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Coupling Coordination Between Geothermal Adoption and Regional Economy Based on Water-Heat-energy Nexus, a Case Study of Beijing

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ABSTRACT

Rapid urbanization has resulted in severe demands on water, heat and energy resources, which threaten the sustainability of the urban economy and environment. Geothermal energy is one of the cleanest sources of energy and it plays an important role in the sustainability of the urban economy and environment. This paper employs Vector Autoregressive Model (VAR) model to detect the effects of water, heat and energy consumption on geothermal adoption and interactions among them. Beijing is chosen as a case study to investigate the water-heat-energy nexus and coupling coordination between geothermal adoption and regional economy. The results reveal that water consumption has mainly affected on geothermal adoption. water consumption and energy consumption have negative effects on geothermal adoption while centralized heat supply has a positive effect on geothermal adoption. This paper also adopts gear model to investigate coupling coordination between geothermal adoption and regional economy. The rates of geothermal adoption and regional economy are various but they are in the good state of coupling coordination. In addition, the coupling coordination of geothermal adoption and regional economy has the potential to promote.

1. INTRODUCTION

With the rapid development of China's economy, energy consumption based on fossil fuel continues to increase. Air pollution, greenhouse effect and other environmental problems have become increasingly prominent, seriously restricting the sustainable development of China's economy(Fan and Lei, 2015). The State Council put forward the target to reduce the emissions intensity of economic growth by 40%–45% below 2005 levels by 2020 (The State Council, 2009). China also announced its goal to reach its carbon emissions peak in around 2030, with the intention of peaking earlier, and to raise the non-fossil fuel share of primary energy supply to approximately 20% by 2030(Xinhuanet, 2014). As China's capital and its political and cultural center, Beijing should play a leading role in mitigating and adapting to climate change. Utilization of geothermal energy is becoming more desirable in Beijing with the growing demand for energy and increasing concern for climate change.

In order to guarantee the development geothermal adoption, Beijing municipal government formulated a series of policies and regulations. In 2011, Beijing municipal government pointed out development of geothermal adoption is an essential target in promoting "Green Beijing" implementing the "Development plan of new energy and renewable energy in Beijing in 12th Five-Year". China's National Energy Administration, Ministry of Finance, Ministry of Land and Resources, and Ministry of Housing and Urban-Rural Development jointly issued a document "Guidelines on promoting of geothermal energy development and utilization" in January 2013. Beijing Municipal Commission of Development and Reform jointly with 6 bureaus issued a document "Guildelines on further promoting the development of geothermal energy and implementation of heat pump systems in Beijing" in December 2013. It explicitly stated that the enterprises could get 50% of government subsidies for heating when they drill geothermal wells while the heating projects can get 30% of government subsidies for using shallow geothermal energy. National Development and Reform Commission, the National Energy Administration and Ministry of Land and Resources jointly issued a document "thirteen five" plan of Geothermal energy development and utilization" in January 2017 and it explicitly stated that the scale of shallow geothermal heating (cooling) area will be increased by 80 million square meters and the scale of hydrothermal geothermal heating area will be increased by 30 million square meters up to 2020(Jiang, 2016).

Beijing is rich in low-temperature geothermal resources. The identified geothermal area covers over 2760km^2 with 10 geothermal fields(Liu et al., 2010). The temperature of geothermal water is 25℃ to 89℃. For nearly 40 years geothermal waters have been used intensively (e.g. for space heating, bathing, swimming pools, health spas, recreation, greenhouses, fish farming) bringing significant social, economical, and environmental benefits to the region (Wang, 2007). However, Beijing is lack of water resource and energy restrictions have gradually become a bottleneck in restricting the Beijing's economic and social development. For better implementation of geothermal adoption, the contribution of factors influencing geothermal adoption from water consumption, centralized heat supply and energy consumption in Beijing should be explored and it is necessary to explore the diversity of coupling coordination degree between geothermal adoption and Beijing's economy to promote sustainability of geothermal resources.

