

An Emergy-Based Hybrid Method for Assessing Sustainability of an Resource-Dependent Region

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Abstract: As the natural resources are getting exhausted, the concept of sustainable development of region has received increasing attentions, especially for resource-dependent cities. In this paper an innovative method that emergy analysis and IPAT (Human Impact Population Affluence Technology) model were combined in order to analyze the quantitative relationship of economic growth and energy consumption and further to evaluate its overall sustainability level. Taiyuan, a traditional, resource-dependent city in China, is selected as the case study region. The main results show that total emergy of Taiyuan increased from 9.023×10^{23} sej in 2007 to 9.116×10^{23} sej in 2014, with 38% reduction on non-renewable emergy and 125% growth on imported emergy. Regional emergy money ratio (RMB) was reduced by 48% from 5.31×10^{13} sej/\$ in 2007 to 2.74×10^{13} sej/\$ in 2014, indicating that the increasing speed of consuming resources and energy was faster than the increase of GDP, and that Taiyuan's money purchasing power declined. The lower emergy sustainability index (ESI) indicates that Taiyuan was explored and produced large quantities of mineral resources, which puts more stress on the environment as a consequence, and that this is not sustainable in the long run. The IPAT analysis demonstrates that Taiyuan sticks to the efforts of energy conservation and environmental protection, in order to promote regional sustainable development, it is necessary to take an integrated effort. Policy insights suggest that resourceful regions should improve include energy and resource efficiency, optimizing energy and resourceful structure.

Keywords: sustainability; resource-dependent city; emergy analysis; IPAT (Human Impact Population Affluence Technology); Taiyuan

1. Introduction

The sustainability of natural resources is a critical consideration in the development of modern societies, as natural resources are the key factors on promoting economic development and supporting our daily life [1]. One important aspect that must be considered is the consequence of the rapid resource consumption and the associated waste generation and polluting emissions, such as air pollutants emission, wastewater discharge and solid wastes[2-6]. Also, the increasing income and improved life quality require more natural resources [7], Thus, it is essential, and of tremendous significance, to study the complicated interactions between economic, ecological and social systems and quantify various flows[8-9], and to try to provide scientific decision support to policy makers so that they can prepare appropriate policies on promoting regional sustainability.

Several methods have been used to evaluate regional sustainability, material flow accounting[10-12], energetic life cycle analysis[13-15] and ecological footprint[16-18]are methods that are widely used to account for inputs, out-puts, throughputs and storages in the regions. Indeed, the present study drew on emergy analysis, it provides a way to incorporate environmental and socioeconomic flows, as emergy is "the total amount of available energy of one kind that is directly and indirectly required to make a given product or to support a given flow" [19]. This

method was conducted from a deep environmental sustainability perspective[20]and has received increasing attentions because it can provide a bio-centered perspective to quantify resources use [21]. Emergy analysis is an appropriate method for evaluating and comparing the regional sustainability [22].

Many empirical cases were carried out for assessing resource consumption, overall economic outputs and social benefits by emergy analysis. This method has been successfully applied at the national level[23-24], at the regional level including provinces [25-26],and cities[6] [27-28], and at the industrial park level [29-30]. For instance, Wei chen et al[23] estimated the sustainability of cement production in China and suggest that adjusting industrial structure, improving energy efficiency, and applying alternatives to replace raw materials are effective approaches to improve the sustainability of cement industry. Liu Hao et al. [25] evaluated the ecological-economic system in Liaoning Province of China and found the principles of reduction, reutilization and recycling should be taken as the guidelines for promoting the reuse of wastes and the closed fine circulation of resources to minimize the discharge of wastes by conducting emergy analysis. Z liu et al. [6]compared different characteristics among different four Chinese mega-cities (Beijing, Tianjin, Shanghai and Chongqing)by conducting emergy analysis and imply that big cities are further dependent on energy supplies from neighboring regions. Similar studies were also undertaken in Texas, namely Odum H T and Blissett M [24], in which they examined and evaluated the relationships of natural and environmental resources to the Texas economy. Such a research finding can help local governments make appropriate regional sustainable production and consumption policies.

