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RESEARCH ARTICLE

Configurational conditions of national carbon intensity: a fuzzy set analysis of 136 countries

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Abstract

Drawing on the insights from the literature in environmental economics and politics, this study examines the configurational conditions of national carbon intensity by constructing a new analytical framework integrating six factors, i.e. population, affluence, industrial structure, energy intensity, urbanization rate and democracy. A fuzzy set analysis of 136 countries shows that national carbon intensity is not determined by any single factor but rather by the combined effects of multiple factors. There are two configurational pathways to low-carbon development while four pathways to high-carbon development, each with its own configuration. Low-carbon development occurs most often in those affluent, highly urbanized and democratic countries with low intensity of energy use, while high-carbon development is most likely in those small, poor countries with high intensity of energy use. This study also shows that the role of particular factor should be understood in the context as its combinations with different sets of other factors may produce opposite effects on national carbon intensity. That is, the policy efforts concentrated on single factor may be ineffective to reduce carbon intensity. These findings permit a more contextualized and systematic understanding of the determinants of national carbon intensity.

Keywords Carbon intensity · Configurational conditions · Qualitative comparative analysis · Cross-national data

Introduction

Global warming has become one of the major environmental issues facing the world today. According to the special report provided by the Intergovernmental Panel on Climate Change (IPCC), humans will suffer unprecedented climate-related risks if the global temperature rises by 1.5 °C. To mitigate this disaster, global net anthropogenic carbon dioxide (CO_2) emissions have to decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range)[1]. As such, it is urgent for countries around the world to reduce CO_2 emissions when pursuing their growth targets.

In recent years, many countries, like China and India, have adopted carbon intensity (CO_2 emissions per unit of GDP) as their reduction targets to control CO_2 emissions. Low levels of carbon intensity indicate that a country is able to produce each unit of output with fewer carbon emissions (i.e. *low-carbon development*; Mulugetta and Urban 2010). Herzog et al. (2006) argue that the goal of reducing carbon intensity is to generate a maximum of economic growth with a minimum of carbon emissions. Thus, the most important question is *under what conditions will low levels of carbon intensity be possible at the national level?*

Prior studies have shown that national carbon intensity can be affected by multiple socio-economic factors, including population size, economic growth, industrial structure, energy intensity and urbanization (Roberts and Grimes 1997; Ebohon and Ikeme 2006; Fan et al. 2007; Zhu et al. 2014; Zhang et al. 2014; Dong et al. 2016; Rodríguez and Pena-Boquete 2017; Chang et al. 2017; Pappas et al. 2018). Besides, an increasing number of literature on environmental politics argues that democracy may play a key role in the design and enforcement of environmental policy (Lægreid and Povitkina 2018; Joshi and

[1] IPCC, 2018: Summary for Policymakers. Global Warming of 1.5 °C. This report can be downloaded from the official website of IPCC. https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/

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Beck 2018; Mao 2018; Adom et al. 2018). However, the previous research has failed to integrate all these factors into a comprehensive framework and reveal which combinations of them can lead to low-carbon development. The main reason for this gap may be the lack of appropriate tools to capture the complex interactions among multiple factors. Traditional regression analysis employs the logic of net effects thinking, assuming the effect is linear, additive and unifinal, thus focusing on the net effects of individual variables (Ragin 2008). To address this gap, this study adopts a novel method called fuzzy set qualitative comparative analysis (fsQCA), which emphasizes the complexity of causal relations between multiple conditions and the outcome of interest (Misangyi et al. 2016). The core objective of this study is to reveal the configurational conditions of national carbon intensity.

This study contributes to the extant knowledge in several ways. First, drawing on the insights from the literature in environmental economics and politics, it constructs a configurational analytical framework to integrate six key determinants of national carbon intensity, namely population, affluence, industrial structure, energy intensity, urbanization rate and democracy. Second, it shows that no single condition by itself can sufficiently lead to low (or high)-carbon development. However, there are multiple configurational pathways to the outcome of interest (or the opposite). Specifically, low-carbon development occurs most often in those affluent, highly urbanized and democratic countries with low intensity of energy use, while high-carbon development appears most often in those small, poor countries with high intensity of energy use. Third, the role of particular factor should be understood by examining its combinations with other factors. For example, this study shows that high level of urbanization combined with different sets of factors produces opposite effects on national carbon intensity. Fourth, it shows that fsQCA is complementary to traditional regression analysis and thus, employing them simultaneously can provide researchers with a more complete understanding of social realities.

The remainder of this paper is organized as follows: the "Literature review" section reviews the literature on the determinants of national carbon intensity and then constructs a configurational analytical framework; the "Method and data" section provides a detailed explanation of method, i.e. fsQCA, measurement and data; the "Results" section presents the results and the "" "Discussion" section discusses their implications; the "Conclusion and policy implications" section concludes this paper and offers ideas for future research.