In this study, the water-heat-energy nexus was defined as the relationships among water consumption, centralized heat supply and energy consumption in the system of geothermal adoption. The present study is concerned with geothermal adoption which is coupling coordinated with regional economy. The remainder of this paper is organized as follows: Section 2 presents a review of the relevant literature. Section 3 introduces the study's methodology and data sources. Section 4 discusses the empirical results and analysis. Conclusions and policy implications are presented in Section 5.

2. LITERATURE REVIEW

The scope of the water-energy nexus studies has also been extended to relevant environmental impacts and climate change implications(Wang et al., 2017). Mo et al. studied how water consumption impacted embodied energy, greenhouse gasemission, and energy cost and found the importance of assessing the energy–water nexus when pursuing demand-side control targets(Mo et al., 2014). Yang and Chen developed a new energy–water nexus analysis framework for wind power generation systems, which includes both element and pathway nexus analyses to investigate the dominant sectors and pathways for energy–water circulation and the mutual relationships between pairwise components of the wind power generation system(Yang and Chen, 2016). Zhou et al. measured the climatic co-benefit of water conservation based on a water flow analysis to reduce energy demands and GHG emissions in an optimized water supply system(Zhou et al., 2013). Mroczek et al. described small scale field experiments undertaken at the Wairakei and Ohaaki Geothermal Fields to measure the silica scaling potential of cooled separated geothermal water and to assess whether it could be safely disposed of by injection(Mroczek et al., 2017). Daniilidis et al. outlined a method in which the heat production of a geothermal system was controlled in relation to the demand from a district-heating network. A model predictive control strategy was designed, which used volume measurements in the storage tank, and predictions of the demand, to regulate the production of the geothermal system in real time(Daniilidis et al., 2017).

In the issue of water-heat nexus, It is important to match the heat supply and demand in district heating systems, and daily discrepancies can be bridged with the use of a storage component, while the geothermal production level can be adjusted to match the seasonal changes(Eicker et al., 2015; Sayegh et al., 2016; Kyriakis and Younger, 2016). However, applying a seasonally variable production rate to the geothermal system can have several consequences at reservoir level, among which are changes in chemical composition, pressure and possibly also temperature. Moreover, a seasonally variable production rate could also affect the cold front breakthrough time of the reservoir, when compared with a constant production level. Cui et al. proposed a new method for geothermal exploitation from hot dry rocks by recycling heat transmission fluid in a horizontal well via a closed loop and calculate the heat mining rate for the new technology to assess its technical and economic feasibility using numerical simulation models(Cui et al., 2017). Bu et al. established a numerical simulation to study the feasibility of geothermal exploitation from existing abandoned wells, and conducted parametric studies to specify the optimum values(Bu et al., 2012). Cheng et al. analyzed the influence of insulation on the geothermal power generation using the double-pipe heat exchanger(Cheng et al., 2014). Aliyu et al. aimed to guide reservoir engineers/managers in the selection of a combination of parameters from amongst various possible alternatives in developing deep geothermal reservoirs which can meet the desired temperature at the production wellhead for sustainable energy production. They found that fluid injection temperature is the parameter that influences the experiment the most during exploitation involving production temperature, whereas injection pressure rate happens to have a more significant impact on reservoir cooling(Aliyu et al., 2017).

For the geothermal industry in particular, recent research has emphasized the sustainability. Sam et al. modified an economic model illustrating the application of fiscal instruments in geothermal development for electricity generation based on simplifying assumptions(Sam et al., 2015). Zhou et al. clarified the composition of geothermal industry including the business process and the organization forms of the exploitation and utilization of geothermal resources(Zhou et al., 2014). Shortall et al. described the development of a sustainability assessment framework for geothermal energy projects in Iceland, New Zealand and Kenya using the input of international multi-stakeholder groups and internationally recognized methods(Shortall et al., 2015). Pellizzone et al. explored the role of public and stakeholder engagement in the processes of innovation in the geothermal energy sector and consolidated a methodological framework for comparative analysis of case studies on citizens' engagement to bring a social scientific perspective into geothermal energy research(Pellizzone et al., 2017).

