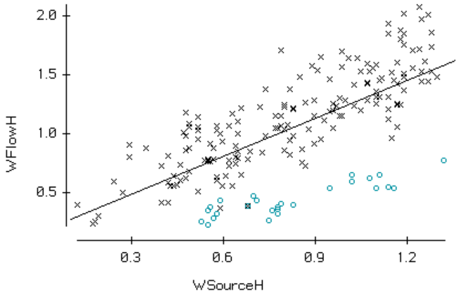


Fig SI 10 Actual value vs predicted values

11. Water Flow Diversity VS Water Source Diversity

Table SI 11. Result of linear model represented by equation 1

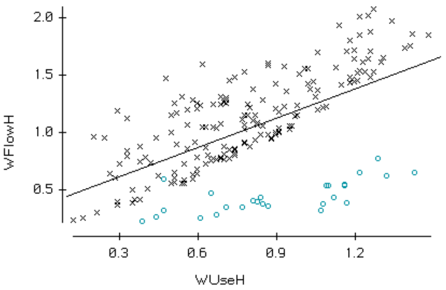


R squared = 48.5% R squared (adjusted) = 48.2%					
s = 0.3199 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	19.0816	1	19.0816	186	< 0.0001
Residual	20.2681	198	0.102364		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	0.161948	0.06827	2.37	0.0186	
WSourceH	1.07558	0.07878	13.7	< 0.0001	

Fig SI 11 Actual value vs predicted values

12. Water Flow Diversity VS Water Use Diversity

Table SI 12. Result of linear model represented by equation 1

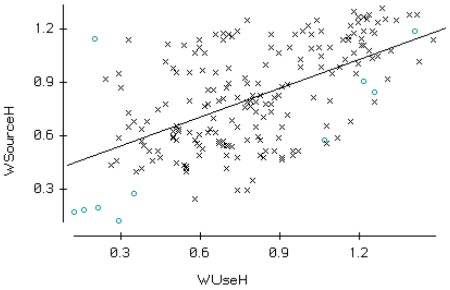


R squared = 35.2% R squared (adjusted) = 34.9%					
s = 0.3589 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	13.8426	1	13.8426	107	< 0.0001
Residual	25.5071	198	0.128824		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	0.353115	0.07109	4.97	< 0.0001	
WUseH	0.857738	0.08275	10.4	< 0.0001	

Fig SI 12 Actual value vs predicted values

13. Water Source Diversity VS Water Use Diversity

Table SI 13. Result of linear model represented by equation 1



R squared = 33.3% R squared (adjusted) = 32.9%					
s = 0.2358 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	5.48528	1	5.48528	98.7	< 0.0001
Residual	11.0089	198	0.0556003		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	< 0.0001
Intercept	0.384398	0.0467	8.23	< 0.0001	
WUseH	0.53994	0.05436	9.93	< 0.0001	

Fig SI 13 Actual value vs predicted values

14. Energy Amount = State Population + Year + Energy Category

Table SI 14. Result of linear model represented by equation 1

Source	df	Sums of Square	Mean Square	F-ratio	P-value
Intercept	1	3.32E+08	3.32E+08	1718.9	< 0.0001
Pop	1	2.62E+08	2.62E+08	1359.5	< 0.0001
Yr	3	362326	120775	0.62602	0.5982
CCp	8	6.63E+07	8.29E+06	42.947	< 0.0001
Error	1787	3.45E+08	192926		
Total	1799	6.74E+08			
R squared = 48.8% R squared (adjusted) = 48.8%					
s = 306 with 1800 - 2 = 1798 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	1.61E+08	1	1.61E+08	1.72E+03	< 0.0001
Residual	1.68E+08	1798	93628.7		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	219.633	8.81	24.9	< 0.0001	
Amt	0.488297	0.01179	41.4	< 0.0001	

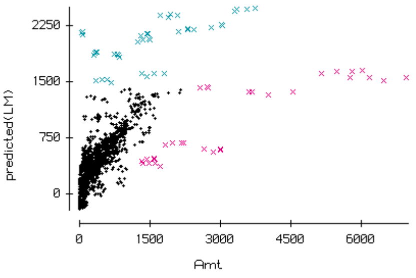


Fig SI 14 Actual value vs predicted values

15. Water Amount = State Population + Year + Category

Table SI 15. Result of linear model represented by equation 1

Source	df	Sums of Square	Mean Square	F-ratio	P-value
Intercept	1	3.00E+09	3.00E+09	626.24	< 0.0001
Pop	1	1.44E+09	1.44E+09	300.46	< 0.0001
Yr	3	17331600	5777200	1.2041	0.3068
CCp	10	4.20E+09	4.20E+08	87.612	< 0.0001
Error	2185	1.05E+10	4797970		
Total	2199	1.61E+10			
R squared = 35.0% R squared (adjusted) = 35.0%					
s = 1293 with 2200 - 2 = 2198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	1.98E+09	1	1.98E+09	1.19E+03	< 0.0001
Residual	3.67E+09	2198	1670820		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	759.269	30.01	25.3	< 0.0001	
Amt	0.350306	0.01018	34.4	< 0.0001	

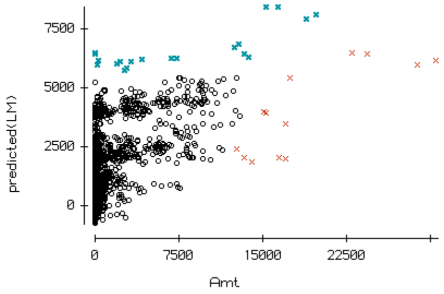


Fig SI 15 Actual value vs predicted values

16. Energy Intensity = Energy Source Diversity + Energy Flow Diversity + Saturation

Table SI 16. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	22813.1	22813.1	830.41	< 0.0001
SrH	1	239.268	239.268	8.7095	0.0036
FlH	1	50.0472	50.0472	1.8218	0.1787
Stn	1	178.773	178.773	6.5075	0.0115
Error	196	5384.52	27.472		
Total	199	5919.2			
R squared = 9.0% R squared (adjusted) = 8.6%					
s = 1.567 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	48.2975	1	48.2975	19.7	< 0.0001
Residual	486.382	198	2.45648		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	9.71541	0.2442	39.8	< 0.0001	
Int	0.0903298	0.02037	4.43	< 0.0001	