It is clear that emergy analysis has been employed to assess renewable, nonrenewable, local and imported resource flows, as well as human-dominated ecosystems. However, at the regional level , most published studies are focused on the metropolitan cities like Beijing, Texas, Rome and Italy[6][24][31–32],the specific types of cities, such as Suzhou, an export-oriented city in Eastern China[33],and Liaoning, an industrial city in the northeast of China[25]. It is concluded that existing research rarely discusses the sustainability of resource-dependent cities, and, in previous research, there are some researchers who use the emergy method to analyze the development of resource-dependent cities, and the papers are mainly focused on the development level of a circular economy[34], evaluation of economic system[35], eco-efficiency[36], and urban development level evaluation[37], but there is little research on the sustainability of resource-dependent cities , especially of cities located in Shanxi Province of Western China. Shanxi Province has been determined as the “Experimental area of comprehensive reform of resource-dependent economy”. Moreover, few studies focused on the dynamics of the anthropogenic drivers on total resource use and the overall sustainability. Under such a circumstance, it is critical to evaluate resource-dependent regions by employing emergy analysis so that proper sustainable development strategies can be prepared. The unique contribution is that this study will combine emergy analysis with the IPAT (Human Impact Population Affluence Technology) model so that the relationship between population dynamics, human well-being and resource consumption can be examined. A case study approach is adopted to investigate its development and evaluate its overall sustainability.

Taiyuan city, a traditional, resource-dependent city center in the hinterlands of China, is selected as our case study region. There are abundant mineral resources, such as iron,

manganese, copper, aluminum, lead, zinc, etc., and it is facing various challenges brought by these resources exploitation and utilization. These resource-dependent cities possess characteristics, such as are higher energy consumed, are heavier polluted, have a higher waste emission, and are more ecologically and environmentally fragile than other cities [38]. The potential policy insights from this study can also provide useful references to other resource-dependent regions with the similar challenges. The whole paper is organized as below. After this introduction section, we present our data source and research methods, including energy analysis procedures, the IPAT model. We then present our research results and discussions, finally, we give the policy implications before drawing our conclusions.

2. Materials and Methods

2.1. Research Area

Taiyuan City (lat. $32^{\circ}20' N - 34^{\circ}08' N$, long. $101^{\circ}30' E - 103^{\circ}30' E$, elevation 800 m above mean sea level), shown in Fig 1, the capital of Shanxi Province, lies in the fragile ecological environment of the eastern Loess Plateau. With a total area amounting to 6988 km², Taiyuan is the political, economic, cultural and educational heart of Shanxi province, has been oriented as one of the major centers in China for energy production and for chemical and metallurgical industries, and the proportion of heavy metal industries in Taiyuan is ranked second out of 20 major metropolitans in China [39,40]. It is the national important energy sources and heavy chemical city which is characteristic by outputting energy, raw materials and other products, taking the metallurgy, chemical engineering etc as the pillar. Similar to other Chinese cities, Taiyuan City has experienced rapid urbanization and economic development. The GDP of Taiyuan City increased from 1.04×10^{11} yuan in 2007 to 2.53×10^{11} yuan in 2014.

