Research on energy status and forest fire spreading
---Based on data in America

Summary

This article presents a report of the energy status based on data from America (Part I) and research on fire spreading analysis (Part II).

Part I introduces a method to evaluate the performance of energy usage based on the data from 4 states in America, and then successfully compares the energy performance among four states. To achieve that, we define an **Energy Profile Index (EPI)** to describe the overall status of clean, renewable energy usage with 6 sub-metrics constructed in a '3E' structure to measure whether a state has a better energy system. After the data processing, **Fuzzy Evaluation** and **GDM method** is used for weighting. We then calculate the EPI and the 6 sub-metrics in a time-series of each state and present them as an Energy Profile for each state.

Part II analysis the spreading of forest fire from 4 aspects: the introduction of recent fires, the reason of fire, the comparison of fire in different forests and the simulation of forest fire with **Cellular Automata** method. In the process of simulation, we define the **spread rate** to describe how serious a fire would be, and then test the relationship between spread rate and three variables: the original forest density, the spreading possibility and the fire point. Thus, we could better prevent forest fires from happening and spreading.

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REPORT MEMO

Date: May 6th, 2018

Miss. Shi:

Thank you for taking time to read our report on the research of energy status and fire spreading. We choose this subject due to two reasons. One the one hand, we are all concerned of the ecological environment under the fact that we humans are encountering more pollutions and natural disasters recently, with the shortage of energy being another threat to our planet. On the other hand, four of us are from mathematical department, hence we want to adopt some math modeling and programing while analyzing our problem.

In order to investigate in the energy status, we use data from four states in America, including California (CA), Arizona (AZ), New Mexico (NM), and Texas (TX).

In order to look into the disasters around the world, we only choose forest fires to analysis (because there are too many kinds of disasters and we have limited time). In this part, we consciously use what we learned in class, including writing skills about cause & effect, comparison & contrast and graphs.

Here are our key results:

Part I Energy Profile (2009)

With the EPI we created, the energy performance of the four states are as follows (Year2009):

- ✓ Arizona: Arizona performed the best in the overall energy usage, the state in doing well in the efficiency of energy using and performed the best in using energy for growth requirement.
- ✓ California: It's a state still needs improvement in the overall energy usage situation and it's also a state having relatively abundant energy with the most RE (Renewable energy) resources consumption among the four states.
- ✓ New Mexico: New Mexico is performing in the middle place in terms of the overall situation, it's also have the second highest Clean Score in RE resource usage.
- ✓ Texas: It's a state still needs improvement in the overall energy usage, it's rich in access to diversify kinds of energy. However, it's deteriorating in self-efficiency.

The Energy Profile Index (EPI) of each of the five state is listed below:

	AZ	CA	NM	TX
EPI	39895.61	32527.5	34213.31	28958.17

Part II Forest Fire

Density%	Spread rate%	Pro of fire%	Spread rate%
50	0.7	100	99.8
55	1.8	90	98.9
57	5.5	80	96
59	37	69	78
60	58	68	60.2
61	78	67	33.9
62	84.4	66	6.2
64	90	65	1.5
70	98.3	54	0.1

Sincerely,

Best Wishes

1 Introduction

Nowadays, clean and renewable resources (RE resources) have been paid a great attention due to the increasing need of energy consumption and rapid reduction of energy reserves. Exploitation and utilization of RE resources is the key to ensure a sustainable development of energy system, hence plenty of regions have wondered how to evaluate the performance of the usage of energy. If they could find a perfect way to quantity whether they are using RE well, they could then adjust their strategies according to that.

On the other hand, frequent natural disasters are bothering many regions, for example, the forest fire is killing our environment, as trees are the key to life. This phenomenon is especially concerned around Amazon rain forest while it is referred to the lung of earth and is now under huge catastrophes. Therefore, people are interested in how serous a fire would be and how to better prevent them from happening and spreading.

2 Definition and Structure of Energy Profile

2.1 Objectives for Energy Profile Index (EPI)

In order to reflect the status of the whole energy system in a state intuitively, we need to define an **Energy Profile Index (EPI)** that can present comprehensive energy usage in both **Environment Sustainability (which means clean, renewable energy usage), Economic Growth and Development, and Energy Accessibility** of a certain state. And this index should be comparative across states in order to show the similarities and differences between them. The World economic forum had given us a reference by publishing its algorithm of the 'Energy Architecture Performance Index' (EAPI). However, the EAPI didn't pay enough attention to the usage of RE resources in its 'Sustainability' part. Thus, we replace the original 'sustainability' metrics with **Clean & Renewable Metric** creatively. And here's our EPI structure:

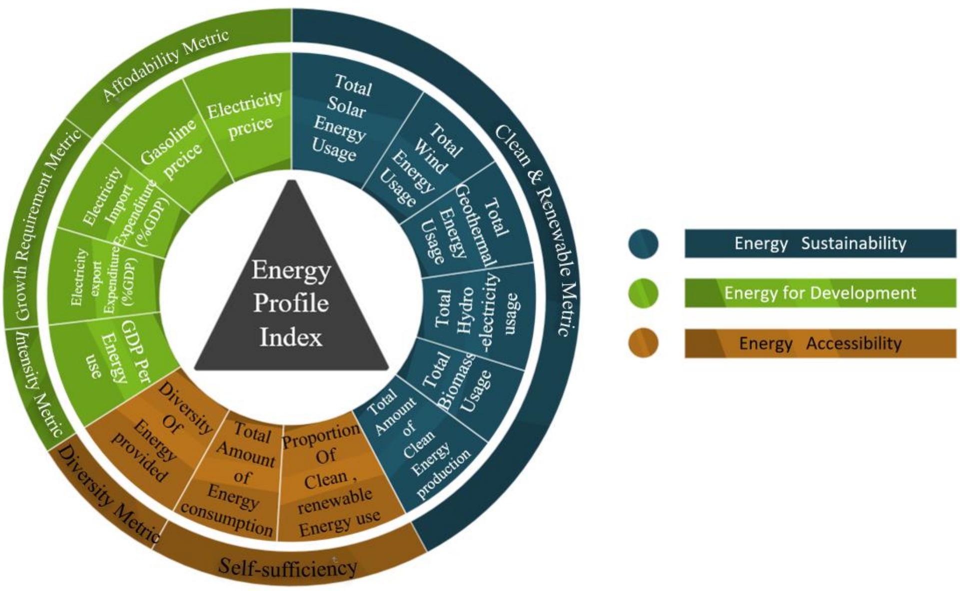


Figure 1

As is shown in the graphic, We put forward 6 metrics under the '3E' structure, and for every metric, we introduce related parameters picked out from our dataset and weight them with Fuzzy Evaluation method and GDM method.

2.2 Energy Sustainability

2.2.1 Clean & Renewable Metric

To measure whether a state is doing well in developing RE resources, following two parts should be considered: 1) The proportion of the total clean & renewable energy usage to the total energy consumption, the higher the proportion is, the better the state is doing in developing RE resources. 2) The usage amount of each type of renewable energy, the higher these amounts are, the better the energy system.

There are five commonly used renewable energy sources: biomass, hydropower, geothermal, wind and solar energy. These energies have their own pros and cons in different aspects, among them we use costs, safety, economic development, environment sustainability and accessibility as the criteria.

With the GDM method we discussed later in 5.2.2, we built the Clean & Renewable Metric through the following formula:

$$\textit{Clean \& Renewable Metric} = Contribute\ \ Rate \times (BI, HY, GE, WI, SO)^T$$

$$Contribute\ \ Rate\ \ = (0.1752\ \ , 0.4218\ \ , 0.0845\ \ , 0.0988\ \ , 0.2197\ \ )$$

2.3 Energy for Development

2.3.1 Affordability Metric

Price is a key factor that determines the usage amount of clean energy. Only when price is affordable will the clean energy be used in production and bring economic growth. In this dimension, we choose *Electricity price in the industrial sector*, *gasoline price for all sectors* to reflect energy prices. (1)Electricity price in the industrial sector reflects energy usage by the industrial sector, which is an important sector in the production and supply of goods. Therefore, the price could reflect the cost of supplying in the entire market. (2)The price of gasoline represents the cost of transporting, which greatly affects people's demand for commodities from the perspective of transaction costs. Therefore, these two indicators can reflect the impact of energy prices on GDP in terms of cost in supply and demand.

$$\text{Affordability\ \ Metric} = Price_e + \frac{Price_{ag} + Price_{mg}}{2}$$

$Price_{\mathrm{e}}$ —— Electricity price in the industrial sector.
$Price_{ag}$—— Average aviation gasoline price in all sectors
$Price_{mg}$—— Average motor gasoline price in all sectors

2.3.2 Growth Requirement Metric

The growth of energy should meet the needs of GDP, and electricity is the major power generated by RE energy. Therefore, in this dimension, we choose Electricity exports expenditures (% GDP) and Electricity imports expenditures (% GDP) to reflect the energy costs of GDP growth. According to the definition of the World Economic Forum [1], Electricity exports expenditures can provides an indication of the extent to which the energy sector has a negative impact on growth. And Electricity imports expenditures can provide an indication of the extent to which the energy sector has a positive impact on growth.

$$Growth\ \ Requirement\ \ Metric = Ele_x + Ele_m$$

Ele_x—— Electricity exports expenditures(%GDP)
Ele_m——Electricity imports expenditures (%GDP)

2.3.3 Intensity Metric

We need to set metric to indicate the efficiency of energy use, that is, the output a unit of energy can bring. The greater the metric, the greater the efficiency of energy use.

$$Intensity\ \ Metric = \frac{P}{C}$$

P——Gross domestic production in a certain state
C——Total energy consumption

2.4 Energy Accessibility

2.4.1 Diversity Metric

Energy diversity reflects the availability of energy as the phenomenon of monopoly often appears when few energy sources are available, which can severely reduce people's access to energy. Herfindahl Index can represent the concentration as well as diversification of energy use. When energy usage is more concentrated, the dispersion of energy types is worse, hence people's ability to acquire multiple energy sources increases. We define Diversity Metric as the inverse of the Herfindahl Energy Index, the larger this index, the greater the diversity of energy.

$$Diversity\ \ Metric = \frac{1}{\sum_{i=1}^{n}\left(\frac{Usage_i}{Usage}\right)^2}$$

n ——Number of energy types
$Usage_i$——total energy consumption of a certain type in residential sector (per capita)
$Usage$——total energy consumption in residential sector (per capita)

2.4.2 Self-sufficiency Metric

Self-sufficiency indicates whether a state can produce enough energy they need. In this aspect, we use the ratio of the total state energy production and total state energy consumption to reflect the value. The larger the ratio, the better they meet their own energy needs.

$$Growth\ \ Requirement\ \ Metric = \frac{TotalProduction_p}{TotalProduction_C}$$

$TotalProduction_p$——Total amount of energy production
$TotalProduction_C$——Total amount of energy consumption
Methodology of EPI Weighting and Calculation

2.5 Weighting

After defining the entire index system, we need to set the weights each index owns. We use fuzzy analysis and Analytic Hierarchy Process to calculate the weight as follows:

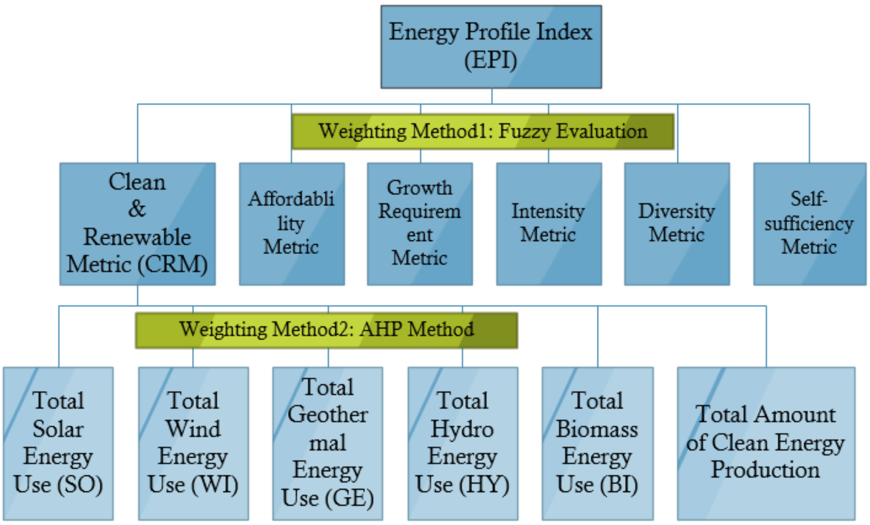


Figure 2

2.5.1 Weighing method1: Fuzzy Evaluation

To measure respective contributing rate of six metrics, we decide to assess them with fuzzy synthetic evaluation method, as following steps:

- Step 1: Defining fuzzy comprehensive evaluation criteria

$$U = \{\boldsymbol{Environment\ \ Sustanbility\ \ u_1, Economic\ \ growth\ \ u_2, Energy\ \ accessibility\ \ u_3}\} \tag{1}$$

- Step 2: Defining the set of evaluation grades

$$V = \{\boldsymbol{Excellent\ \ v_1, Good\ \ v_2, Average\ \ v_3, Bad\ \ v_4}] \tag{2}$$

- Step 3: Endowing the weights to each criteria:

$$\boldsymbol{A} = (\mathbf{0.3, 0.3, 0.4}) \tag{3}$$

- Step 4: Afterwards, we determine fuzzy evaluation matrix R_i $(i = 1 \ldots 6)$ according to each index as the process to carried out single factor fuzzy evaluation and obtain the evaluation matrix.

Results are shown below:

Clean & Renewable Metric:	[0.640, 0.230, 0.130, 0.000];	Grade is excellent $\mathbf{v_1}$
Growth Requirement Metric:	[0.100, 0.460, 0.412, 0.028];	Grade is good $\mathbf{v_2}$
Self-sufficiency Metric:	[0.100, 0.340, 0.330, 0.230];	Grade is good $\mathbf{v_2}$
Affordability Metric:	[0.160, 0.440, 0.305, 0.095];	Grade is good $\mathbf{v_2}$
Intensity Metric:	[0.200, 0.500, 0.300, 0.000];	Grade is good $\mathbf{v_2}$
Diversity Metric:	[0.400, 0.420, 0.180, 0.000];	Grade is good $\mathbf{v_2}$

The grades of six indexes are at least good, and among them, the grade of renewable energy appears to be excellent. Therefore, the grades to those indexes are selected as 0.44,0.46,0.5,0.42,0.64 and 0.34. After normalization, final weight distribution is calculated as

$$\{0.1571, 0.1643, 0.1786, 0.15, 0.2286, 0.1214\}$$

2.5.2 Weighing Method2: Group Decision Making Method (GDM)

In order to complete the synthesis of indicators, we use consistent judgment matrix (GDM) for each primary metric for weighting. We get the indicators in the above text and the GDM for this evaluation is given as below (Figure 3):

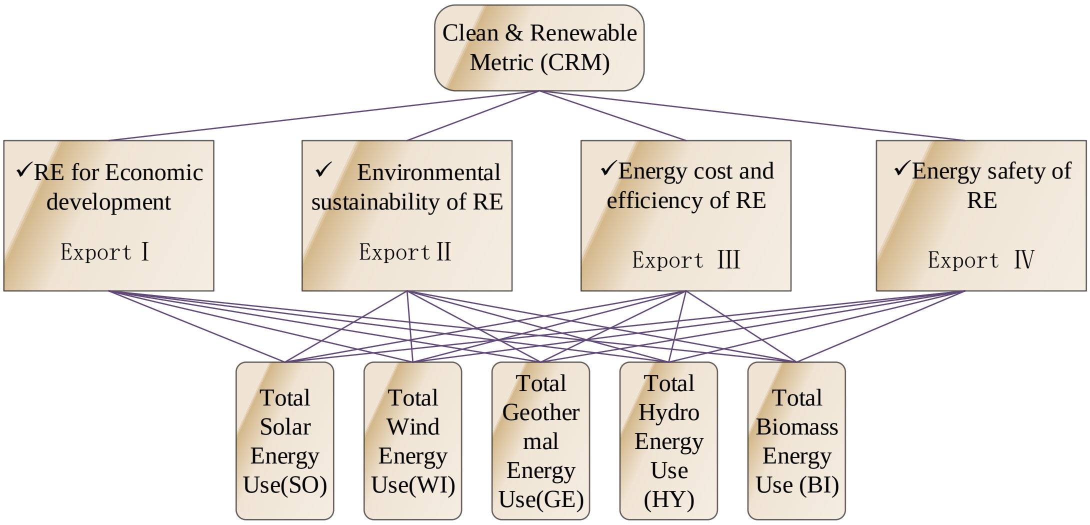


Figure 3

For export one to four, we defined a consistent complementary judgment matrix, which is scored according to the expert's experience with the indicator according to the scoring table. Matrixes are shown as below:

$$E^{\mathrm{I}} = \begin{array}{cc} & \begin{matrix} BI & HY & GE & WI & SO \end{matrix} \\ \begin{matrix} BI \\ HY \\ GE \\ WI \\ SO \end{matrix} & \begin{bmatrix} 1 & 1/5 & 1/3 & 1/7 & 1/9 \\ 5 & 1 & 3 & 1/3 & 1/5 \\ 3 & 1/3 & 1 & 1/5 & 1/7 \\ 7 & 3 & 5 & 1 & 1/3 \\ 9 & 5 & 7 & 3 & 1 \end{bmatrix} \end{array} \quad E^{\mathrm{II}} = \begin{array}{cc} & \begin{matrix} BI & HY & GE & WI & SO \end{matrix} \\ \begin{matrix} BI \\ HY \\ GE \\ WI \\ SO \end{matrix} & \begin{bmatrix} 1 & 1/3 & 3 & 7 & 3 \\ 3 & 1 & 7 & 9 & 5 \\ 1/3 & 1/7 & 1 & 3 & 1/3 \\ 1/7 & 1/9 & 1/3 & 1 & 1/5 \\ 1/3 & 1/5 & 3 & 5 & 1 \end{bmatrix} \end{array}$$

$$E^{\mathrm{III}} = \begin{array}{cc} & \begin{matrix} BI & HY & GE & WI & SO \end{matrix} \\ \begin{matrix} BI \\ HY \\ GE \\ WI \\ SO \end{matrix} & \begin{bmatrix} 1 & 1/5 & 1/3 & 1/3 & 5 \\ 5 & 1 & 7 & 3 & 9 \\ 3 & 1/7 & 1 & 5 & 3 \\ 3 & 1/3 & 1/5 & 1 & 7 \\ 1/5 & 1/9 & 1/3 & 1/7 & 1 \end{bmatrix} \end{array} \quad E^{\mathrm{IV}} = \begin{array}{cc} & \begin{matrix} BI & HY & GE & WI & SO \end{matrix} \\ \begin{matrix} BI \\ HY \\ GE \\ WI \\ SO \end{matrix} & \begin{bmatrix} 1 & 1/3 & 1/3 & 1/5 & 1/9 \\ 3 & 1 & 1 & 1/3 & 1/5 \\ 3 & 1 & 1 & 3 & 1/3 \\ 5 & 3 & 3 & 1 & 1/3 \\ 9 & 5 & 7 & 3 & 1 \end{bmatrix} \end{array}$$

We can obtain the weights by solving the eigenvectors of the above matrix. According to the group decision-making method, the final weight can be obtained by combining the weight of experts and the weight of judgment matrix using the following equation

$$\mathbf{W}^{*} = \sum_{i=1}^{4} \lambda_i W^i \tag{4}$$

where the result of the W can be seen in the follows.

Table 1

Criteria	Production(W^1)	Environment(W^2)	Cost(W^3)	Safety(W^4)	Rank
weights	0.2027	0.6574	0.0942	0.0457	weights
Hydroelectricity	0.03	0.24	0.08	0.04	0.4218
Solar	0.13	0.52	0.53	0.10	0.2197
Biomass	0.06	0.07	0.22	0.09	0.1752
Geothermal	0.26	0.03	0.14	0.23	0.0988
Wind	0.51	0.13	0.03	0.54	0.0845

Calculation:

Based on metrics and their weights, we can calculate a state's EPI that reflects the state's energy performance. Among them, Clean & Renewable Metrics (CRM) could reflect clean energy usage.

- **Data description:**

We use provided dataset (1960-2009) in AZ, CA, NM and TX. However, due to different states' policy on data records, there are some missing values in certain years, such as 1960-1970.

- **Selection of useful variables:**

We select 14 variables from the 605 sample, including the total consumption of all types of new energy and electricity, and we also select total population, total production, total volume of imports and exports of various energy sources to indicate geographical, demographic and economic characteristics of the four states.

- **Process of missing value:**

Noticing that missing values were all from 1960 to 1970 and there will be a series of value zero after recording, we assume that the distribution of these variables in unrecorded years is the same with adjacent years. Thus, We use 0 to replace the missing part.

- **Data normalization:**

Since the selected data are of different dimensions and differ greatly in magnitude, they are standardized as follows:

$$x' = \frac{x_{max} - x_{min}}{x_{min}}$$

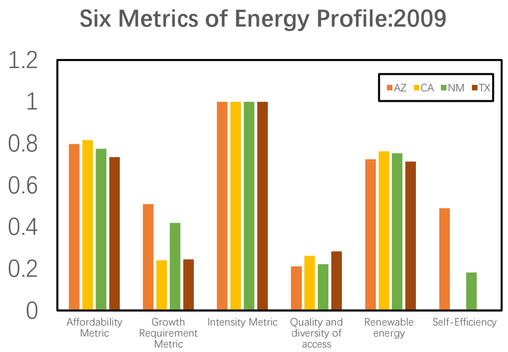
Based on the selected variables and calculated weights, the Energy Profile Index targeted on clean, renewable energy usage of each state can be computed.

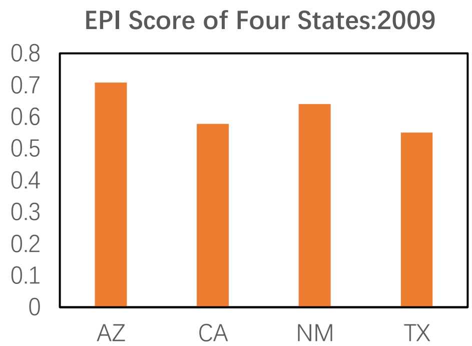
3 Presentation of Energy Profile in Four States

3.1 Energy Profile 2009

Here we only show the calculated EPI of four states based on our definition of energy profile because the traditional energy profile for each year derived from the dataset can be easily found on EIA website.[1].