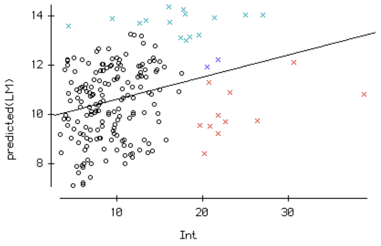


Fig SI 16 Actual value vs predicted values

17. Energy Intensity = Energy Use Diversity + Energy Flow Diversity + Saturation

Table SI 17. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	22813.1	22813.1	1632.8	< 0.0001
UsH	1	2885.28	2885.28	206.51	< 0.0001
FlH	1	164.648	164.648	11.784	0.0007
Stn	1	92.3745	92.3745	6.6114	0.0109
Error	196	2738.5	13.972		
Total	199	5919.2			
R squared = 53.7% R squared (adjusted) = 53.5%					
s = 2.726 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	1709.15	1	1709.15	230	< 0.0001
Residual	1471.54	198	7.43202		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	4.94115	0.4247	11.6	< 0.0001	
Int	0.537352	0.03543	15.2	< 0.0001	

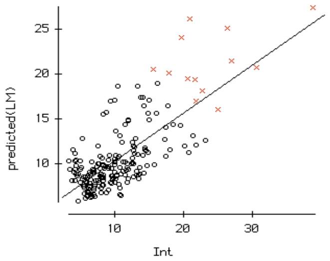


Fig SI 17 Actual value vs predicted values

18. Water Intensity = Water Source Diversity + Water Flow Diversity + Saturation

Table SI 18. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	62171.1	62171.1	105.46	< 0.0001
SrH	1	21348.8	21348.8	36.212	< 0.0001
FlH	1	583.459	583.459	0.98967	0.3211
Stn	1	72.439	72.439	0.12287	0.7263
Error	196	115552	589.551		
Total	199	148064			
R squared = 22.0% R squared (adjusted) = 21.6%					
s = 11.32 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	7138.84	1	7138.84	55.7	< 0.0001
Residual	25372.7	198	128.145		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	13.7597	0.9538	14.4	< 0.0001	
Int	0.219578	0.02942	7.46	< 0.0001	

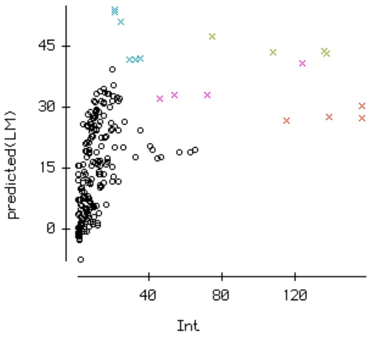


Fig SI 18 Actual value vs predicted values

19. Water Intensity = Water Use Diversity + Water Flow Diversity + Saturation

Table SI 19. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	62171.1	62171.1	101.18	< 0.0001
FlH	1	10.8877	10.8877	0.017719	0.8942
UsH	1	16464.9	16464.9	26.795	< 0.0001
Stn	1	198.184	198.184	0.32253	0.5707
Error	196	120436	614.469		
Total	199	148064			
R squared = 18.7% R squared (adjusted) = 18.2%					
s = 10.65 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	5155.16	1	5155.16	45.4	< 0.0001
Residual	22472.6	198	113.498		
R squared = 18.7% R squared (adjusted) = 18.2%					
s = 10.65 with 200 - 2 = 198 degrees of freedom					
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	14.3412	0.8976	16	< 0.0001	
Int	0.186594	0.02769	6.74	< 0.0001	p-value

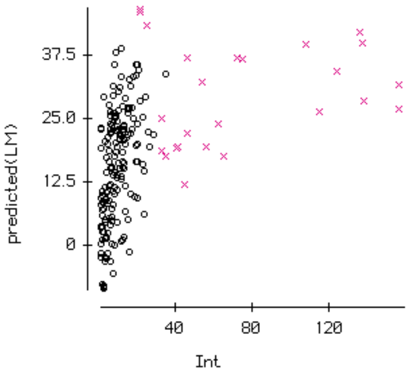


Fig SI 19 Actual value vs predicted values

20. Energy Source Amount = GDS + State Population + Year

Table SI 20. Result of linear model represented by equation 1

Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	7.47E+08	7.47E+08	679.32	< 0.0001
GDS	1	4.86E+06	4.86E+06	4.4187	0.0368
Pop	1	5.61E+08	5.61E+08	509.53	< 0.0001
Yr	3	1.63E+06	543119	0.49363	0.6871
Error	194	2.13E+08	1.10E+06		
Total	199	7.77E+08			
R squared = 72.5% R squared (adjusted) = 72.4%					
s = 884.2 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	4.09E+08	1	4.09E+08	523	< 0.0001
Residual	1.55E+08	198	781820		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	531.163	87.58	6.06	< 0.0001	
Amt	0.725235	0.03172	22.9	< 0.0001	

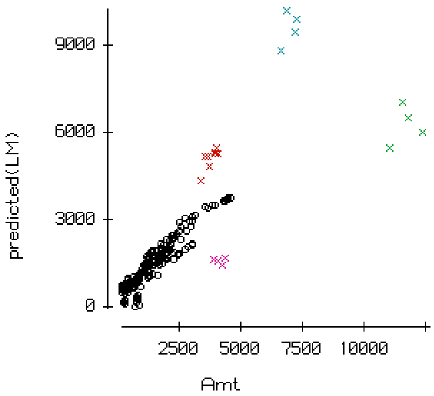
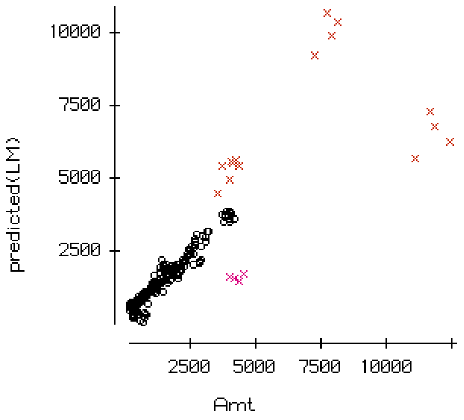