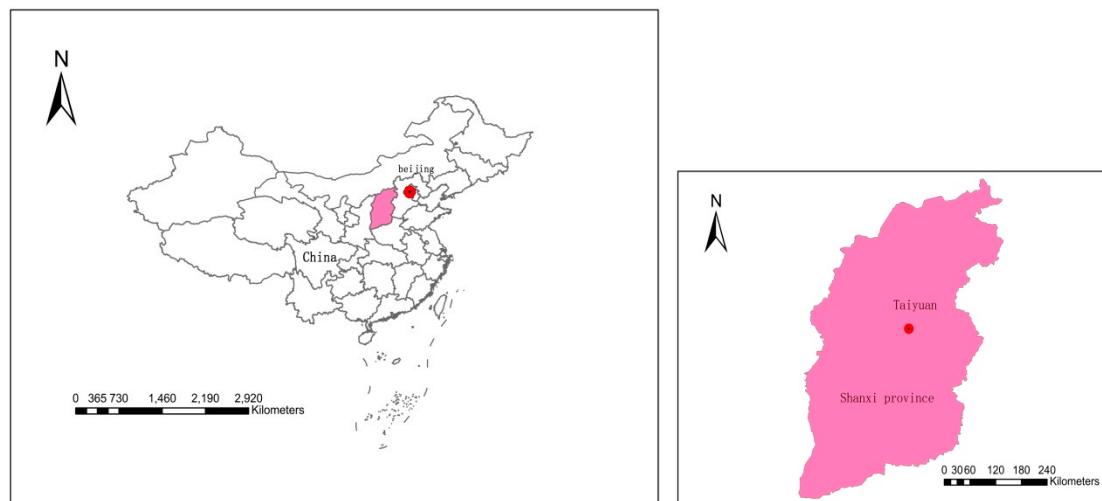


Fig. 1. A sketch map showing the geographical location of Taiyuan.

The orientation of Taiyuan is “national important energy sources and heavy chemical city”, which has run counter to the concept of sustainable development of city. In 1998, Taiyuan was listed by some related organization in United Nations as one of the world’s top 10 polluted cities. Natural resources are getting exhausted because of the unreasonable use. Such series of problems are bothering the development of Taiyuan. Taiyuan has done better in controlling the pollution and economic structure transformation. This makes Taiyuan City an

appropriate case study for assessing the sustainability. However, for it to take on the path of sustainable development, it still has a long way to go.

2.2. Data Source

The original research data were derived from Taiyuan Statistics Yearbook (2007–2015)[41]

2.3. Emergy Analysis

Emergy was first introduced by the ecologist Odum, and is defined as the amount of energy of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. Emergy synthesis projects local input flows on a biosphere scale, by converting all the materials, energy sources, human labor, and services required, directly and indirectly, into emergy units that are summed up to yield the total emergy [42]. The emergy of all inputs to a system is calculated in terms of solar emjoules (sej) by means of suitable conversion factors called transformities (expressed in sej/J) or specific emergy (expressed in sej/g-or other units). Emergy analysis has been widely applied in recent years to study the socio-economic-environmental system of many cities, e.g., Campania in Italy[32], Beijing[28], and Chinese mega cities [6]. In this paper, the following steps were used to conduct the emergy analysis:

The first step is to analyze the main ingredients and energy flows of the study area, and establish a basic database consisting of the natural environment, agriculture, industry, and other economic and social sectors. It is crucial to define the system boundary and identify the main features of the research area so that the interactions of resource flows and primary resources can be clearly reflected. The second step is to distinguish main renewable, local non-renewable, imported and exported emergy categories, and then calculate the emergy value in terms of solar emjoules (sej) by the process of conversion. The conversion equation is as follows:

$$E_m = \sum_i T_i \times E_i \quad (1)$$

In the equation: T_i stands for the solar transformity of the i th input flow, while E_i is the actual energy content of the input flow to the process.

The third step is to calculate the emergy value of each category comprised of renewable resources (R), non-renewable resources (N), imported resources (IM) and exported resources (EX). Renewable resources include natural energy, such as solar energy, wind energy, rainfall energy (chemical), rainfall energy (geo-potential), planet cycle energy, and local renewable resources, such as agricultural products, livestock, and aquatic products. Non-renewable resources include electricity, cement, steel, gasoline diesel, etc. The imported and exported resources mainly consist of raw and commercial products, and tourism is also included in the imported resources. The values of solar transformity are drawn from published research, by researchers including Odum and Huang[43-45]. The detailed flows and corresponding transformity are shown in Table 1.

Table 1. Emergy flows and corresponding transformity.