To demonstrate the value of our research, we will show the calculated energy profile index, as well as the comparison of four states since none of them can be directly derived from available sources.

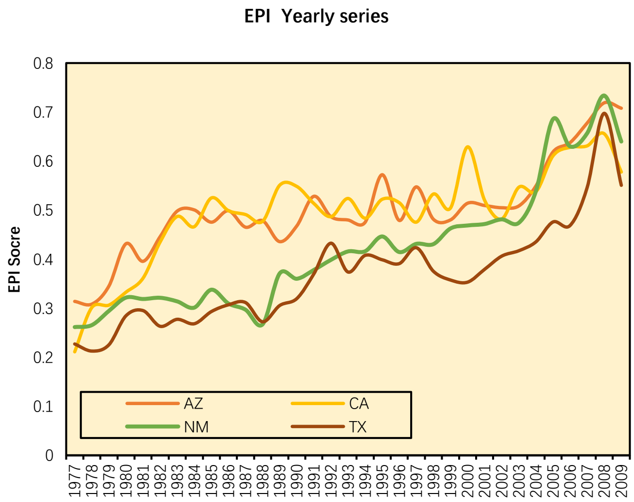


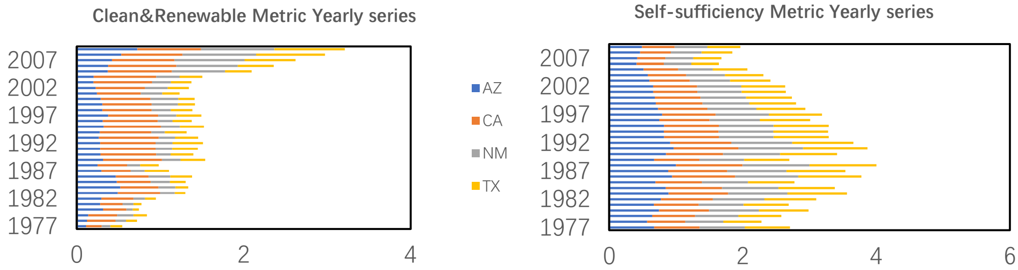


As can be seen from the figure above, in 2009, AZ's energy system performed best through higher Growth Requirement Metrics and self-sufficient metrics.

CA performs best in terms of Clean & Renewable Energy, but its self-sufficient index is very low due to the huge gap between current energy production and required energy consumption. At the same time, perhaps affected by the 2008 economic crisis, it performs poorly on Growth Requirement Metrics and as a result, the energy system performed less well in 2009.

3.2 Energy Profile Index Time Series




Clean&Renewable Metric Yearly series
2007
2002
1997
1992
1987
1982
1977
0 2 4
AZ
CA
NM
TX
Self-sufficiency Metric Yearly series
2007
2002
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1992
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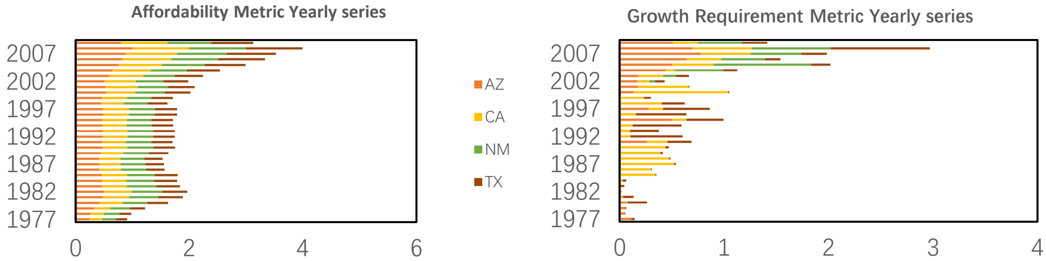
1982
1977
0 2 4 6


Affordability Metric Yearly series
2007
2002
1997
1992
1987
1982
1977
0 2 4 6
AZ
CA
NM
TX
Growth Requirement Metric Yearly series
2007
2002
1997
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1982
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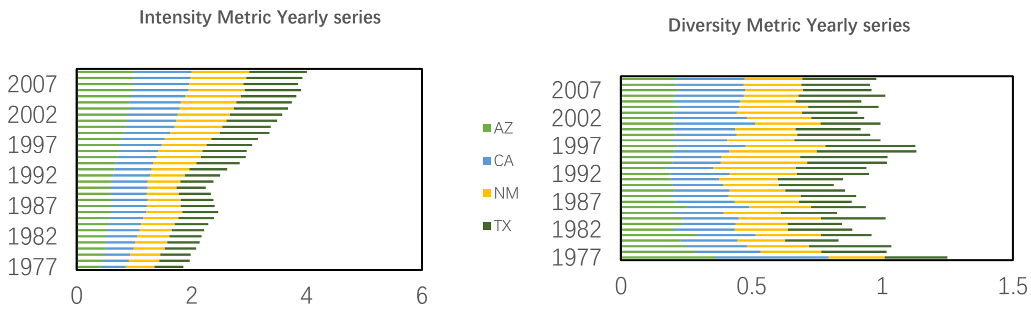
0 1 2 3 4


Intensity Metric Yearly series
2007
2002
1997
1992
1987
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0 2 4 6
AZ
CA
NM
TX
Diversity Metric Yearly series
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0 0.5 1 1.5

4 Presentation of Energy Profile in Four States

4.1 Introduction

The Amazon rainforest, also known in English as Amazonia or the Amazon Jungle, is a moist broadleaf forest in the Amazon biome that covers most of the Amazon basin of South America. This basin encompasses 7,000,000 km2, of which 5,500,000 km2 are covered by the rainforest. This region includes territory belonging to nine nations. The majority of the forest is contained within Brazil, with 60% of the rainforest, followed by Peru with 13%, Colombia with 10%, and with minor amounts in Venezuela, Ecuador, Bolivia, Guyana, Suriname and French Guiana. States or departments in four nations contain "Amazonas" in their names. The Amazon represents over half of the planet's remaining rainforests,and comprises the largest and most biodiverse tract of tropical rainforest in the world, with an estimated 390 billion individual trees divided into 16,000 species.