Fig SI 20 Actual value vs predicted values

21. Energy Use Amount = GDS + State Population + Year

Table SI 21. Result of linear model represented by equation 1

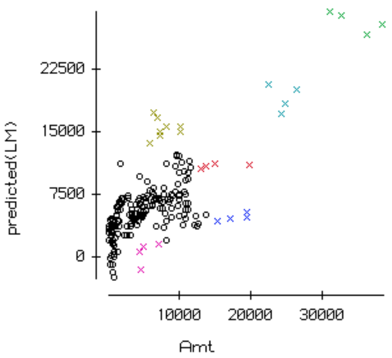


Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	7.46E+08	7.46E+08	744.26	< 0.0001
GDS	1	2.71E+06	2.71E+06	2.7083	0.1014
Pop	1	6.26E+08	6.26E+08	624.93	< 0.0001
Yr	3	1.16E+06	386626	0.3858	0.7633
Error	194	1.94E+08	1.00E+06		
Total	199	8.26E+08			
R squared = 76.5% R squared (adjusted) = 76.3%					
s = 866.5 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	4.83E+08	1	4.83E+08	643	< 0.0001
Residual	1.49E+08	198	750807		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	454.472	84.52	5.38	< 0.0001	
Amt	0.764659	0.03015	25.4	< 0.0001	

Fig SI 21 Actual value vs predicted values

22. Water Source Amount = GDS + State Population + Year

Table SI 22. Result of linear model represented by equation 1

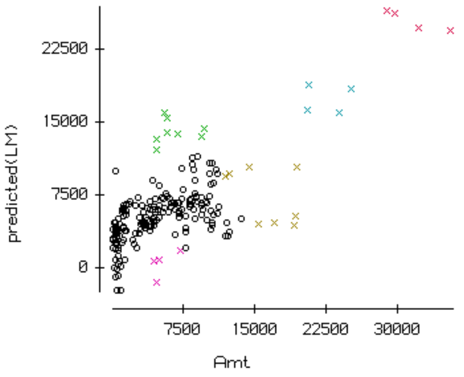


Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	8.81E+09	8.81E+09	491.25	< 0.0001
Yr	3	7.25E+07	2.42E+07	1.3482	0.26
GDS	1	3.99E+08	3.99E+08	22.259	< 0.0001
Pop	1	4.73E+09	4728840000	263.79	< 0.0001
Error	194	3.48E+09	1.79E+07		
Total	199	8.32E+09			
R squared = 58.2% R squared (adjusted) = 58.0%					
s = 3198 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	2.82E+09	1	2.82E+09	276	< 0.0001
Residual	2.02E+09	198	10225100		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	2772.79	324.4	8.55	< 0.0001	
Amt	0.582142	0.03505	16.6	< 0.0001	

Fig SI 22 Actual value vs predicted values

23. Water Use Amount = GDS + State Population + Year

Table SI 23. Result of linear model represented by equation 1



Source	df	Sums of Squares	Mean Square	F-ratio	P-value
Intercept	1	7.74E+09	7.74E+09	437.16	< 0.0001
Yr	3	5.80E+07	1.93E+07	1.0916	0.3538
Pop	1	3.81E+09	3.81E+09	215.12	< 0.0001
GDS	1	3.98E+08	397669000	22.47	< 0.0001
Error	194	3.43E+09	1.77E+07		
Total	199	7.39E+09			
R squared = 53.5% R squared (adjusted) = 53.3%					
s = 3046 with 200 - 2 = 198 degrees of freedom					
Source	Sum of Squares	df	Mean Square	F-ratio	p-value
Regression	2.12E+09	1	2.12E+09	228	< 0.0001
Residual	1.84E+09	198	9280380		
Variable	Coefficient	SE(Coeff)	t-ratio	p-value	
Intercept	2891	308.2	9.38	< 0.0001	
Amt	0.535185	0.03545	15.1	< 0.0001	

Fig SI 23 Actual value vs predicted values

Table C-24: Multiple comparison by ANOVA (Mean difference by year; Turkey HSD; Mean difference is significant at 0.05 level)