The relationships among water consumption, heat supply and energy consumption in specific processes as well as the entire geothermal industry are not yet well understood. What are the heat, energy and water requirements and how do heat supply, water use and energy supply influence geothermal adoption? Based on the literature review and to the authors' best knowledge, there are no studies of influencing factors of geothermal adoption and coupling coordination analysis between geothermal adoption and regional economy. The main objective of this study is therefore to evaluate the influencing factors of geothermal adoption in Beijing using water-heat-energy nexus model and adopt gear model to assess the coupling coordination degree between geothermal adoption and regional economy taking Beijing as a case study.

3. MATERIALS AND METHODS

3.1 VAR model

Without imposing theoretical restrictions on endogeneity among variables, a vector autoregression procedure is appropriate to establish the dynamics between crude oil prices and exchange rates. These two variables are jointly treated as endogenous and are assumed to have no restrictions on the structural relationships in the present analysis. The VAR is commonly used in systems forecasting interrelated time series and analyzing the dynamic impact of random disturbances on a system of variables. The VAR procedure avoids the need for structural modeling by treating every endogenous variable in the system as a function of lagged values of all of the endogenous variables in the system(Bragnasrebe et al., 2014).

The mathematical representation of a VAR model is:

$$y_t = c_t + \sum_{i=1}^{k} \alpha_i y_{t-i} + \sum_{i=1}^{k} \beta_i x_{t-i} + u_t \tag{1}$$

Where y_t is an endogenous variable; y_{t-i} ($i = 1, 2, \dots, p$) is a lagged exogenous variable; x_{t-i} is an endogenous variable; c_t ($c_1, c_2, c_3, \dots, c_t$) is a constant term; α_i and β_i are matrices of coefficients to be estimated; u_t is a random disturbance term.

3.2 Gear Model

This paper uses the mechanics of gear transmission principle to analyze the relationship between geothermal industry and regional economy. As shown in Figure 1, there are three meshing gears in mechanics(Zhao et al., 2017).

Gear 1 represents the geothermal industry, Gear 2 represents the regional economy, and Gear 3 represents other industries in the economic system. The rotation of Gear 1 drives the rotation of Gear 2 while the rotation of Gear 3 drives the rotation of Gear 2. whether gears rotate faster or slower is depending upon the number of teeth on the basic wheels. The meshing rotation relationship of Gear 1 and Gear 2 is like the interaction between the regional economy and geothermal industry to promote each other. The gear model provides a useful tool to analyze and understand this dynamic process of the development of geothermal adoption. Gear ratio i refers to the ratio of the speed of Gear 2 and Gear 2. the formula is as follows:

$$i = w_1 / w_2 = z_2 / z_1 \tag{2}$$

Where, w_1 is the angular velocity of Gear 1, the speed of geothermal development; w_2 is the angular velocity of Gear 2, the speed of regional economic development; z_1 is the number of teeth for the Gear 1, and z_2 is the number of teeth on Gear 2.

According to the principle of gear transmission, the speed has increased after the linkage operation between Gear 1 and Gear 2. The total speed of Gear 1 is set to $\Delta\omega_1$, and the speed of Gear 2 is increased by $\Delta\omega_2$. The final speed of Gear 1 is $V_1 = \omega_1 + \Delta\omega_1$. The speed of Gear 2 is as follows.

$$V_2 = (z_1 / z_2) \times (\omega_1 + \Delta\omega_1) = (z_1 / z_2) \times \Delta\omega_1 \tag{3}$$

$$\Delta\omega_2 = (z_1 / z_2) \times \Delta\omega_1 \tag{4}$$

$$T = \Delta\omega_1 / \Delta\omega_2 = z_2 / z_1 \tag{5}$$

where, T is the ratio of developemtn between geothermal adoption and regional economy. $\Delta\omega_1$ and $\Delta\omega_2$ are the rate of development speed of geothermal adoption and regional economy.