However, fires happened frequently these days. And a fire occurred just now.

A reporter came to the scene and talk to the best ranger in Amazon. The content of the interview is shown below.

Interview: A ranger and a reporter:

Reporter : Today we have the best ranger in Amazon, Issac.

Ranger : Hello

Reporter : As we can see, the fire is burning. I heard it’s is not the first time.

Ranger : Yes, the third time, though it is just April.

Reporter : That is terrible, because we all know the Amazon forest is the largest rainforest.

Ranger : Also called “The lung of the earth”.

Reporter : Unfortunately, disasters happened frequently these days. One fifth of the forest have been destroyed. Can you tell us more details?

Ranger : Yes. Though the Brazilian government and we rangers try our best, over 20 percent of the forest has flattened in the last 40 years. The most serious fire happened in 1987, the fire area reached 20 thousand hectares, which is equal to two Switzerland.

Reporter : I do hope such a tragedy will never repeat again. Could you tell us which part is the most damaged?

Ranger : That must be mato grosso forest, 38 percent of the forest disappeared because of the fire and excessive deforestation. Here used to be a whole used, but now farmers grow soybeans.

Reporter : What a sharp contrast.

Ranger : And the forest will never come back.

Reporter : It really hurts to think of it. What cause the terrible disaster?

Ranger : It is regrettable that mostly people cause fire.

Reporter : You mean that people set fire deliberately.

Ranger : Yes, in fact, we caught two arson criminals 2 weeks ago. To punish these criminals, the military in Brazil has launched Green Wave Action.

Reporter : I hope things will get better.

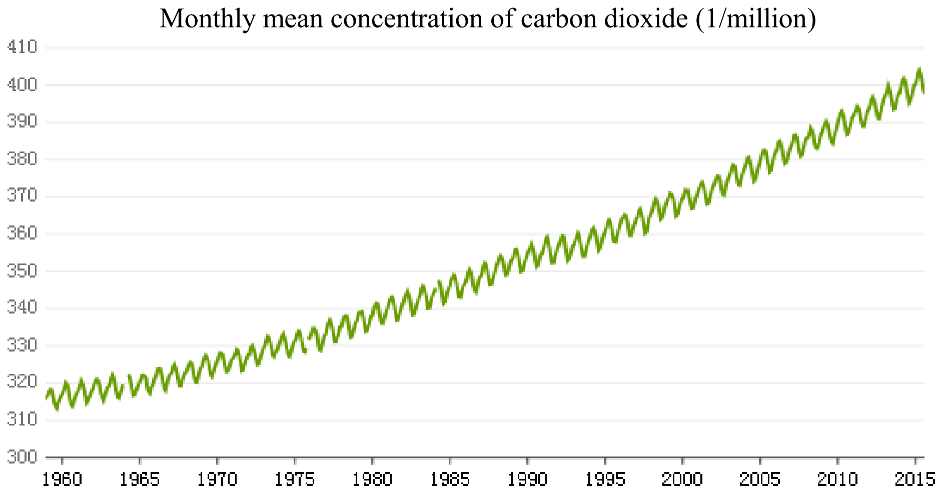
Ranger : Actually, we need more government control and scientific research.

Reporter : And everyone’s efforts.

4.2 Cause and effect

(1) Climate

Due to green house effect, the temperature is getting higher. As a result, there are more strong wind weather and dry weather days. Dry deadwood and leaf are easily to be burned, while strong wind will speed up the fire to swallow trees which are not afire.



In this condition, fire may happens more easily and frequently.

(2) Season

During autumn and winter, the environment becomes dry because of the weather and the dead of most plants. The fact is many departments of forest protecting set the special forbidden time in autumn and winter. And it has been proved that the decision is generally correct.

(3) Natural environment

Depends on the density, the more serried the forest is, the more probability the fire will happen. So in the man-made forest, trees are planted at a fixed distance so that the probability will be decreased prominently.

What's more, the kind of trees is a cause of fire. For example, because of the organic tissue, Larch（落叶松）、Pinus sylvestris（樟子松）、Pinus koraiensis（红松）contain grease(油脂) which are the helper of fire. Another instance is evergreen broad leaved forest(常绿阔叶林),which are normal in south of china, it have lush leaf which make the fire spread quickly.

(4) Human activity

Human activities, such as lumbering, planting, cultivation, entertainment and so on, may cause fire because of careless action. Nowadays, more and more departments have settled law about lumbering, planting and cultivation. But the entertainment is still the most annoying problem because there are always tourists in the forest area. And smoking, riding, barbeque all are the dangerous action in the forest. So for the human activities, we should focus on the entertainment activities.

4.3 Comparisons by Countries

In the previous section, we talked about causes of forest fires. We may already notice that even they are caused by the same reasons, the profiles of different forest fires are various. In the part we would like to investigate differences between all these forest fires. Through several dimensions can we get a clear image of such differences?