Flows	Item	Unit	Transformity (sej/unit)	Reference
Renewable resource emergy (R)	Solar energy	J	1	[43]
	Wind Energy	J	2.45×10^3	[44]
	Rainfall energy(chemical)	J	3.05×10^4	[44]
	Rainfall energy(geo-potential)	J	4.70×10^4	[44]
	Earth cycle energy	J	5.80×10^4	[44]
	Agricultural products	g	4.08×10^{11}	[43]
	Livestock	g	2.50×10^{11}	[43]
	Aquatic products	g	3.02×10^{10}	[43]
Non-renewable resource emergy (N)	Losses of topsoil	t	1.71×10^3	[44]
	Electricity	J	2.69×10^5	[43]
	Steel	g	3.02×10^9	[43]

	Raw coal	J	6.72×10^4	[43]
	Petroleum	J	1.86×10^5	[43]
	Diesel	J	1.86×10^5	[43]
	Natural gas	J	8.06×10^4	[43]
	Fuel oil	J	6.25×10^4	[44]
	Chemical fertilizer	t	8.28×10^6	[45]
Imported emergy (IM)	Goods income	\$	9.37×10^{12}	[44]
	Toursim income	\$	1.66×10^{12}	[45]
Exported emergy (EX)	Goods and service income	\$	6.34×10^{12}	[44]

Note: Unit Emergy Values are relative to the 15.83×10^{24} sej/yr planetary baseline value, RMB is transformed into US\$ using the annual exchange rate from 2007 to 2014.

Finally, emergy indicators were selected to examine the properties and environmental performances of the urban system, in this paper, several emergy indicators are established based on published papers from Odum, Song and Brown [43,46,47]. The main dynamic indicators can be seen in Table 2.

Table 2. Emergy-based indicator system for the regional sustainability.

Emergy Indicators	Unit	Formula	Explanation
Total emergy per year (U)	Sej	$R + N + IM$	Total emergy (the export is not included)
Emergy money ratio (EMR)	sej/yuan	U/GDP	Emergy flux produced per unit of purchasing power
Emergy per capita (EP)	sej/cap	$U/Population$	The ratio can reflect the true life quality of local citizens
Environmental loading ratio (ELR)	1	$(N + IM)/R$	The ration can reflect the pressure of economic activities on the local ecosystem
Emergy yield ratio (EYR)	1	$(R + N + IM)/IM$	The capacity of resource output of the local system
Emergy sustainable index (ESI)	1	EYR/ELR	The sustainability capacity of the local system

Note: The total emergy $U = R + N + IM$

2.4. The IPAT model

In order to further analyze the quantitative relationship of economic growth and energy consumption, this article employees IPAT equation and expands this model to carry out empirical analysis. The IPAT equation, proposed by Ehrlich and Holdren [48] in 1970, is a mathematical equations, including the relationship of environmental impact (I) with population (P), affluence (A) and technology (T), to study the relationship among economic growth, resources and environment of the form. In this study, we employ this identical model to reveal the contribution of the three driving factors, the equations can be expressed as

$$I = P \times A \times T \quad (2)$$

Where, P indicates the total population, A indicates per capita GDP, T indicates emergy consumption per unit of GDP (total emergy/GDP, namely consumption intensity).

So this equation could be simplified as:

$$I = G \times T \quad (3)$$

Where G refers to GDP.

If G_0 represents GDP in the base year , g represents the annual growth rate of GDP, t represents the decline rate of technology improvement, then energy use in target year (n) can be calculated by Equation:

$$\begin{aligned} I_n &= G_n T_n \\ &= G_0 \times T_0 \times (1+g)^n \times (1-t)^n \\ &= G_0 \times T_0 \times (1+g-t-gt)^n \end{aligned} \quad (4)$$

In case of $g-t-gt > 0$, it means that environmental impact increases year by year.

In case of $g-t-gt = 0$, it means that environmental impact will constant.

In case of $g-t-gt < 0$, it means that environmental impact decreases year by year. GT is defined as indicator to measure environmental impact.