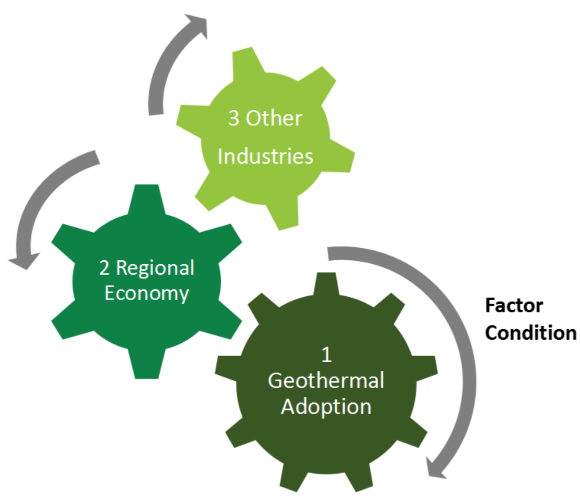

Figure 1. Gear model

3.3 Coupling coordination degree model

The coupling coordination model is obtained based on the concept and coefficient model of capacity coupling in physics(Wang et al., 2017). This coupling system incorporates two subsystems, i.e., geothermal subsystem and economic subsystem. Coupling degree can only show how strong the two subsystems are interacted with each other without reflecting the level of system coordination, making it necessary to introduce coordination degree to exhibit the positive coupling degree and build the coupling coordination model of geothermal adoption in economic region. Coupling coordination degree model can better identify the coupling and coordination evolution between two subsystems. The computation formula is as follows.

$$D=\left\{\frac{R_{GA}\times R_{RE}}{\left(\frac{R_{GA}+R_{RE}}{2}\right)^{2}}\right\}^{k} \tag{6}$$

Where, D is system coupling coordination degree; R_{GA} and R_{RE} are the rate of development speed of geothermal adoption and regional economy. The higher the D value is, the higher the coupling coordination degree between the systems is. This paper adopt max-min normalization method to standardize the data in the range of 0 to 1. The system has two subsystem so that k is 1/2.

3.4 Data sources

This study is based on years 2001-2015, and the sources mainly include: data about geothermal water exploitation mainly come from Beijing Geothermal Research Institute; data on water consumption, centralized heat supply, energy consumption, GDP and GDP per capita in Beijing come from Beijing Statistical Yearbook of 2001-2015. In order to eliminate the heteroskedasticity possibly existing in the model and facilitate hypothesis testing, geothremal adoption, water, Heat and Energy take logarithmic form and Y, W, H and E are their logarithmic forms.

4. RESULTS AND DISCUSSION

4.1 Geothermal adoption

According to the survey data in 2015, there are 184 geothermal wells developed and exploited in Beijing, including 149 exploited wells and 35 recirculated wells(Figure 2). Geothermal energy is mainly utilized in Changping and Chaoyang Districts with 34 wells and 49 wells respectively. the exploitation is increasing from 1971. the recirculation technology is becoming mature from 2000. Heating and hot springs are the two main modes of geothermal utilization(Liu and Lei, 2016).