Literature review

The socio-economic determinants of carbon intensity

With the growing concerns about global warming, a large body of literature has explored how to reduce the intensity of CO_2 emissions at the national level. The environmental Kuznets curve (EKC) hypothesis suggests economic development may initially damage the environment but enhance its quality eventually (Grossman and Krueger 1995; Stern et al. 1996), while the Impact = Population × Affluence × Technology (IPAT) formula claims that the environmental impact is a function of population size (P), affluence (A) and technology (T) (Ehrlich and Holdren 1971; Dietz and Rosa 1997; York et al. 2003; Rosa et al. 2004). Here T can be understood as the level of environmentally damaging technology adopted in the production of goods and services, often proxied by some variables, like industrial structure and energy intensity (Shi 2003; Martínez-Zarzoso et al. 2007; Liddle 2015). Furthermore, recent studies have also incorporated the level of urbanization into the IPAT model, arguing that urbanization may produce various forms of environmental pressure, including CO_2 emissions (Poumanyvong and Kaneko 2010; Martínez-Zarzoso and Maruotti 2011; Jorgenson et al. 2014; Du and Xia 2018). In general, the existing literature has identified the following key potential socio-economic determinants of national carbon intensity:

1. Population

The size of population is one of the major driving forces of environmental change, including the increasing concentration of CO_2. Some researchers, like Dietz and Rosa (1997) and York et al. (2003) have examined how population growth may affect CO_2 emissions, suggesting that the carbon elasticity for population is close to unity. However, by employing the panel data for 93 countries over the period 1975–1996, Shi (2003) finds that global population change is more than proportionally associated with growth in CO_2 emissions and the impact of population change on emissions is much more pronounced in developing countries than in developed countries.

2. Affluence

Economic development is excepted to not only increase the environmental concerns of the public but also make them more articulate and better equipped to assert their rights (Welzel and Inglehart 2008). The well-known EKC hypothesis suggests an inverted U-shaped relationship may exist between economic development and environmental degradation (Grossman and Krueger 1995; Stern et al. 1996). Empirically, some studies support the EKC hypothesis while others not. For example, Roberts and Grimes (1997) find the relationship between economic development and carbon intensity has changed from essentially linear in 1962 to strongly curvilinear in 1991. However, Zhu et al. (2014) investigate the reduction rate of carbon intensity among 89 countries, finding that keeping fast and steady economic growth does significantly reduce carbon intensity, although there is no evidence of inverted U curve between them.

3. Industrial structure

Usually, the higher percentage of the industrial activity with respect to the total production tends to cause more damage to the environment. Many scholars have employed industrial structure to proxy the national level of environmentally damaging technology. For example, Shi (2003) finds that countries where manufacturing represents larger fraction of GDP have higher emissions, whereas countries where services are a larger fraction of GDP typically have lower emissions. Likewise, Zhang et al. (2014) find that the increase in the share of tertiary industry, i.e. the ratio of tertiary industry value added to gross domestic product (GDP), plays a significant role in curbing carbon emission intensity in China.

4. Energy intensity

The amount of energy consumption per unit of economic output (i.e. energy intensity) is another indicator often used as the proxy of technology. A number of studies have shown that energy intensity is an important contributor to carbon intensity. Fan et al. (2007) reveal that the decline of real energy intensity is the overwhelming contributor to the reduction of energy-related carbon intensity in China from 1980 to 2003. Ebohon and Ikeme (2006) adopt the Laspeyres index method to investigate the carbon intensity in sub-Saharan African countries and find that the intensity and structure of energy use as well as economic growth exert great impact on carbon intensity. Moreover, after reviewing 80 peer-reviewed papers on this issue, Xu and Ang (2013) conclude that reducing energy intensity can facilitate reduction of carbon intensity in both developing and developed countries.

5. Urbanization

The impact of urbanization on the environment is complex: on the one hand, the spatial concentration of people, production and consumption may increase the demand of energy and resources, thus generating more emissions, but, on the other hand, increased urban density may improve the efficiency of public infrastructure and achieve the economy of scale, thus leading to the reduction of energy use and emissions (Poumanyvong and Kaneko 2010; Jorgenson et al. 2014). Recent empirical studies also show the conflicting results. For example, Poumanyvong and Kaneko (2010) find that urbanization is positively associated with emissions for all the income groups, and this impact is more pronounced in the middle-income group than in the other income groups. Some scholars find that urbanization tends to increase China's carbon intensity (Zhang et al. 2014; Dong et al. 2016). However, by investigating a long panel dataset including 69 nations from 1960 to 2010, Jorgenson et al. (2014) find that the effects of urbanization on per capita and per unit of GDP CO_2 emissions are far from monolithic.

Democracy and carbon intensity

A fledgling group of literature on environmental politics attempts to reveal how political institutions can affect environmental quality (Dasgupta and De Cian 2018). Classical political theory suggests that democratic governments have to disproportionately invest state resources in public goods that benefit large segments of society, so as to gain the broad support to achieve political survival, while autocratic governments tend to ignore the public needs as their survival mainly depends on the support from a relatively small group of people (Olson 1993; Bueno de Mesquita et al. 2003). Thus, democracy is conducive to the environment because it can improve the level of public accountability by nurturing civic participation and free medias (Payne 1995; Barrett and Graddy 2000; Winslow 2005; Farzin and Bond 2006; Li and Reuveny 2006; Buitenzorgy and Mol 2010). However, some studies suggest that democracy may lead to environmental degradation as it may suffer from problems like interest capture, frequent election and budget restraints (Heilbroner 1974; Ophuls 1977; Midlarsky 1998; Beeson 2010; Arvin and Lew 2011). These disagreements suggest a complex relationship between democracy and environmental quality.