Dependent Variable			Mean Difference (I-	Std. Error	Sig.	95% Confidence Interval	
						Lower	Upper
Water Flow	1995	2000	.26540*	0.08750	0.014	0.0387	0.4921
		2005	0.13420	0.08750	0.419	-0.0925	0.3609
		2010	0.08820	0.08750	0.745	-0.1385	0.3149
	2000	1995	-.26540*	0.08750	0.014	-0.4921	-0.0387
		2005	-0.13120	0.08750	0.440	-0.3579	0.0955
		2010	-0.17720	0.08750	0.182	-0.4039	0.0495
	2005	1995	-0.13420	0.08750	0.419	-0.3609	0.0925
		2000	0.13120	0.08750	0.440	-0.0955	0.3579
		2010	-0.04600	0.08750	0.953	-0.2727	0.1807
	2010	1995	-0.08820	0.08750	0.745	-0.3149	0.1385
		2000	0.17720	0.08750	0.182	-0.0495	0.4039
		2005	0.04600	0.08750	0.953	-0.1807	0.2727
Water Source	1995	2000	-0.01480	0.05787	0.994	-0.1648	0.1352
		2005	-0.01380	0.05787	0.995	-0.1638	0.1362
		2010	-0.05500	0.05787	0.778	-0.2050	0.0950
	2000	1995	0.01480	0.05787	0.994	-0.1352	0.1648
		2005	0.00100	0.05787	1.000	-0.1490	0.1510
		2010	-0.04020	0.05787	0.899	-0.1902	0.1098
	2005	1995	0.01380	0.05787	0.995	-0.1362	0.1638
		2000	-0.00100	0.05787	1.000	-0.1510	0.1490
		2010	-0.04120	0.05787	0.892	-0.1912	0.1088
	2010	1995	0.05500	0.05787	0.778	-0.0950	0.2050
		2000	0.04020	0.05787	0.899	-0.1098	0.1902
		2005	0.04120	0.05787	0.892	-0.1088	0.1912
Water Use	1995	2000	.20860*	0.05839	0.002	0.0573	0.3599
		2005	-0.01940	0.05839	0.987	-0.1707	0.1319
		2010	-0.05360	0.05839	0.795	-0.2049	0.0977
	2000	1995	-.20860*	0.05839	0.002	-0.3599	-0.0573
		2005	-.22800*	0.05839	0.001	-0.3793	-0.0767
		2010	-.26220*	0.05839	0.0001	-0.4135	-0.1109
	2005	1995	0.01940	0.05839	0.987	-0.1319	0.1707
		2000	.22800*	0.05839	0.001	0.0767	0.3793
		2010	-0.03420	0.05839	0.936	-0.1855	0.1171
	2010	1995	0.05360	0.05839	0.795	-0.0977	0.2049
		2000	.26220*	0.05839	0.000	0.1109	0.4135
		2005	0.03420	0.05839	0.936	-0.1171	0.1855
Energy Flow	1995	2000	0.04240	0.04399	0.770	-0.0716	0.1564
		2005	0.08300	0.04399	0.237	-0.0310	0.1970
		2010	0.07980	0.04399	0.270	-0.0342	0.1938
	2000	1995	-0.04240	0.04399	0.770	-0.1564	0.0716
		2005	0.04060	0.04399	0.793	-0.0734	0.1546
		2010	0.03740	0.04399	0.830	-0.0766	0.1514
	2005	1995	-0.08300	0.04399	0.237	-0.1970	0.0310
		2000	-0.04060	0.04399	0.793	-0.1546	0.0734
		2010	-0.00320	0.04399	1.000	-0.1172	0.1108
	2010	1995	-0.07980	0.04399	0.270	-0.1938	0.0342
		2000	-0.03740	0.04399	0.830	-0.1514	0.0766
		2005	0.00320	0.04399	1.000	-0.1108	0.1172
Energy Source	1995	2000	0.00340	0.04362	1.000	-0.1096	0.1164
		2005	0.00700	0.04362	0.999	-0.1060	0.1200
		2010	-0.04260	0.04362	0.763	-0.1556	0.0704
	2000	1995	-0.00340	0.04362	1.000	-0.1164	0.1096
		2005	0.00360	0.04362	1.000	-0.1094	0.1166
		2010	-0.04600	0.04362	0.717	-0.1590	0.0670
	2005	1995	-0.00700	0.04362	0.999	-0.1200	0.1060
		2000	-0.00360	0.04362	1.000	-0.1166	0.1094
		2010	-0.04960	0.04362	0.667	-0.1626	0.0634

	2010	1995	0.04260	0.04362	0.763	-0.0704	0.1556
		2000	0.04600	0.04362	0.717	-0.0670	0.1590
		2005	0.04960	0.04362	0.667	-0.0634	0.1626
Energy Use	1995	2000	-0.01440	0.01645	0.818	-0.0570	0.0282
		2005	-0.01800	0.01645	0.694	-0.0606	0.0246
		2010	-0.01920	0.01645	0.648	-0.0618	0.0234
	2000	1995	0.01440	0.01645	0.818	-0.0282	0.0570
		2005	-0.00360	0.01645	0.996	-0.0462	0.0390
		2010	-0.00480	0.01645	0.991	-0.0474	0.0378
	2005	1995	0.01800	0.01645	0.694	-0.0246	0.0606
		2000	0.00360	0.01645	0.996	-0.0390	0.0462
		2010	-0.00120	0.01645	1.000	-0.0438	0.0414
	2010	1995	0.01920	0.01645	0.648	-0.0234	0.0618
		2000	0.00480	0.01645	0.991	-0.0378	0.0474
		2005	0.00120	0.01645	1.000	-0.0414	0.0438

Appendix D

Water and energy demand diversity of the US sectors

Comparison between water and energy demand is presented in Figure D.1.

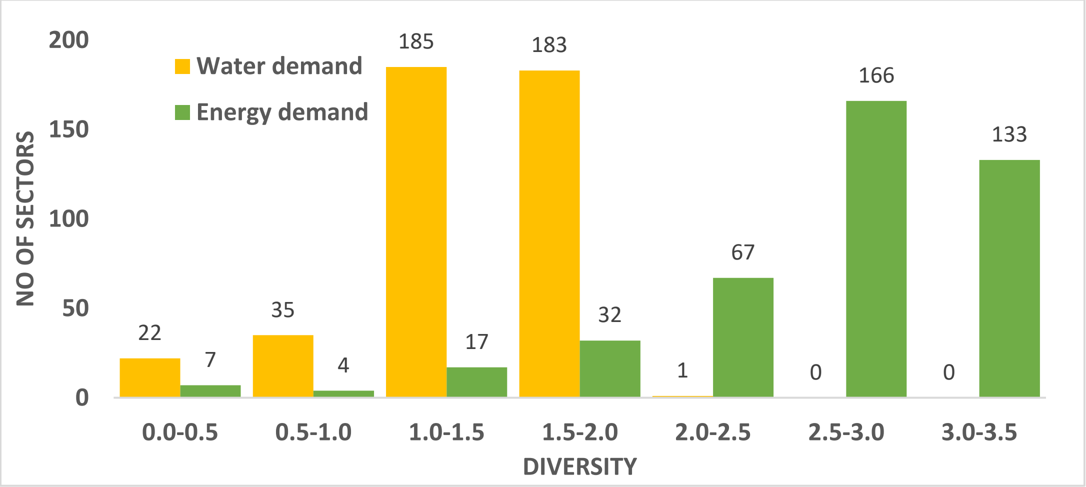


Figure D-1: Comparison of Water and energy demand diversity of the US sectors

Figure D-1 shows the diversity values of water and energy demand calculated for the 426 sectors that exist in EIO-LCA database. Most of the sectors have the water demand diversity between 1.0 to 2.0, and energy demand diversity between 2.5 to 3.5, respectively. The mean of diversity values of water and energy demand of all the US sectors are 1.37 and 2.62, respectively.