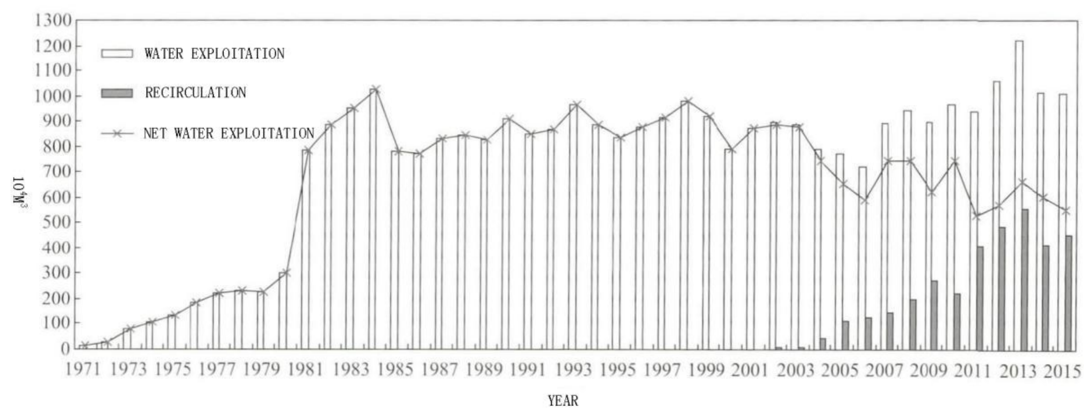

Figure 2 Beijing's geothermal net production from 1971 to 2015

Geothermal exploration in Beijing began in the mid-20th century in the southeast city. As shown in Table 1, 504 geothermal wells had been drilled by the end of 2015, one with a depth of over 3500 m(Table 1). The temperature of the return water is about 25–38℃. The overall thermal utilization ratio is about 53.2%. Because of ever increasing demands, the geothermal resource has long been overexploited. Since the 1980s in most parts of the geothermal field, water levels in the wells have declined by 1–2.5m per year (Che, 2004). To improve conditions for the sustainable use of the geothermal resources, injection has been carried out in the Xiaotangshan geothermal field since 2001. Return water from the geothermal heating systems, with temperatures of 24–37℃, is injected back into the reservoir. In 2007, there were seven injection wells in operation with a total injection of 1.232×106m3, accounting for 53.3% of the annual production(Pan, 2010). Since 2005, the water level in the geothermal reservoir has begun to gradually recover, showing that injection is effective in aiding the sustainable use of the Xiaotangshan geothermal resource(Duan et al., 2011).

Table 1. The summary table of Beijing's geothermal exploration data from 1971 to 2015

Year	Number of wells	depth(m)	Mean depth(m)	Max depth(m)
1971-1975	25	23943.96	957.76	2537.00
1976-1980	24	22341.21	930.90	2600.50
1981-1985	35	42040.62	1201.16	2605.00
1986-1990	29	31328.78	1080.31	2105.57
1991-1995	22	31159.45	1416.34	2572.00
1996-2000	75	151384.34	2108.50	3766.00
2001-2005	152	359191.94	2363.10	4051.36
2006-2010	115	369685.87	3214.65	4088.88
2011-2015	27	73600.68	2725.95	3616.00

4.2 Unit root test

This paper adopts the ADF test to determine whether the time-series data are stationary. The unit root test lag length is determined by the Schwarz information criterion (SIC). The ADF unit root test results in Table 2 suggest that the variables are not all a stationary sequence, but their first-order difference is a stationary sequence. Therefore, Y, W, H and E are all integrated of order 1.

Table 2. Results of the unit root test

	Variables	1% Critical value	5% Critical value	10% Critical value	t-Statistic	Prob.
Levels	Y	-2.740613	-1.968430	-1.604392	0.220539	0.7353
	W	-2.740613	-1.968430	-1.604392	-10.148640	0.0000
	H	-2.792154	-1.977738	-1.602074	1.716257	0.9698
	E	-2.740613	-1.968430	-1.604392	-4.623671	0.0002
First difference	Y	-2.754993	-1.970978	-1.603693	-5.367611	0.0001
	W	-2.792154	-1.977738	-1.602074	-1.899733	0.0479
	H	-4.992279	-3.875302	-3.388330	-4.997906	0.0099
	E	-2.754993	-1.970978	-1.603693	-1.737597	0.0281

4.3 Cointegration test

The trace statistic and Maximum Eigenvalue test are used to determine whether there is a co-integration relationship. The results of co-integration tests between Y, W, H and E are presented in Tables 3-4. As is evident in these tables, all null hypotheses in which there is no co-integration equation are rejected and there are one or two equations between variables. Therefore, a co-integration relationship exists between the Y and W, H and E.