The empirical studies on the democracy-CO_2 relationship also find mixed results. Some studies show democracy helps mitigate CO_2 emissions (Policardo 2016; Mayer 2017). However, Midlarsky (1998) shows that, although democracy has significant positive impact on protected land area, it has no significant impact on freshwater availability and soil erosion by chemicals, and tends to significantly increase deforestation, carbon dioxide emission and soil erosion by water. Mao (2018) estimates the causal effect of democratic transition in Indonesia on its carbon intensity with synthetic control method. Empirical results show that democratic transition in Indonesia increases its national carbon intensity. Therefore, the democracy-CO_2 relationship needs more contextualized analysis.

A configurational analytical framework

The existing studies have outlined the potential determinants of carbon intensity, including population, affluence, industrial structure, energy intensity, urbanization rate and democracy. Among them, a few scholars have noticed the interaction effect among some of these factors. For example, Bhattacharyya and Ussanarassamee (2004) find that the relationship between energy intensity and carbon intensity in Thailand from 1981 to 2000 is moderated by some contextual factors, including national economic conditions, industrial structure and the structure of fuel. Poumanyvong and Kaneko (2010) find that the impact of urbanization on CO_2 emissions is more pronounced in the middle-income group than in the other income groups. Furthermore, by using quantile regression technique, Lv (2017) explores the interaction effects of democracy and income on CO_2 emissions in 19 emerging countries over the period 1997–2010, finding that democracy reduces CO_2 emissions but only if the country has already reached to a certain income level. Likewise, Lægreid and Povitkina (2018) find democracy can, to some extent, moderate the GDP-CO_2 relationship. However, they have failed to capture the complex interactions among all these factors and reveal their combined effects on national carbon intensity. In fact, as stated by Mackellar et al. (1995), the aim of the IPAT model is to reveal how environmental impact is not only due to a single factor. To address this gap, the current study constructs a configurational analytical framework (Fig. 1) integrating all the above-mentioned factors and then determines how they jointly contribute to national carbon intensity. Methodologically, this study employs fsQCA, a set-theoretic method, as the primary analytical strategy, which attempts to uncover the configurational conditions of national carbon intensity, rather than simply show the positive or negative net effects of individual variables (Ragin 2008).

Method and data

Fuzzy set qualitative comparative analysis

In this study, a novel method called qualitative comparative analysis (QCA), developed by Charles Ragin in the 1980s (Ragin 2008), is adopted as it is able to do configurational analysis of social phenomena. Traditional multiple regression analysis (MRA), although widely used in the social science research, is guided by the simple additive logic, focusing on the "net effects" of single factors on the outcome of interest, rather than the combined effects of these factors (Ragin 2008). Different from MRA, QCA is a set-theoretic method, which takes each case as a configuration, calibrates them into different sets, conceptualizes social relations as set relations and then interprets these set relations in terms of sufficiency and necessity (Schneider and Wagemann 2012). Sufficiency and necessity can be defined as follows: if set X is a subset of set Y, then X is logically sufficient for Y because X can always produce Y, while if set X is a superset of set Y, then X is logically necessary for Y because Y cannot occur without X. The primary goal of QCA is to reveal under what conditions (or configurations of conditions) the outcome of interest tends to happen. By combining set analysis with causal explanation, QCA provides a configurational understanding of social phenomena.

Many scholars have argued that QCA is more powerful than regression analysis to embrace causal complexity (Misangyi et al. 2016). First, by using Boolean algebra, rather than statistical correlation, as its inference technique, QCA can identify the conditions for the presence or absence of outcome respectively, thus revealing the situation of *causal asymmetry* (i.e. the cause of the negative outcome is not the inverse of the cause of the positive outcome). Second, QCA focuses on the overlaps of the sets of conditions and outcome and reveals which combinations of conditions can produce the outcome of interest. This configurational analysis can explain the situation of *conjunctional causation* (i.e. multiple conditions combine to produce the outcome). Third, by applying QCA, we may find that there is more than one configuration of conditions being the subsets of outcome set. This situation is called as *equifinality* (i.e. multiple pathways to the same outcome). Hence, QCA tends to be an appropriate tool for this research that aims to determine how political and socio-economic factors combine to promote low-carbon development.

Generally, there are four steps to apply fsQCA in the empirical research. First, researchers should rescale the raw data into the membership scores in some causal sets of attributes. Based on the fuzzy set logic, the membership scores range from 0 to 1, with higher scores indicating greater membership in the set-theoretical space. For instance, 0.1 refers "mostly out of the set" while 0.9 presents "mostly in the set". It is such calibration that translates the following data analysis into the fuzzy set language.