Among all economic sectors, the agricultural sector is seen to have the highest water use due to increasing population responsible for the high-water withdrawal (Duarte, 2014).

Table D-1. Top 10 and bottom 10 energy diverse sectors of the US

Top 10	Energy use diversity	Energy intensity TJ/mill$)	% contribution to total US energy consumption	Bottom 10	Energy use diversity	Energy intensity (TJ/mill$)	% contribution to total US energy consumption
Motor home manufacturing	3.48	9.01	0.17	Power generation and supply	0.23	111.00	2.04
Seasoning and dressing manufacturing	3.47	12.30	0.23	Water transportation	0.65	43.10	0.80
Upholstered household furniture manufacturing	3.37	9.14	0.17	Cement manufacturing	0.84	74.40	1.37
Mattress manufacturing	3.36	8.24	0.15	Pipeline transportation	0.89	52.30	0.97
Internet publishing and broadcasting	3.36	3.75	0.07	Air transportation	0.96	28.40	0.52
Manufactured home, mobile home, manufacturing	3.35	10.80	0.20	Paperboard mills	1.11	57.40	1.06
Electro medical apparatus manufacturing	3.35	5.52	0.10	Brick, tile and other structural clay product manufacturing	1.17	31.40	0.58
Boat building	3.34	8.34	0.15	Carbon black manufacturing	1.20	59.70	1.10
Laboratory apparatus and furniture manufacturing	3.33	6.53	0.12	Couriers and messengers	1.20	17.20	0.32
Computer terminals and another computer peripheral equipment manufacturing	3.32	5.41	0.10	Iron ore mining	1.30	53.70	1..00

The low water demand diversity values indicate that the economic activities of most US sectors heavily depend on a large amount of water consumed in certain sectors; thus, they signify a vulnerability due to dependence on very few sectors for water. For example, grain farming, and other agricultural sectors are those sectors that consume a high amount of water to create unit economic activity. Power generation and supply have the lowest water diversity among all the sector with a value of 0.026. Almost 100% of water use in this sector comes from the direct water power generation and supply, unlike other sectors that have high water use diversities. The most diverse sector in terms of water use, residential maintenance, and repair, has the direct water use of 3%. An analysis of the less-diverse sectors indicates that these sectors are uninvolved/or transparent industries which produce intermediate goods for certain larger sectors. For example, power generation & supply and cotton farming were found to be the most water consuming sector though it had the lowest water use diversity (0.026 and 0.148 respectively). This industry requires large amounts of water to produce cotton and the product is supplied to the textile sector as an input. Since mostly the sectors that have low diversity use high resources, it reveals that diverse water use among sectors may result in lower water consumption. This implies that water is either cheap or not used strategically in the production of high-value products. Among all economic sectors, the agricultural sector is seen to have the highest water use due to increasing population responsible for the high-water withdrawal (Duarte, 2014).

Table D-2. Top 10 and bottom 10 sectors with lowest water diversity values

Top 10	Energy use diversity	Energy intensity TJ/mill$)	% contribution to total US energy consumption	Bottom 10	Energy use diversity	Energy intensity (TJ/mill$)	% contribution to total US energy consumption
Motor home manufacturing	3.48	9.01	0.17	Power generation and supply	0.23	111.00	2.04
Seasoning and dressing manufacturing	3.47	12.30	0.23	Water transportation	0.65	43.10	0.80
Upholstered household furniture manufacturing	3.37	9.14	0.17	Cement manufacturing	0.84	74.40	1.37
Mattress manufacturing	3.36	8.24	0.15	Pipeline transportation	0.89	52.30	0.97
Internet publishing and broadcasting	3.36	3.75	0.07	Air transportation	0.96	28.40	0.52

Manufactured home, mobile home, manufacturing	3.35	10.80	0.20	Paperboard mills	1.11	57.40	1.06
Electro medical apparatus manufacturing	3.35	5.52	0.10	Brick, tile and other structural clay product manufacturing	1.17	31.40	0.58
Boat building	3.34	8.34	0.15	Carbon black manufacturing	1.20	59.70	1.10
Laboratory apparatus and furniture manufacturing	3.33	6.53	0.12	Couriers and messengers	1.20	17.20	0.32
Computer terminals and another computer peripheral equipment manufacturing	3.32	5.41	0.10	Iron ore mining	1.30	53.70	1..00