Table 3. Unrestricted co-integration rank test (Trace)

Hypothesized No.of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical value	Prob.**
None*	0.990559	120.3838	47.85613	0.0000
At most 1	0.951077	59.76931	29.79707	0.0000
At most 2	0.769731	20.54180	15.49471	0.0079
At most 3	0.105627	1.451224	3.841466	0.2283

Trace test indicates 1 cointegrating eqn(s) at the 0.05 level

*denotes rejection of the hypothesis at the 0.05 level

** MacKinnon-Haug-Michelis(1999) p-values

Table 4. Unrestricted co-integration rank test (Maximum Eigenvalue)

Hypothesized No.of CE(s)	Eigenvalue	Max-Eigen Statistic	0.05 Critical value	Prob.**
None*	0.990559	60.61451	27.58434	0.0000
At most 1	0.951077	39.22751	21.13162	0.0001
At most 2	0.769731	19.09058	14.26460	0.0080
At most 3	0.105627	1.451224	3.841466	0.2283

Max-Eigenvalue test indicates 1 cointegrating eqn(s) at the 0.05 level *denotes rejection of the hypothesis at the 0.05 level

** MacKinnon-Haug-Michelis(1999) p-values

4.4 VAR model

4.4.1. Optimal Lag Order Analysis

The longer the lag period is, the lower the degree of freedom and the weaker the explanatory power. Therefore, it is necessary to select an optimal lag period for the variables in the model to have a strong explanatory power. In this paper, a lag of 1-2 are selected as a result of the logarithmic likelihood ratio (LogL), AIC, SC, sequential modified LR test statistic (lR), FPE (final prediction error) and HQ (Hannan-Quinn) information criterion, as shown in Tables 5. Hence, this paper selects the lag of 2.

Table 5. Lag selection criteria for Geothermal application

Lag	LogL	LR	FPE	AIC	SC	HQ
0	60.73498	NA	1.91E-09	-8.728459	-8.554629	-8.764189
1	110.6431	61.42543*	1.22E-11	-13.9451	-13.07595	-14.12375
2	145.0197	21.15482	2.20e-12*	-16.77227*	-15.20779*	-17.09384*

* indicates lag order selected by the criterion

LR: sequential modified LR test statistic (each test at 5% level)

FPE: Final prediction error

AIC: Akaike information criterion

SC: Schwarz information criterion

HQ: Hannan-Quinn information criterion

4.4.2. VAR Estimates and Stability Tests

Through the unit tests and the co-integration tests, we identified that all variables are stationary after first-order differencing and there is a co-integration relationship between Y and W, H, and E. Therefore, the VAR model, which includes these variables, can be estimated using the AIC and SC criteria. It is necessary to test the stability of VAR model before use the mode to conduct impulse response. The characteristic roots of the coefficient matrix, pesaran and pesaran procedure are used in the stationary test. Figures 2 show that the characteristic roots are less than 1 and lie inside the unit circle. This indicates that the model satisfies the stability condition. It can be seen from the above analysis, the results of unit-root tests and co-integration test show that the variables is stationary. The reliability of the model estimation results depends on the stationariness of the variables. Meanwhile, the model has been proved to be stable and has a high degree of fit to the sample. Hence, the estimation results of data is reliable.

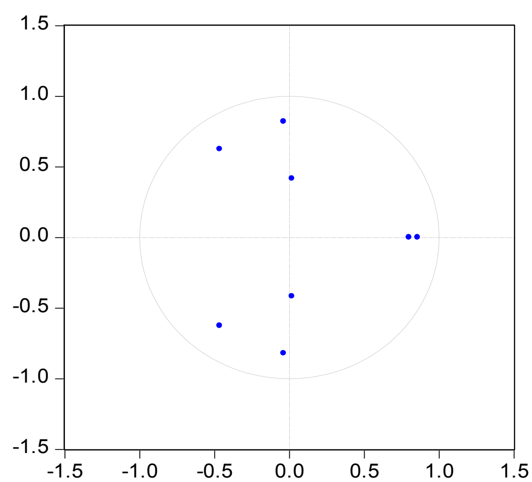

Figure 2. VAR roots of characteristic polynomial. Note: blue dots indicate characteristic roots

4.4.3. Impulse Response Functions

As observed in Figure 3, Water consumption has a negative response to geothermal adoption while centralized heat supply has a positive response to geothermal adoption. Energy consumption shows a negative response in the first two years and then has a positive response in the third year but subsequently achieve equilibrium prior to showing a negative response in the long-term. Meanwhile, geothermal adoption has its own historic interaction and it has the fluctuation in the long term.