Second, researchers should test the necessity and sufficiency of single condition for the outcome. To perform these tests, the threshold of consistency should be specified. Consistency

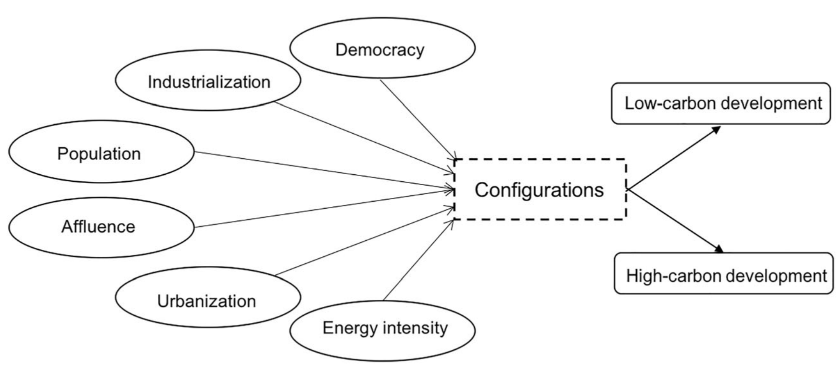

Fig. 1 The configurational analytical framework

represents "the degree to which the cases sharing a given combination of conditions agree in displaying the outcome in question. That is, consistency indicates how closely a perfect subset relation is approximated" (Ragin 2008, p. 44). The calculation of fuzzy set-theoretic consistency can be formalized as follows:

$$\text{Consistency } (X_i \leq Y_i) = \Sigma[\min(X_i, Y_i)]/\Sigma(X_i)$$

where X_i and Y_i are the membership scores in the causal condition X and the outcome Y for the specific case i respectively, and operator min indicates the selection of the lower of the two values. For necessity test, a high threshold of 0.9 is recommended as a logically necessary condition will not need to be included in the following sufficiency analysis (Skaaning 2011). For sufficiency test, many QCA researchers have shown that a consistent subset relation can be established with a minimal consistency of 0.8 (Ragin 2009; Greckhamer et al. 2013). In this study, I adopt the common threshold levels for necessity and sufficiency tests, namely 0.9 and 0.8.

Third, the sufficiency of combinational conditions for the outcome is tested. A truth table displays all empirically observed configurations and their related outcomes. Although there are 2^k logically possible combinations of conditions where k refers to the number of conditions, only part of them can be empirically observed. Researchers can set the threshold of frequency, i.e. the minimum amount of cases that exceed the crossover point of 0.5 membership in each configuration. Those configurations not reaching the frequency threshold are termed as "logical remainders" which will be dealt with in the following step.

Finally, researchers should conduct Boolean minimization to eliminate the irrelevant conditions. The Boolean minimization proceeds according to the following principle: if two configurations produce the same outcome but differ in only one condition, then the condition that differentiates the two configurations is irrelevant. By eliminating these irrelevant conditions, QCA can reveal the more essential configurational conditions for the outcome. There are three types of solutions for interpretation: complex, parsimonious and intermediate. They are different in how the logical remainders are included into the process of minimization (please see Ragin 2008 for a detailed explanation). Following Ragin's suggestion, this study employs the intermediate solution that only uses the remainders surviving counterfactual analysis based on theoretical and substantive knowledge.

Measurement and data sources

Outcome

The outcome of interest in this research is national carbon intensity, which is measured by CO_2 emissions per unit of GDP (kg per constant 2010 US$ of GDP). The data are obtained from World Development Indicators (WDI) provided by the World Bank. It should be noted that here CO_2 emissions are those stemming from the burning of fossil fuels and the manufacture of cement. Sun (2005) calls the decrease of carbon intensity as the process of "decarbonization". Table 1 shows the top 10 countries with the lowest (highest) level of carbon intensity in the sample 136 countries. The level of carbon intensity (average value from 2005 to 2014) ranges from 0.068 (Switzerland) to 2.974 (Uzbekistan) kg per constant 2010 US$ of GDP.

Conditions

According to the configurational framework, there are six conditions that may affect national carbon intensity: five of them are socio-economic factors, supported by the extended STIRPAT literature (Dietz and Rosa 1997; York et al. 2003; Poumanyvong and Kaneko 2010), including population, affluence, industrialization, energy intensity and urbanization, while the sixth condition is a political factor, i.e. the level of democracy, which is emphasized by the literature on environmental politics (Mao 2018; Dasgupta and De Cian 2018). Table 2 gives a description of variables and the corresponding data sources.

The socio-economic conditions are measured by using the data from WDI. (1) Population size is measured by the total population indicator from WDI. The values of this indicator are midyear estimates. (2) Affluence or economic development at the national level is measured by GDP per capita (constant 2010 US$). (3) The level of industrialization is measured by value added of industrial sector expressed as a percentage of GDP (% of GDP). (4) Urbanization is measured by urban population (% of total). (5) Energy intensity is measured by total energy use per GDP (kg of oil equivalent per constant 2010 US$ of GDP). Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.

To measure the level of democracy in each country, this research employs the indicator, i.e. fh_ipolity2, which is provided by the Quality of Government Standard Dataset[2]. This indicator is computed by using the relative variables from Freedom House and Polity IV projects. Specifically, the average of Freedom House indicators (political rights and civil liberties) is transformed to a scale of 0–10 and the revised combined Polity score is also transformed to a scale of 0–10. Then, these variables are averaged into a new combined indicator, i.e. fh_polity2, ranging from 0 to 10 where 0 is least democratic and 10 most democratic. Here we use the imputed version (fh_ipolity2) which tackles the missing values by regressing Polity on the average Freedom House measure.

[2] This dataset can be downloaded from https://qog.pol.gu.se/data.