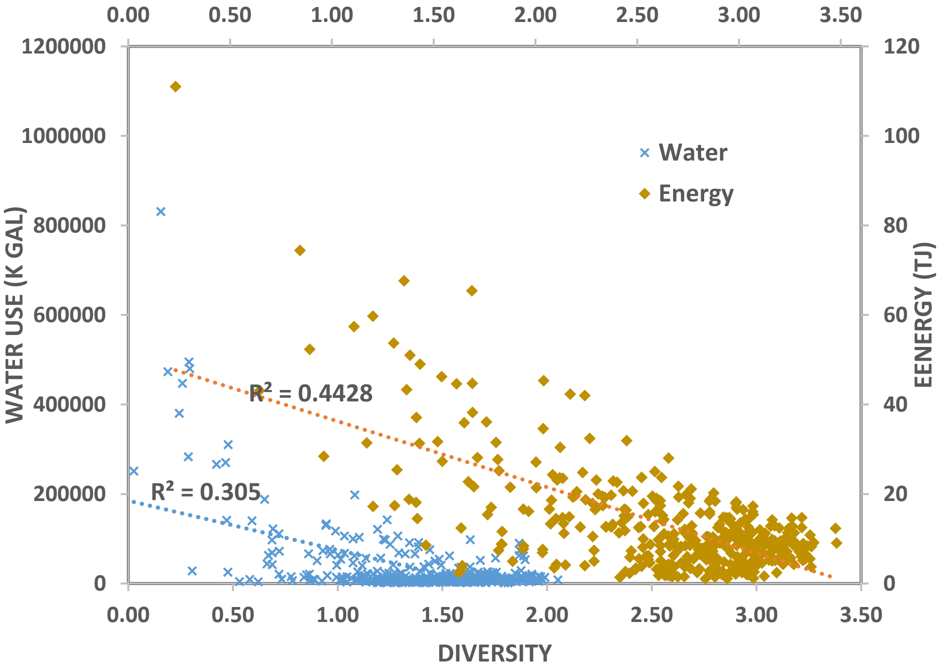


Figure D-2. Demand diversity of water and energy of US sectors vs use intensity

Figure D-2 shows how the value of water and energy intensity decreases with increase in diversity. The r values between energy intensity and diversity are -0.51 (moderately negatively related). There is a trend of decrease of water use intensity with the increase in the diversity value.

The r-value of water use and water use diversity of all the sectors was calculated as -0.46 which is almost equal to energy. From our analysis, we can see that both resources categories, water, and energy show a negative relationship between intensity and diversity which also indicates that diversity increases efficiency.

All sectors of the economy have different roles to forward the alternative input-output routes during disaster and diversity is seen to be an essential trait of the system which helps to maintain economy functional during such challenges (Xu et al., 2011). Fig D-3 shows how the value of the economic activity of various industrial economic input-output sectors increases with the increase in diversity of economic activity. There is a strong positive correlation between the two parameters (r = 0.81). Generally, when many sectors are involved and have an equitable share in the economic activity, the economic value is seen to increase. Increased diversity enhances efficiency in resources demand and use and decrease entropy of resource use (P. H. Templet 1996).

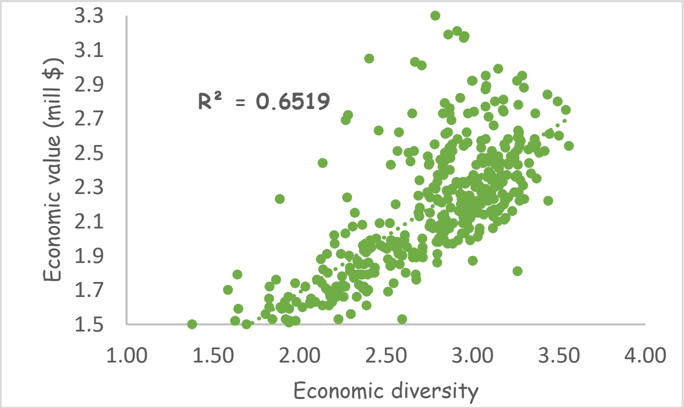


Fig D-3. Correlation between energy diversity and GDP in 1995 and 2005

Resiliency is positively related to the redundancy. Higher values of resource use of more diverse sectors indicate that the economic system, water, and energy use by the sectors are trying to be more stable by providing insurance or complementarity and response diversity such that even some disturbance in few sectors can be resisted and compensated by other sectors.

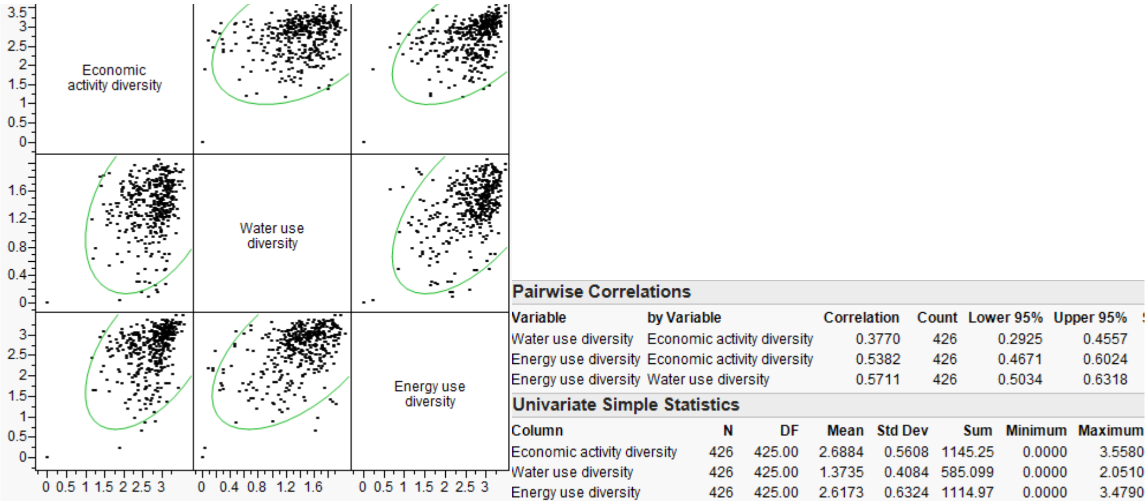
Appendix E

Diversity of water, energy, and economic activity

Water use and energy use diversities can be further linked with the economy. The economy is expected to be more diverse and efficient in generating the outputs as more number of energy and water flows are involved. In addition, productivity rises in diverse economies and higher gross national products (GNP) are expected to generate. In this section, we compare the diversities of economic activity, water, and energy use.

Figure E-1 shows the correlation among diversities of economic activity, water, and energy

use. The results show that water and energy use diversities positively correlates with economic diversity. Results indicate a strong correlation between energy use diversities and economic diversities (r = 0.538). However, water use diversities and economic diversities is somewhat less correlated (r = 0.377). The diverse economic sectors will have more diverse use of water and energy as we can see from the graph and correlation coefficient and more proportional to energy diversity.