(1) Times & areas of fire

国　家	林火 (起数 /年)	受害森林面积 (hm^2 /a)	占森林面积 (%)	受害森林面积 (hm^2 /次)	统计年代
澳大利亚	1 772	360 073	0. 4	203. 2	1970~ 1980
美　国	117 724	1 840 495	0. 6	15. 6	1970~ 1980
加拿大	7 162	891 330	0. 2	121. 6	1970~ 1980
日　本	6 906	12 867	0. 05	1. 86	1972~ 1981
瑞　典	2 359	2 807	0. 01	1. 1	1970~ 1980
前苏联	28 000	164 000	0. 21	73. 6	1970~ 1988
芬　兰	604	1 119	0. 07	1. 85	1970~ 1980
德　国	1 498	2 279	0. 06	1. 51	1970~ 1980

From the statistics, we can see that during 1970s, American had the largest times of forest fires. What`s more, it had the largest areas of damaged forest, too. Both indexes were far bigger than any other countries. But, we can also see that for each time`s fire, American had relatively low area of damage. To figure out the reason, the fact that American had large area of forest could not be ignored. As a developed country, after so many times of fire, it certainly accumulated experiences of dealing with fire. So, damage forest of each time`s fire was controlled in a low level, but still, a large area in total.

Russia, Canada, Japan also had large times of fire due to various reasons. Quite strange that Australia had very low times of fire but very severe damage for each fire, made it also a country with large area of fire damage.

(2) Cause of fire.

	1990	1991	1992	1990	1991	1992	1990	1991	1992	1990	1991	1992
	合计			人为放火			跑火			天然火源		
白俄罗斯	2 469	–	–	–	…	…	2 469	…	…	2	…	…
芬　兰	440	221	480	28	17	48	412	204	432	86	42	250
法　国	…	…	…	…	…	…	…	…	…	…	…	…
德　国	688	1 188	…	225	460	…	463	728	…	28	11	…
意大利	7 845	5 267	6 885	5 284	3 751	4 950	2 561	1 516	1 935	82	54	37
土耳其	684	…	501	296	…	70	388	…	431	30	…	100
加拿大	4 900	5 904	…	475	806	…	4 425	5 098	…	4 895	4 151	…
美　国	33 203	…	…	30 634	…	…	52 569	…	…	16 463	…	…

From the table we can find that in Europe, forest fire was mainly caused by people who deliberately set a fire, while in America, it was caused by natural reasons like a lightening. It is quite weird that people would set a forest fire. As the economics grows, people are more likely to get into forest to make use of its abundant resources. As a consequence, human`s activity makes a forest more likely to get burned. Illegal acts of human like sneak-hunting also make forest fire more frequent.

(3) Type of forest

国家	针叶林			阔叶林			萌生林			其它林地		
	1990	1991	1992	1990	1991	1992	1990	1991	1992	1990	1991	1992
白俄罗斯	0. 75	0. 27	8. 2	…	…	…	0. 53	0. 03	7. 8	0. 04	0. 008	2. 6
芬　兰	0. 43	0. 23	1	°	°	°	–	–	–	–	–	–
法　国	…	…	…	…	…	…	14. 6	…	…	12. 9	…	…
德　国	0. 5	0. 9	…	°	°	°	–	–	…	–	–	…
意大利	25. 4	5. 8	6. 8	11. 24	3. 4	5. 3	59. 6	15. 15	27. 6	–	–	–
土耳其	6. 1	6. 2	6. 5	°	°	°	0. 8	0. 5	1. 44	3. 33	2. 11	2. 5
加拿大	122	276. 7	…	°	°	°	160	96. 8	…	544. 5	1 192	…
美　国	…	…	…	…	…	…	…	…	…	…	…	…

Type of forest also makes a difference. It seems that coniferous forest is more likely to catch a fire while broad-leaved forest is not. That is because the coniferous forest is dry, and easy to extend fire, even easier in autumn and winter. Broad-leaved forest grows in wet area and can prevent a fire naturally.

4.4 Comparisons by Countries

In last section, we investigated in different kinds of forest and analyzed how serious a fire disaster can influence the forest respectively. In this section, we try to quantify this influence.

In order to achieve that, we use Cellular Automata(元胞自动机) method to simulate the spread of fire under different conditions. More specifically, we calculate the **spread rate** as the dependent variable, while setting independent variable as the **original forest density**, the probability a neighbor tree will catch a fire and the ignite point. These four variables are denoted respectively as

$$spread\ rate = \frac{trees\ burned\ out}{Total\ number\ of\ trees}$$

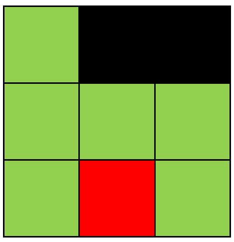
$$pro = the\ probability\ a\ neighbor\ tree\ will\ catch\ a\ fire \in (0,1)$$

$$density = the\ original\ density\ of\ forest \in (0,1)$$

$$fire\ point = the\ ignite\ point \in \{\text{the center}, \text{the corner}\}$$

4.4.1 The construction of forest environment

The world of the forest was discretized into small squares of $1\text{m} \times 1\text{m}$ in size. The size of the world is initially designed as 250×250. The following figure shows a 3×3 grid.



Each small square has three states：

- Tree，Filled with color green.
- Fire，Filled with color red
- Ember，Filled with color black

4.4.2 The laws of fire spreading

We discretize time into 1s, and each small squares in each time step evolve according to the following rules:

✓ Tree → Fire

The fire area will ignite the nearest 4 trees with a certain probability pro.

1	2	3
4	5	6
7	8	9

For example, in the image above, the No. 5 fire zone (red) will light 2, 4, 6, and 8 trees with probability pro.

✓ Fire → Ember

When a tree is on fire, it will gradually become ashes. We use the red to black dimming to demonstrate this process. This process is irreversible, and, after a certain time (here set to 12s), the area becomes ashes.