3. Results and discussion

3.1. Energy flows of the city from 2007 to 2014

In the composition and structure of the energy flows, the values of total energy per year (U) demonstrate an upward trend, but there are no significantly increased amplitudes for this region. From 2007 to 2014, the total energy of Taiyuan increased from 9.024×10^{23} sej to 9.116×10^{23} sej (Fig 2). In terms of a growth range, the value of total energy in Taiyuan increased by only 1.02%. These results show that the materials and energy involved in the city increased due to an accelerated development of urbanization and industrialization in recent years, but because the entire scale of Taiyuan is too large, the potential rising speed was slowed. More specifically, Renewable and Nonrenewable energy, imported and exported energy are the four main components. Renewable resources including Solar, rain, wind, earthcircle, agricultural products, livestock and aquatic products kept nearly steady on the whole. Nonrenewable energy decreased from 1.166×10^{23} sej in 2007 to 0.741×10^{23} sej in 2014, which demonstrates that Taiyuan is abundant in mineral resources and decrease of nonrenewable energy in Taiyuan was mainly induced by consumption of mineral a key feature of manufacturing based resource city, so it develops its economy mainly through exploiting and producing mineral resources, which are generally non-renewable. With regard to imported and exported energy, the imported energy increased from 5.59×10^{22} sej in 2007 to 1.26×10^{23} sej in 2014, while the exported energy increased from 2.35×10^{22} sej in 2007 to 4.16×10^{22} sej in 2014, and the imported energy is higher to exported energy in Taiyuan. This indicates that local commodity and services cannot support local economic development and have to rely more on importing resource.

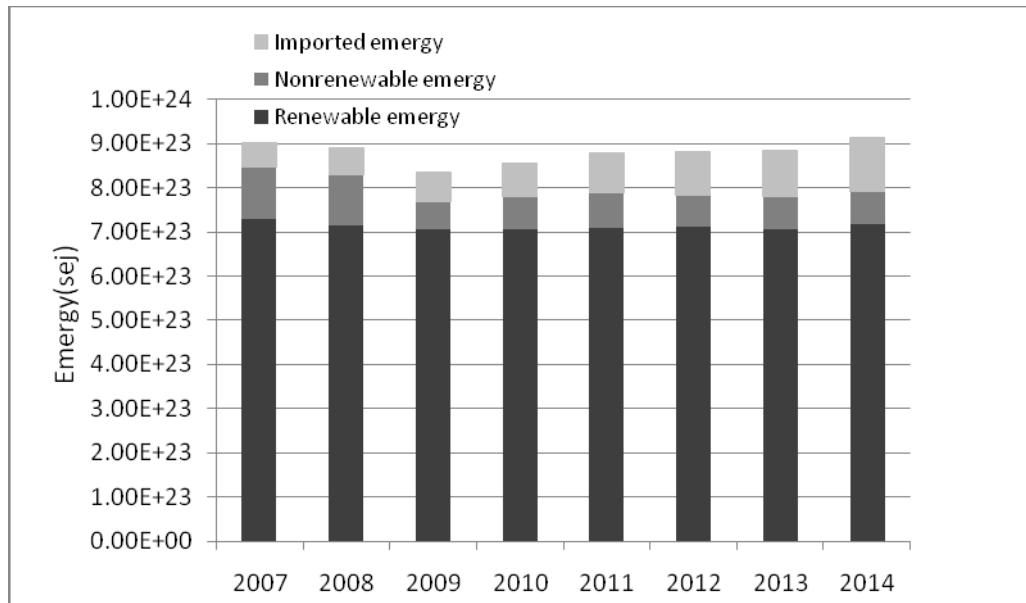


Fig 2. Total energy use per year and its components for Taiyuan .

3.2. Energy indicators

EMR is an indicator to evaluate how the economic system depends on local resource consumption and money purchasing power. The higher the value of EMR is, the fewer resources are being used to generate the same amount of GDP. Fig.3 shows that EMR in Taiyuan reduced by 48% from 5.31×10^{13} sej/\$ in 2007 to 2.74×10^{13} sej/\$ in 2014, indicating that the increasing speed of consuming resources and energy was faster than the increase of GDP, and that Taiyuan's money purchasing power declined. Resource-dependent city Taiyuan due to a large amount of natural resources.

EP calculated by dividing total energy by the local population, which is an indicator to evaluate the living standard of the region, including both renewable and nonrenewable resources. During 2007-2014, Taiyuan's population increased from 3.56 million to 3.7 million. EP for Taiyuan remained at the level of approximately 2.42×10^{17} sej/cap, this demonstrates that the increasing growth of population has been equivalent to the available resources and the energy increment in Taiyuan. As an industrial city, Taiyuan has a high value of energy use, mainly from the mining of local coal and metal ores, but the benefits were not completely conveyed to local residents since the fact that an increasing number of workers and trained staff from neighboring cities pour into Taiyuan, as there are more employment opportunities and better living standards.