Table 1 The top 10 countries with the lowest (highest) level of carbon intensity

Countries	Carbon intensity	Comparison with the world average level (%)
Switzerland	0.068	11.774
Sweden	0.099	17.035
Congo, Democratic Republic	0.112	19.41
Norway	0.116	20.061
France	0.132	22.744
Denmark	0.135	23.212
Iceland	0.149	25.688
Zambia	0.15	25.808
Congo	0.168	28.963
Austria	0.169	29.224
Uzbekistan	2.974	513.14
Turkmenistan	2.544	439.003
Mongolia	2.245	387.383
Ukraine	2.081	359.205
Trinidad and Tobago	2.068	356.821
Kyrgyzstan	1.572	271.303
Kazakhstan	1.567	270.419
China	1.431	246.946
Iran	1.29	222.554
South Africa	1.261	217.684

Note: The carbon intensity for each country is the average value from 2005 to 2014. The world average carbon intensity (136 countries) is 0.579

Some empirical political analyses have shown that this average index outperforms its constituent parts in both validity and reliability (Hadenius and Teorell 2005; Teorell 2010).

Calibration

As a prerequisite step to perform fsQCA, calibration rescales the raw data into the fuzzy set relations by using the membership scores ranging from 0 to 1. Following Ragin (2008), this research adopts the direct calibration method, which specifies the three thresholds (fully membership, crossover point and full non-membership) as anchors to perform the calibration of fuzzy sets. More specifically, the full non-membership threshold is set at the 15th percentile, the full membership threshold is set at the 85th percentile, and the crossover point with maximum ambiguity is set at the 50th percentile. The threshold values for calibration are shown in Table 3. To facilitate interpretation, this study calibrates these sample countries into two sets, i.e. low-carbon development and high-carbon development, according to their levels of carbon intensity. It needs to be noted that the data of carbon intensity are reversely calibrated when the target set is "low-carbon development". For example, a country is fully out of the "low-carbon development" set if its carbon intensity is higher than the 85th percentile of the whole sample (0.915 kg per constant 2010 US$ of GDP), while it is fully in of this set if its carbon intensity is lower than the 15th percentile (0.211 kg per constant 2010 US$ of GDP). Technically, the logistic function is used so that the thresholds of full membership and full non-membership correspond to the set membership scores of 0.95 and 0.05 respectively. This study computes the membership with the "QCA" R package (Dusa 2018).

Results

Results of MRA

A simple regression analysis is conducted to assess the "net effect" of each factor on the national level of carbon intensity. To reduce the problem of heteroscedasticity, all variables are natural logarithm–transformed prior to the regression analysis. This research adds 1 to the democracy variable to avoid missing observations due to the use of natural logarithm. Table 4 presents the results of MRA with cross-sectional data of 136 countries. There are only three variables showing significant

Table 2 Variable measurement and descriptive statistics

Variables	Mean	SD	Min	Max	Measurement	Sources
Carbon intensity	0.579	0.485	0.068	2.974	CO_2 emission per GDP (kg per constant 2010 US$ of GDP)	WDI
Population size	48.20	158.21	0.32	1,334.27	Total population in midyear estimates (millions)	WDI
Affluence	15,241.05	19,692.21	321.822	105,285.50	GDP per capita (constant 2010 US$)	WDI
Industrialization	33.081	12.967	11.646	86.731	Value added of industrial sector expressed as a percentage of GDP (% of GDP)	WDI
Urbanization	61.52	21.05	9.191	100	The share of urban population in total amount (% of total)	WDI
Energy intensity	0.302	0.243	0.045	1.461	Total energy sue per GDP (kg of oil equivalent per constant 2010 US$ of GDP)	WDI
Democracy	6.645	3.121	0	10	The imputed version of combined democracy indicator based on the Freedom House and Polity IV variables. It ranges from 0 to 10 where 0 is least democratic and 10 most democratic	The Quality of Government Standard Dataset

Table 3 Threshold values for calibration

Set	Abbreviation	Fully out	Crossover point	Fully in
Low-carbon development	LCD	0.915	0.415	0.211
Large population	POP	2.917	10.73	63.459
Affluent	AFF	1250.46	6082.92	40,707.90
High industrialized	IND	22.572	29.876	42.69
Highly urbanized	URB	37.612	63.806	84.776
High intensity of energy use	EI	0.107	0.236	0.469
High level of democracy	DEM	2.808	7.696	10

impacts on the level of carbon intensity, including affluence (and its squared term), energy intensity and democracy. In terms of standardized coefficients, they are also the most predictive factors of carbon intensity in this regression model. More specifically, the EKC of carbon intensity is supported, i.e. an inverted U relationship exists between carbon intensity and economic growth (Grossman and Krueger 1995; Stern et al. 1996). The level of energy intensity, measured by total energy use per GDP (kg of oil equivalent per constant 2010 US$ of GDP), exerts a positive and highly significant impact on carbon intensity, showing that the higher intensity of primary energy use tends to cause more carbon-intensive development. Regarding the impact of democracy, MRA shows that the elasticity of carbon intensity to democracy is significantly negative, indicating that high level of democracy may, on average, contribute to low-carbon development. As for model efficiency, the coefficient of determination, R square (adjusted R square), is 0.704 (0.688), indicating that this regression model has a moderate fit for the raw data. In this research, the results of MRA are used for comparison with the results of fsQCA.