✓ Ember → Tree

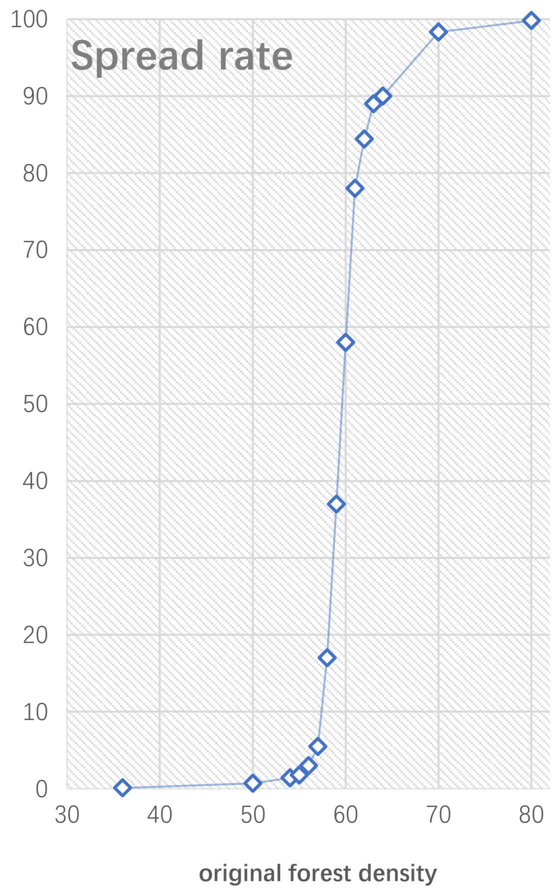
This setting is meaningless and unreasonable when examining whether a fire will spread to the entire forest. Actually, it usually takes a long time for the trees to recover, and in such a long period of time, the fire is long gone.

```
FAKE CODE:
FOR fire ∈ whole forests{
        ask its four neighbors
          if tree? ignite with probability pro
        turn to ember gradually
}
```

4.4.3 Run the model under different parameters

（1） density

With fixing the probability trees catch fire pro = 1 and the fire point at the exact center, we studied the effect of the original forest density on the fire spread rate.



Density%	Spread rate%
36	0.1
50	0.7
54	1.4
55	1.8
56	3
57	5.5
58	17
59	37
60	58
61	78
62	84.4
63	89
64	90
70	98.3
80	99.8

It can be seen that in the case of a single ignition point, the initial forest coverage density is not linearly related to the fire propagation rate. In fact, when the original forest density is below 40%, the fire situation will end very quickly. The 60% ratio is a **demarcation point** where the curve has abruptly changed. This means that once the original forest density exceeds 60%, the rate of fire spread will increase sharply.

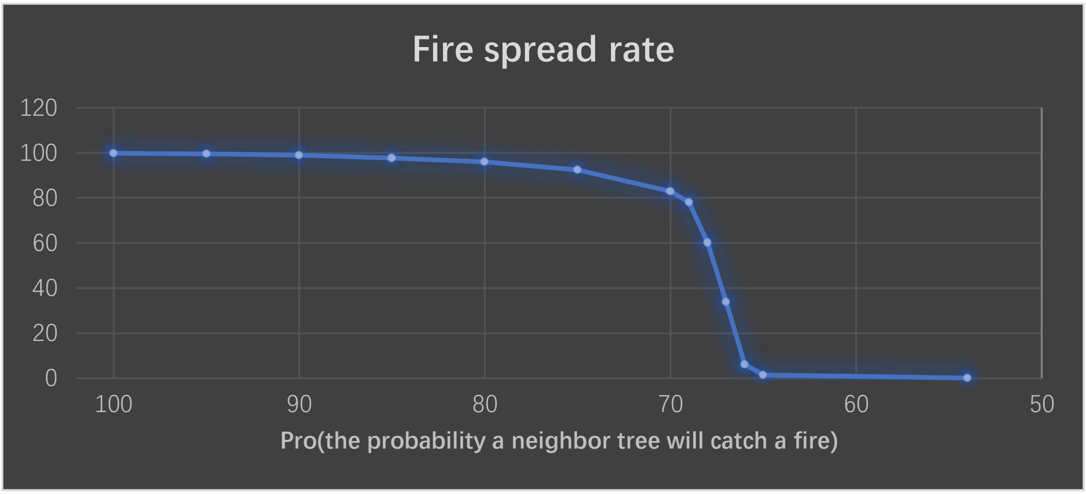
（2） Pro(the probability a neighbor tree will catch a fire)

With a fixed initial forest coverage density of 80% and the ignition point at the exact center, we investigated the impact of fire probability on the fire spread rate.

The reason for selecting density=80% is to eliminate the influence of this factor on the final fire spread rate as much as possible.

It is conceivable that in the case of only one ignition point, the forest can only be burned entirely if the probability of catching a fire is extremely high. In fact, the results of the model simulation also prove this.

pro	100	95	90	85	80	75	70	69	68	67	66	65	54
Spread rate	99.8	99.5	98.9	97.7	96	92.4	82.9	78	60.2	33.9	6.2	1.5	0.1



It can be seen that the probability of catching fire and the fire spread rate have similar tipping point. At density=80%, this mutation point occurs around pro=68%, which means that once the probability of catching a fire is lower than this value, the probability that the forest will be completely burned will be greatly reduced.

（3）Fire point

The location of the fire point is also a factor worth considering. If the fire point happens to be located at the edge of the forest, such as the upper left corner, how will the spread of fire evolve? The rest of the fire points can be approximated as the central area of the forest. Therefore, we only need to compare the above two situations. In order to evaluate the difference between the two, we have a fixed fire probability of 100%

Based on simulation performance and data, there is little difference between the two when the forest cover area density exceeds 65%. However, in the case of density less than 65%, the ignition point in the lower left corner has a negligible contribution to the fire spread rate, compared to the central fire point.

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