EYR can be used to measure the investment efficiency of external resources to exploit local resources and contributes to the economy. A larger EYR value indicates that the economic development relies more on local resources, so the higher the value of EYR, the more efficient the energy and materials are used in the local urban system. As can be seen in Figure 4, the EYR of Taiyuan decreased gradually from 16.15 in 2007 to 7.56 in 2014, with an almost double decrease. It demonstrates that less local resources can be exploited, and that the utilization efficiency of resources has been decreasing, and the configuration of resources in Taiyuan still need to be optimized. ELR reflects environmental pressure from the perspective of environmentally renewable capacity to support economic processes, the ELR in Taiyuan is on the rise with some fluctuations, increasing from 0.24 in 2007 to 0.27 in 2014, the above result demonstrates that the use of non-renewable resources were consumed, and there exists a great deal of potential opportunity for Taiyuan to adjust its industrial structure and to implement an energy saving strategy. ESI is the system performance indicator to measure one system's overall sustainability. An increasing value of

ESI indicates that one region is moving toward sustainable development, with a feature of using less nonrenewable resources locally available and with less import, while a lower ESI value reflects that one region consumes more nonrenewable energy and imports more energy from outside, moving toward unsustainable development. In the study period, the ESI of Taiyuan shows a downward tendency, declining from 68.33 in 2007 to 27.80 in 2014, which shows that the self-organization and sustainability of Taiyuan is continuously deteriorating, this result reveals that Taiyuan, a resource-dependent city, explored and produced large quantities of mineral resources, which puts more stress on the environment as a consequence, and that this is not sustainable in the long run. As the capital of Shanxi Province, though tremendous volumes of mineral resources were buried underground the city, its exploration activities were constrained by some influential factors, such as urban land use planning and environmental regulations, etc. but the stress to the environment is still high, it is critical to identify the optimal pathway so that the resource-dependent city can move toward sustainable development.

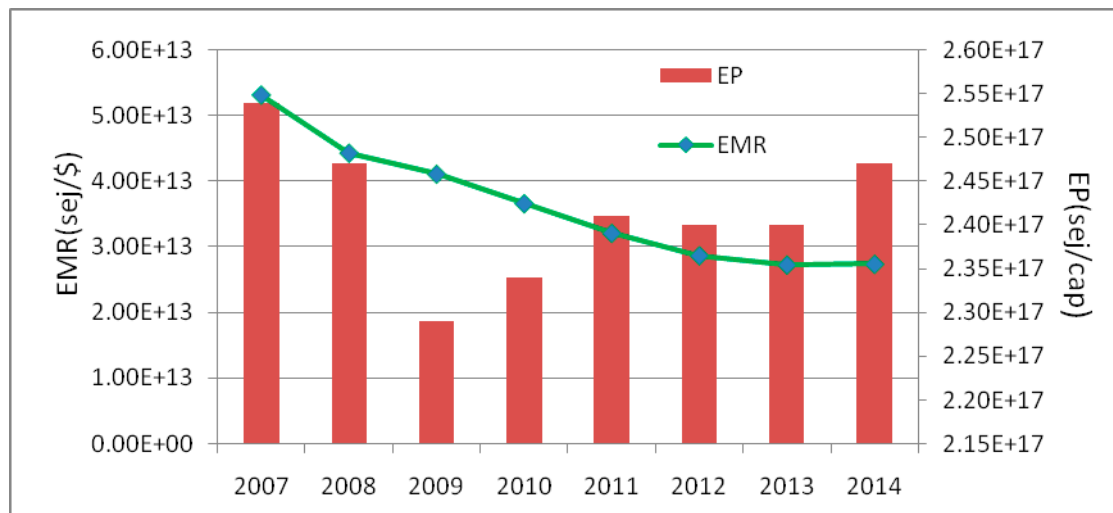


Fig 3. Trends of energy money ratio(EMR) and energy per capita(EP) for Taiyuan.