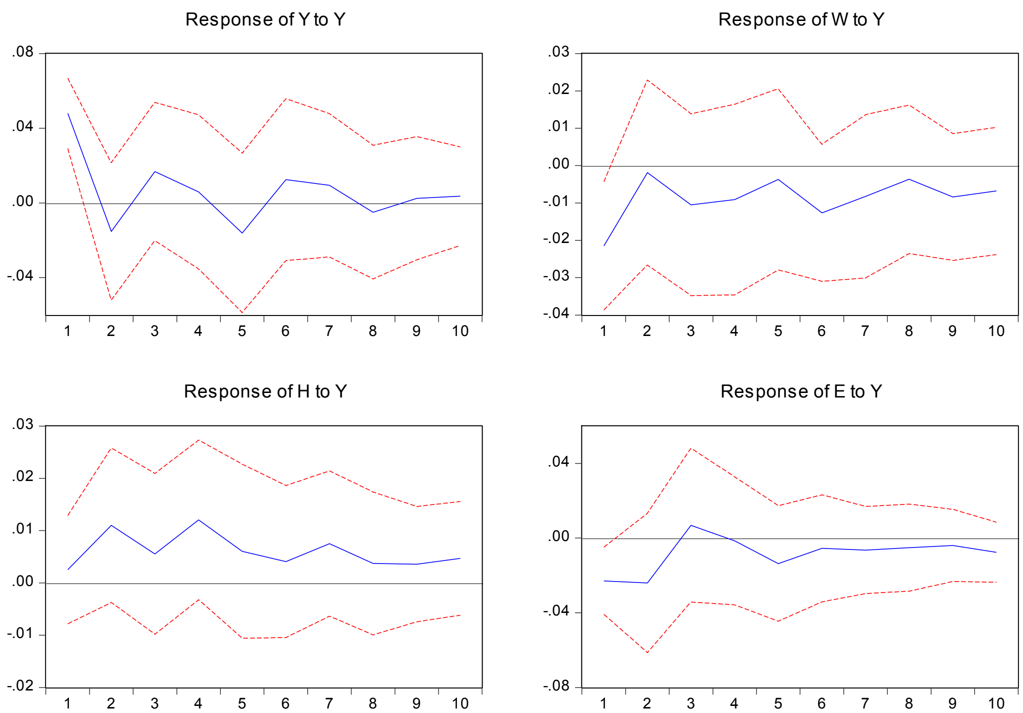

Figure 3. Responses of Y, W, H, E to Y

4.5 Variance decomposition

The variance decomposition results are shown in Table 6, which reports the contribution rate of each variable to the movement of the dependent variable. We can see that Y changes as the variance contribution gradually decreases, from 63.11% to 31.56% from the 1st period to the 10th period. Y is mainly affected by its own historical development in the first two periods and then Y is mainly affected by W. The contribution of W to Y increases from 24.61% to 50.20% at the first 5th period and then keeps stable around 50% from 5th period to the 10th period. The contribution rate of E fluctuates during the periods to this analysis but the contribution rate is very small and it becomes steady near 10%. The contribution rate of H increases from 3.09% and it gets its peak of 7.42% in the 10th period. We can draw the conclusion that Y has its own influencing on itself in the first two periods and then W has the greatest affect on . The degrees of H has the smallest impact on Y while this influencing is increasing and E has greater impact on Y but it has fluctuation.

Table 6. Variance decomposition of Y

Period	S.E.	Y	W	E	H
1	0.048009	100.000000	0.000000	0.000000	0.000000
2	0.063415	63.106350	24.613060	9.191649	3.088943
3	0.072952	53.003630	36.183780	7.104935	3.707656
4	0.086410	38.237010	45.910010	10.990610	4.862372
5	0.094792	34.648790	50.196090	9.387309	5.767809
6	0.097468	34.403690	48.148740	10.768710	6.678864
7	0.102397	32.015520	51.253780	9.965410	6.765296
8	0.102647	32.093130	51.006780	10.114060	6.786026
9	0.103596	31.564240	51.039160	10.042080	7.354518
10	0.103791	31.564740	50.868950	10.147430	7.418879

4.6 Coupling coordination degree between geothermal adoption and regional economy

The degree of coordinated coupling between geothermal adoption and economy in Beijing demonstrated an overall increasing trend from 1979 to 2015. the degrees are over 0.5 which shows that the development of geothermal adoption has coordinated well with the economic development in Beijing(Figure 4). The rates of the speed on the development of geothermal adoption and economy in Beijing have the fluctuation around 0. The average of the rates is 0.2432 which indicated that the development of geothermal adoption has the positive trend with the regional economy.