Pairwise Correlations

Variable	by Variable	Correlation	Count	Lower 95%	Upper 95%
Water use diversity	Economic activity diversity	0.3770	426	0.2925	0.4557
Energy use diversity	Economic activity diversity	0.5382	426	0.4671	0.6024
Energy use diversity	Water use diversity	0.5711	426	0.5034	0.6318

Univariate Simple Statistics

Column	N	DF	Mean	Std Dev	Sum	Minimum	Maximum
Economic activity diversity	426	425.00	2.6884	0.5608	1145.25	0.0000	3.5580
Water use diversity	426	425.00	1.3735	0.4084	585.099	0.0000	2.0510
Energy use diversity	426	425.00	2.6173	0.6324	1114.97	0.0000	3.4790

Fig. E-1 Pairwise correlations between the diversities

Appendix F

Diversity and efficiency of energy system of US states

What happens to energy use diversity with time?

There was insignificant change in the energy use diversity with time from 1995 to 2010. This is visible in the figure 4-1 with colored lines which are almost collinear to each other. Some examples of the states that slightly changed in years are Tennessee and Wisconsin. These states have lower energy use diversity in 1995 than other years. The reason behind low energy use diversity in these states is because they have lower energy use in commercial use in 1995.

What causes the variation of energy use diversity among states?

Few states such as Louisiana, Texas, Wyoming and Alaska have low energy use diversity compared to other states. Energy use diversity is fairly constant for most of the states with diversity of 1.3. To analyze what causes the variation of diversity, we ran a linear model and included year and energy use categories (residential, commercial, industrial and transportation) on the diversity of energy (A-C, Table 27). We found that the energy use is most affected by industrial energy use followed by residential use. Industrial energy use had a negative impact on diversity. The states with low energy use diversity have more than 50% of total energy use making the diversity low. The comparison of industrial energy use per capita and energy use diversity showed opposite trend as seen in the figure 4-1. This was because of energy high intensive industries in these states like bulk chemical industries, refining industries and mining industries.

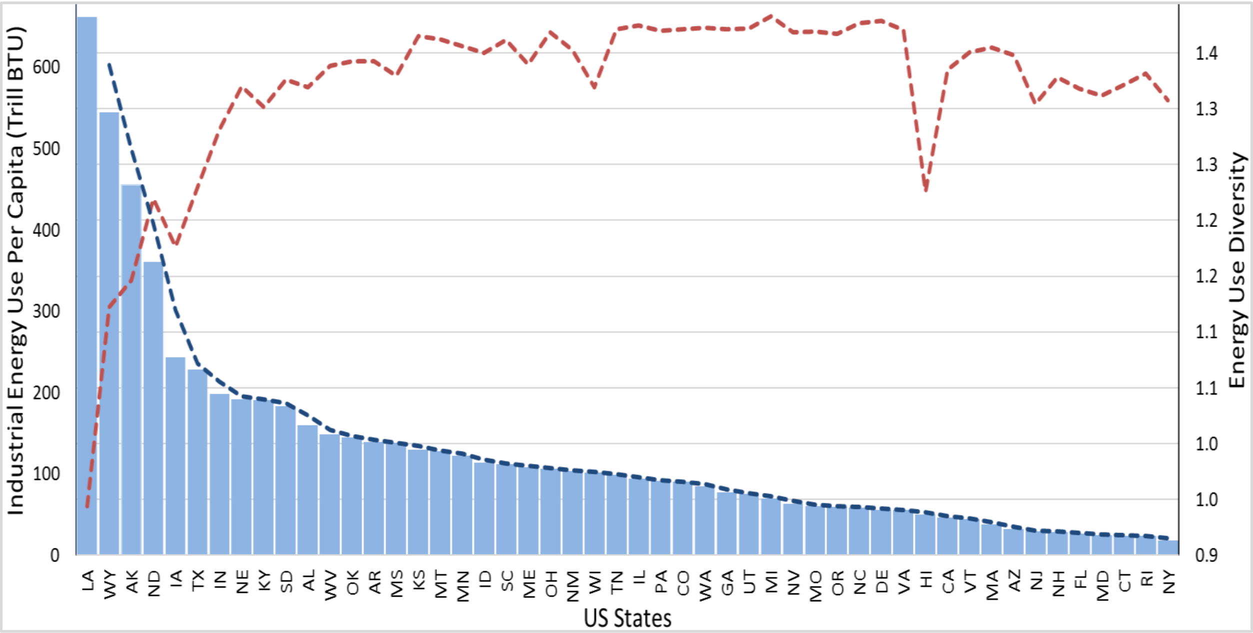


Figure F-1: Opposite trend of industrial energy use per capita and energy use diversity

Several states have very high energy use diversities (1.38) such as Colorado, Michigan, North Carolina and Virginia because energy is used in more equal fraction in all the four energy use categories. For example, in Virginia each of the four energy use categories use around 25% of total energy.

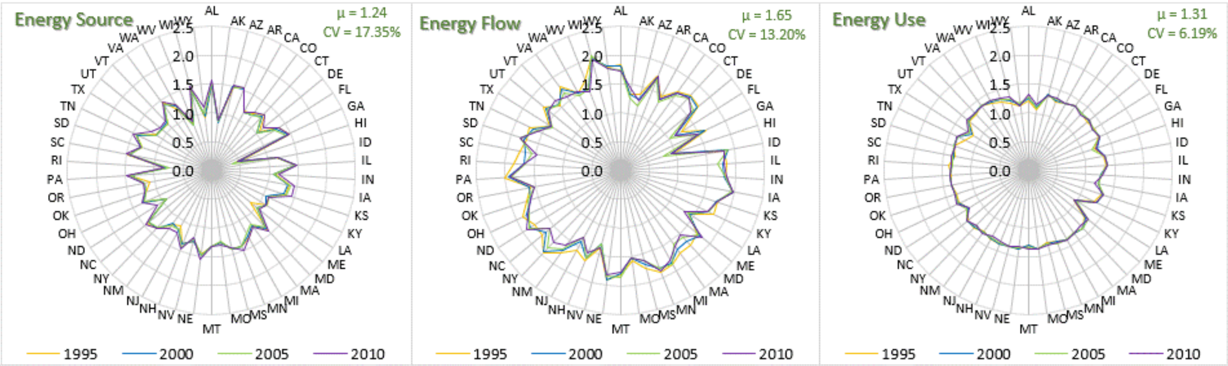


Figure F-2: Diversity of energy source (a), flow (b), and use (c).