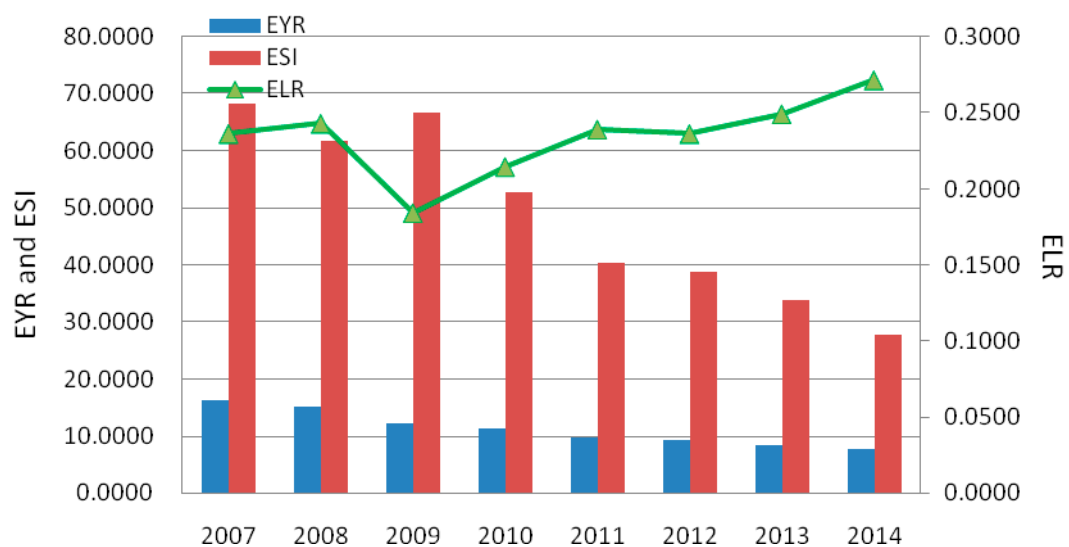


Fig 4. Trends of energy yield ratio(EYR), the environmental loading ratio(ELR) and energy sustainable index (ESI) for Taiyuan .

3.3. The application of IPAT function

As shown in Fig.5, from 2009 to 2014, the values of GT fluctuates in a relatively stable condition, while some unstable values appear from 2007 to 2009. As a whole, the results mean that the impact of economic development on environment tend to decrease by years, and economic development is harmonious with environmental protection. The GT values reached the relatively stable period top of 0.86 in 2011 and declined gradually from 2011 to 2014. Because of the international financial crisis starting in 2008, Taiyuan expanded investment of infrastructure once again in order to ensure its rapid economic growth, in which the effect of investment of infrastructure to the environment is evident and the value of GT decrease disharmony.

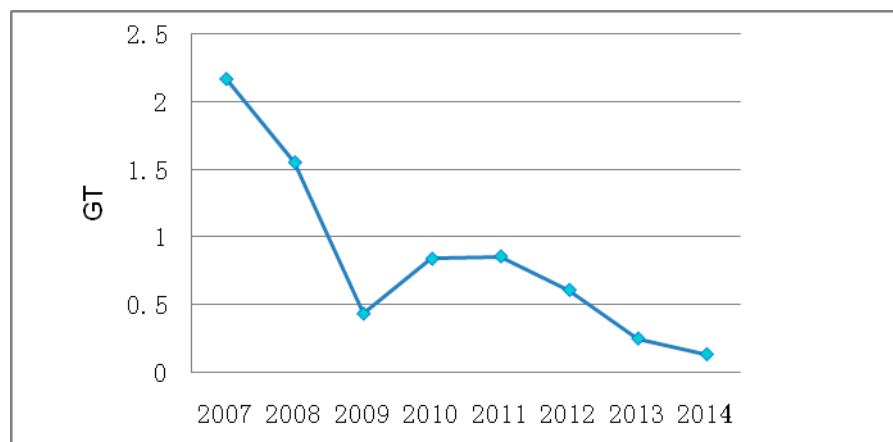


Fig 5. Change of the values of GT

According to the growth rates in all years, we figured out that the average growth rate of GDP in 2007–2014 is 0.12, while the average decline rate of energy consumption is 0.6206 over the same period, in which the average decline rate of the total GT value is 0.8582. In the course of fast development of economy, Taiyuan has not give up the efforts of energy conservation and environmental protection.