Results of fsQCA

The necessity and sufficiency tests of single conditions

This study starts by performing necessity and sufficiency tests of single conditions. A necessary condition is a superset of the outcome, indicating that it has to be present to make outcome possible. As can be seen from the upper half of Table 5, the necessity tests show no single condition exceeds the consistency threshold (0.9), indicating none of them is necessary for achieving low (or high)-carbon development. Furthermore, this study also tests the sufficiency of single conditions for the presence or absence of the outcome. The lower half of Table 5 shows that the consistency scores of all conditions are below the minimal level of 0.8 (Ragin 2009; Greckhamer et al. 2013), demonstrating that any condition by itself can consistently lead to low (or high)-carbon development. For example, although high level of energy intensity is significantly and positively associated with high level of carbon intensity, they are not perfect subset relationship: the consistency score is 0.776, indicating a group of countries are outside the outcome set. Similarly, neither high level of

Table 4 The results of MRA

	ln(Carbon intensity)			
	B	std. beta	CI	Standardized CI
(Intercept)	– 12.7***		– 15.37 to – 10.03	
ln(Population size)	0.02	0.05	– 0.02 to 0.07	– 0.05 to 0.15
ln(Affluence)	3.01***	5.92***	2.36 to 3.66	4.64 to 7.20
ln(Affluence) squared	– 0.16***	– 5.54***	– 0.20 to – 0.13	– 6.76 to – 4.31
ln(Industrialization)	– 0.05	– 0.02	– 0.30 to 0.20	– 0.15 to 0.10
ln(Urbanization)	– 0.1	– 0.06	– 0.34 to 0.15	– 0.20 to 0.09
ln(Energy intensity)	0.85***	0.83***	0.69 to 1.01	0.67 to 0.98
ln(Democracy + 1)	– 0.21**	– 0.16**	– 0.36 to – 0.05	– 0.29 to – 0.04
Observations			136	
R^2/adj. R^2			0.704/0.688	
F-statistics			43.58***	

All variables are natural logarithm–transformed prior to the regression analysis. This research adds 1 to the democracy variable to avoid missing observations due to the use of natural logarithm

** p<0.05, *** p<0.01

Table 5 The results of necessity and sufficiency tests of single conditions

Conditions	LCD		HCD	
	Consistency	Coverage	Consistency	Coverage
Necessity test				
POP	0.556	0.612	0.559	0.585
AFF	0.650	0.726	0.466	0.496
IND	0.454	0.476	0.694	0.692
URB	0.646	0.663	0.527	0.514
EI	0.411	0.437	0.766	0.776
DEM	0.732	0.748	0.455	0.443
~POP	0.623	0.597	0.629	0.574
~AFF	0.548	0.519	0.742	0.668
~IND	0.706	0.708	0.474	0.452
~URB	0.527	0.539	0.654	0.637
~EI	0.789	0.780	0.444	0.418
~DEM	0.455	0.467	0.741	0.725
Sufficiency test				
POP	0.612	0.556	0.585	0.559
AFF	0.726	0.650	0.496	0.466
IND	0.476	0.454	0.692	0.694
URB	0.663	0.646	0.514	0.527
EI	0.437	0.411	0.776	0.766
DEM	0.748	0.732	0.443	0.455
~POP	0.597	0.623	0.574	0.629
~AFF	0.519	0.548	0.668	0.742
~IND	0.708	0.706	0.452	0.474
~URB	0.539	0.527	0.637	0.654
~EI	0.780	0.789	0.418	0.444
~DEM	0.467	0.455	0.725	0.741

LCD (HCD), low (high)-carbon development; *POP*, large population; *AFF*, affluent countries; *IND*, highly industrialized; *URB*, highly urbanized; *EI*, high level of energy intensity; *DEM* high level of democracy. "~" refers to the negation of condition

democracy nor high level of affluence can consistently lead to the low level of carbon intensity. These two simple tests suggest that none of the conditions is necessary or sufficient for the outcome. Therefore, this study attempts to explore the configurational determinants of carbon intensity.

Configurational conditions for low-carbon development

To investigate the configurational conditions for low-carbon development, a truth table is constructed to display all observed combinations of conditions and their related outcomes. As the number of conditions is 6, there are 64 ($2^6 = 64$) logically possible configurations. In fact, some of them cannot be empirically observed. Ragin (2008) calls this situation as "limited diversity". This study sets the threshold of frequency as 3, claiming that at least 3 cases exceed the crossover point of 0.5 membership in each configuration. As is shown in Table 6, 17 out of the 64 configurations with at least 3 countries are observed, and 6 configurations with consistency higher than 0.8 (the consistency threshold) are coded as 1 in the "OUT" column, which indicates these configurations can consistently lead to low-carbon development. Therefore, each row in the truth table can be written as a causal expression with Boolean operators, indicating that there are multiple pathways to the same outcome (i.e. equifinality).