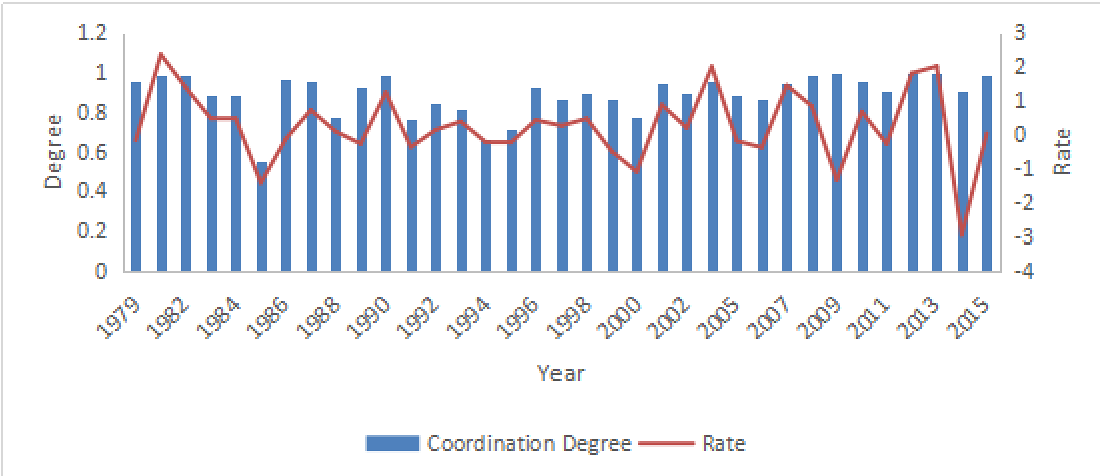

Figure 4 Coupling coordination degree and rate of speed between geothermal adoption and economy in Beijing

5. CONCLUSIONS

This paper aims to investigate the relationships among geothermal water, water consumption, centralized heat supply and energy consumption in the geothermal adoption using water-heat-energy nexus for the time span from 2001 to 2015 using a vector autoregression model, and impulse response function and variance decomposition methods. Based on water-heat-energy nexus, it adopts gear model and coupling coordination model to illustrate the coupling coordination degrees between geothermal adoption and economy in Beijing. It is demonstrated that geothermal adoption changes as the variance contribution gradually decreases and is mainly affected by its own historical development in the first two periods and then it is mainly affected by water consumption. Water consumption has mainly affected on geothermal adoption. Water consumption and energy consumption have negative effects on geothermal adoption while centralized heat supply has a positive effect on geothermal adoption. Centralized heat supply has the smallest impact on geothermal adoption while this influencing is increasing and energy consumption has greater impact on geothermal adoption. The rates of geothermal adoption and regional economy are various but they are in the good state of coupling coordination which is more than 0.5.

This study not only effectively complements existing research but also provides important suggestions for policy makers for regional areas.

(1) Promoting geothermal adoption is a complex system involving exploration, evaluation, development and utilization. Every stage of geothermal adoption should be focused on. Even though China's recent policies actions have broken the high-cost limitation and stimulated investment in the geothermal adoption, utilization of geothermal water, which is related to water consumption, heating and energy use is undoubtedly facing enormous development problems.

(2) Governments should pay more attention on water-heat-energy system when they begin to utilize geothermal sources. They should plan the geothermal adoption which may affect the regional economy and environment.

(3) Governments should formulate the regulations which are related to geothermal adoption. Geothermal enterprises should pay attention on the geothermal water recirculation and geothermal water affecting heating and energy consumption.

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