4. Policy Implications

Resource-dependended cities particularly face more challenges in balancing economic development and environmental protection. In this paper, as a typical Chinese resource-dependended city, Taiyuan was selected as one case study region for quantifying the interactions between its economic, ecological and social systems so that valuable policy implications can be found for policy makers. Emergy analysis and IPAT model were combined in order to evaluate its overall sustainability level. The following policy insights have been achieved and listed below:

Firstly, Taiyuan should improve energy and resource efficiency, reduce local fossil fuel and natural resources exploitation and rely less on imported energy. As a typical Chinese resource-dependended city, Taiyuan has too many different mineral resources, leading to more consumption on fossil fuels. Such an resource development structure cannot be easily changed due to national development plan. Therefore, it is critical for both local government and local residents to work together and support innovative green production technologies [49-50]. Shanxi has experienced the stage of accelerating urbanization process, and this will increase the pressure on its carbon mitigation. Therefore, the government should promote the green

urbanization by developing green construction and improving the public transportation systems. Meanwhile, the clean and renewable energy should be widely popularized and used in people's daily life, heating and power generation, e.g., wind, solar, hydro and biogas [51]. Under such a circumstance, the Taiyuan government should prepare their own green building standards by considering the local weather and other conditions. Meanwhile, innovative concepts, such as cleaner production, process integration, and industrial symbiosis, should be further promoted so that both energy and resource efficiency can be further improved. In addition, it is urgent to develop renewable and clean energy, such as solar power, wind power, and geothermal power, so that energy structure can be optimized toward more sustainable direction.

Secondly, it is rational for Taiyuan to optimize its resourceful structure. The emergy analysis results indicate that Taiyuan is more developed than other resource-exporting cities, but still far away from the most developed regions in China, such as Beijing [28]. With the depleting resources, many resource-oriented cities in Taiyuan are suffering from increasing environmental issues and unemployment. Consequently, this is a signal to regional planners that they must focus more on sustainable development and ecological protection in Taiyuan City due to its fragile ecological environment, so as to maintain a balance between economic development and ecosystem health in the future [52].

5. Conclusions

Taiyuan is experiencing rapid urbanization, fast population growth and resource consumption. However, such rapid development also has brought many challenges, such as resource depletion, environmental pollution and damaged ecosystems. In order to prepare appropriate sustainable development strategies, it is crucial to evaluate its sustainability. In this regard, the study combines both emergy analysis and IPAT model in order to evaluate its overall sustainability level and analyse the parallel driving forces. The results show that the consumption amount of renewable resource remained nearly constant from 88.88% in 2007 to 78.64% in 2014, nonrenewable emergy decreased from 1.166×10^{23} sej in 2007 to 0.741×10^{23} sej in 2014, and the imported emergy increased from 5.59×10^{22} sej in 2007 to 1.26×10^{23} sej in 2014. While the exported emergy increased from 2.35×10^{22} sej in 2007 to 4.16×10^{22} sej in 2014. With regard to key emergy indicators, EMR reduced by 48% from 5.31×10^{13} sej/\$ in 2007 to 2.74×10^{13} sej/\$ in 2014, EP for Taiyuan remained at the level of approximately 2.42×10^{17} sej/cap, respectively. These results indicate that local economy and residents' living quality improved significantly with the higher emergy use. But rapid development resulted in more environmental pressures to local ecosystem and influenced the overall sustainability. The EYR of Taiyuan decreased gradually from 16.15 in 2007 to 7.56 in 2014, the value of ELR increased from 0.24 in 2007 to 0.27 in 2014 and the value of ESI declined from 68.33 in 2007 to 27.80 in 2014. Moreover, the IPAT analysis demonstrates that Taiyuan sticks to the efforts of energy conservation and environmental protection, in order to promote regional sustainable development, it is necessary to take an integrated effort. Useful measures include improving energy and resource efficiency, optimizing energy and resourceful structure. Although the case is based upon Taiyuan and the related policy recommendations are proposed specifically for Shanxi province, such policy insights are also valuable to other resource-dependent cities facing similar challenges.

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