After building the truth table, fsQCA employs the Boolean algebra logic to minimize the above configurations that can consistently lead to low-carbon development. The aim of minimization is to remove the irrelevant components within those configurations. For example, as we can see from Table 6, the first and second configurations which produce the same outcome differ in only one condition, i.e. POP, which means that the size of population is an irrelevant condition and thus can be removed. Another issue in processing Boolean minimization is logical remainders, i.e. configurations not reaching the minimum number of cases (Ragin 2008). As has mentioned in the methodology section, this study adopts the intermediate solution which only uses the remainders that survive counterfactual analysis based on theoretical and substantive knowledge. Table 7 summarizes the major results of intermediate solution.

There are two pathways to low-carbon development, each with its own configuration of conditions. The model consistency score is 0.917, much higher than the threshold. And the solution coverage score is 0.553, indicating that this model covers about 55.3% of the countries achieving low-carbon development. In specific, pathway L1, with high consistency (0.918), shows the highest raw coverage score (0.502) and unique coverage score (0.164), meaning that this configuration of conditions is of the most empirical importance in this model. It can be interpreted as the following statement: low-carbon development appears most often in those affluent, highly urbanized and democratic countries with low intensity of energy use. Each condition in this configuration works as an INUS cause, i.e. *an insufficient but necessary part of a condition that is unnecessary but sufficient for the outcome* (Mackie 1965). In other words, it is the combination of these four conditions, rather than any one of them, that makes low-carbon development possible. It needs to be noted that, for these countries satisfying pathway L1, population size and the level of industrialization tend to be irrelevant. Regarding pathway L2, it also requires countries to be affluent, be democratic and not be energy-intensive, but it does not require a high level of urbanization. However, pathway L2 is only suitable for those countries with small size of population.

Figure 2 shows the degree of membership of all countries in our sample in these two pathways and the outcome of interest, i.e. low-carbon development. In detail, the vertical and horizontal axes present each country's degree of membership in pathways L1 and L2 respectively, while the colour of point indicates the degree of membership in low-carbon

Table 6 The truth table for law-carbon development

Configurations	POP	AFF	IND	URB	EI	DEM	OUT	n	Consistency	Cases
54	1	1	0	1	0	1	1	12	0.947	AUS,BEL,BRA,CAN,FRA,GRC,ITA,JPN,NLD,ESP,GBR,USA
22	0	1	0	1	0	1	1	13	0.939	AUT,CRI,CYP,DNK,ISR,LVA,LUX,MLT,NZL,PAN,SWE,CHE,URY
30	0	1	1	1	0	1	1	6	0.901	CZE,FIN,HUN,LTU,NOR,SUR
18	0	1	0	0	0	1	1	4	0.892	HRV,IRL,MUS,PRT
26	0	1	1	0	0	1	1	3	0.889	BWA,SVK,SVN
62	1	1	1	1	0	1	1	5	0.886	ARG,CHL,DEU,KOR,MEX
24	0	1	0	1	1	1	0	3	0.763	BGR,EST,ISL
35	1	0	0	0	1	0	0	13	0.755	BGD,KHM,ERI,ETH,GTM,KEN,MOZ,MMR,NPL,NER,PAK,TZA,ZWE
41	1	0	1	0	0	0	0	5	0.72	AGO,ECU,PRK,LKA,SYR
4	0	0	0	0	1	1	0	4	0.693	BEN,JAM,MKD,MDA
15	0	0	1	1	1	0	0	3	0.646	BLR,BOL,JOR
3	0	0	0	0	1	0	0	8	0.646	BIH,GEO,HTI,HND,KGZ,NIC,TJK,TGO
11	0	0	1	0	1	0	0	3	0.631	ARM,AZE,TKM
63	1	1	1	1	1	0	0	3	0.605	MYS,RUS,SAU
31	0	1	1	1	1	0	0	7	0.588	BHR,BRN,GAB,KWT,LBY,OMN,QAT
47	1	0	1	1	1	0	0	4	0.585	DZA,IRN,IRQ,UKR
43	1	0	1	0	1	0	0	11	0.561	CMR,CHN,COD,CIV,EGY,NGA,THA,UZB,VNM,YEM,ZMB

PO, large population; *AFF*, affluent countries; *IND*, highly industrialized; *URB*, highly urbanized; *EI*, high level of energy intensity; *DEM*, high level of democracy

development (LCD): the greener the point is, the lower the carbon intensity is. This study divides the graph into four quadrants by using 0.5 membership as the critical value.

Table 7 Configurational conditions for low-carbon development

	Pathways	
	L1	L2
Conditions		
Large population		⊚
Affluent	●	●
Highly industrialized		
Highly urbanized	●	
High intensity of energy use	⊚	⊚
High level of democracy	●	●
Consistency	0.918	0.386
Raw coverage	0.502	0.390
Unique coverage	0.164	0.052
Solution consistency	0.917	
Solution coverage	0.553	

● means the presence of this condition, while ⊚ means the absence of this condition. The threshold of consistency is 0.8 and the threshold of frequency is 3

Apparently, those brown points are mainly in the bottom-left quadrant, indicating that countries that fall outside the above two pathways tend to carry out high-carbon development. At the opposite corner, the upper-right quadrant presents the countries that have high degree of membership in both pathways, like Luxembourg, New Zealand, Norway, and Finland. Most of these countries achieve low-carbon development, except for a few cases, such as the Czech Republic and Suriname. The upper-left quadrant includes countries only belonging to pathway L1, like Japan, the UK, France, and the USA, while the bottom-right quadrant includes countries only belonging to pathway L2, like Ireland and Slovenia. The former group of countries shares a high level of urbanization, while the latter group is all small in population size. It needs to be noted that these two groups also contain a few countries that have relatively poor performance in promoting low-carbon development, such as Mexico, South Korea, Argentina, and Slovakia.