Table F-1 Diversity of energy in the US States for the years 1995, 2000, 2005, 2010.

Diversity	**1995**	**2000**	**2005**	**2010**
Energy Source	1.24	1.23	1.23	1.28
Energy Flow	1.70	1.66	1.62	1.62
Energy Use	1.30	1.31	1.32	1.32

3.3 How does energy use compare to energy source diversity?

Energy source diversity had a smaller mean (1.23) than energy use diversity. This was surprising considering that we had only 4 categories in energy use and 5 in energy source. The fewer number of categories that would have decreased diversity is in contrast increased diversity by the evenness of these categories resulting in higher diversity values for use.

Unlike energy use diversity, the energy source diversity changed somewhat in time. There are states like Delaware, North Dakota, Wyoming and Texas that have increase in their energy source diversity significantly from 2005 to 2010. This was because of the increase in renewable energy by almost 4 times. To analyze which source impact the energy source diversity the most, we ran a linear model for energy use diversity and add year and energy source categories (coal, natural gas, petroleum, nuclear and renewable) as impacting factors. We found that nuclear energy followed by renewable energy affected energy source diversity the most (A-C, Table 26). For example, energy source diversity was high in Illinois (1.48), Pennsylvania (1.48) and South Carolina (1.50) and fall in top 10 diverse states in energy source (A-B, Table B-2). These states also fall in top ten states using nuclear power and support the result of linear model that nuclear energy (figure 4-3) helps to increase energy source diversity the most followed by renewable energy source.

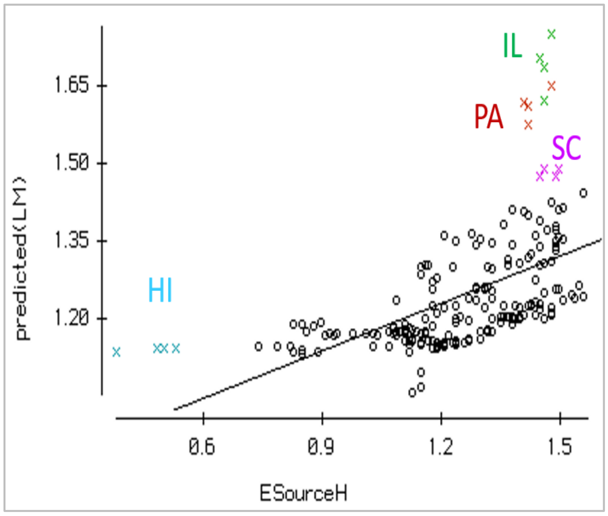


Figure F-3: Energy Source Diversity Vs Predicted values from the model with coal, natural gas, petroleum, nuclear energy, renewable and year as the determining factors

The correlation between energy source and use is also visible when we plot energy source versus energy use (A-C, SI Table 5). This implies that increase or decrease in energy use diversity would also increase or decrease energy source diversity. For example, Alaska has low energy use diversity (1.10) and also low energy source diversity (0.85). Illinois has high energy use diversity (1.46) and also high energy source diversity (1.37).

The relation between energy use and energy source is further supported by the energy flow diversity analysis. Energy flow diversity analysis shows the diversity of connections between source and use. The mean value was 1.65 which is higher than the diversity of the source or the use. We expected the flow diversity to be high because it would have 20 categories but if the flow from source to use are uneven than the flow diversity could have been lower. For example, Arizona has low flow diversity (1.26) than source diversity (1.49) and use diversity (1.35). In the same way, Florida has low flow diversity (1.12) than source diversity (1.29) and use diversity (1.33)

These low flow diversity is because of the concentration of flow from petroleum to transportation (almost 75%) of total energy flow even though the connectivity is same as other states.

3.4 Which states are energy efficient and inefficient and why?

Energy efficiency is fairly constant among the states between 5 to 20 MJ/$ except Louisiana, which has lower efficiency (30 MJ/$). In Louisiana, there are highly energy intensive industries i.e. uses more energy for producing same economic output. The intensity of energy use in 2010 in Louisiana was the highest of all (21 MJ/$).

New York and Massachusetts were the most energy efficient states which means that these states use less energy compared to other states for same economic output. In 2010, only 3.3 MJ energy is used for 1$ economic output in New York, most energy efficient state followed by Massachusetts (3.74 MJ/$). Other states like New Hampshire and Hawaii also have high efficiency.

The coefficient of variance of energy efficiency (43%) is high compared to the coefficient of variance of energy use diversity (6%). This variation includes both temporal as well as state wise variation.

3.5 Does diversity lead to efficiency in energy use?

According to the linear model, energy intensity has strong relation with energy source diversity, use diversity and saturation. Louisiana, Wyoming, Alaska in all the years under study, and North Dakota and Texas in 1995 were away from clusters (A-C, figure 17) because they have very high energy intensity compared to other states and they fall in the bottom ten least energy diverse states in both source and use, and top 10 high energy intense states. Louisiana, Wyoming, North Dakota, Alaska and Texas have a tendency to export their energy to other states as well as other nations. According to USEIA, Wyoming supplies more energy (60% of electricity) to other states than any other US states; Louisiana is seen to be the highest energy consuming state being one of the nation’s largest coal exporting ports; Alaska export almost 50% of energy in the form of coal. Being industrial states, North Dakota and Texas have high intensities.