Configurational conditions for high-carbon development

This study takes a step further to analyse what configurations of conditions are consistently associated with high-carbon development. The causal asymmetry logic of QCA stresses that the

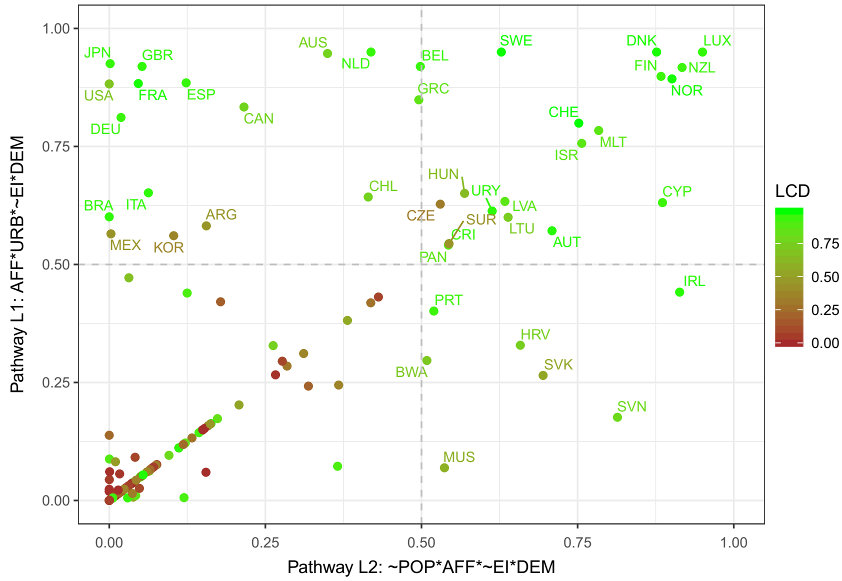

Fig. 2 Two configurational pathways to low-carbon development. LCD, low-carbon development; POP, large population; AFF, affluent; URB, highly urbanized; EI, high level of energy intensity; DEM, high level of democracy. "~" refers to the negation of conditions

absence of conditions for low-carbon development does not guarantee high-carbon development. Just like the above analysis, this study constructs a truth table to display all empirically observed configurations and their related outcomes. As is shown in Table 8, 17 configurations are observed with at least 3 cases and 10 of them (above the dash line) meet the consistency threshold (0.8). For example, configuration 63 in the first row of truth table has the highest consistency score (0.975), indicating that, without high level of democracy, the presence of all other five conditions can consistently lead to high-carbon development, e.g. Malaysia, Russia, and Saudi Arabia. In addition, configuration 43 is supported by the largest number of cases, i.e. 11 countries, such as Cameroon and China.

Then, this study proceeds with the Boolean minimization. Table 9 summarizes the intermediate solution that presents four pathways to high-carbon development. The solution

Table 8 The truth table for high-carbon development

Configurations	POP	AFF	IND	URB	EI	DEM	OUT	n	Consistency	Cases
63	1	1	1	1	1	0	1	3	0.975	MYS,RUS,SAU
47	1	0	1	1	1	0	1	4	0.971	DZA,IRN,IRQ,UKR
31	0	1	1	1	1	0	1	7	0.949	BHR,BRN,GAB,KWT,LBY,OMN,QAT
15	0	0	1	1	1	0	1	3	0.925	BLR,BOL,JOR
24	0	1	0	1	1	1	1	3	0.884	BGR,EST,ISL
41	1	0	1	0	0	0	1	5	0.877	AGO,ECU,PRK,LKA,SYR
11	0	0	1	0	1	0	1	3	0.872	ARM,AZE,TKM
4	0	0	0	0	1	1	1	4	0.866	BEN,JAM,MKD,MDA
3	0	0	0	0	1	0	1	8	0.848	BIH,GEO,HTI,HND,KGZ,NIC,TJK,TGO
43	1	0	1	0	1	0	1	11	0.837	CMR,CHN,COD,CIV,EGY,NGA,THA,UZB,VNM,YEM,ZMB
26	0	1	1	0	0	1	0	3	0.757	BWA,SVK,SVN
62	1	1	1	1	0	1	0	5	0.732	ARG,CHL,DEU,KOR,MEX
30	0	1	1	1	0	1	0	6	0.702	CZE,FIN,HUN,LTU,NOR,SUR
35	1	0	0	0	1	0	0	13	0.688	BGD,KHM,ERI,ETH,GTM,KEN,MOZ,MMR,NPL,NER,PAK,TZA,ZWE
18	0	1	0	0	0	1	0	4	0.68	HRV,IRL,MUS,PRT
54	1	1	0	1	0	1	0	12	0.471	AUS,BEL,BRA,CAN,FRA,GRC,ITA,JPN,NLD,ESP,GBR,USA
22	0	1	0	1	0	1	0	13	0.449	AUT,CRI,CYP,DNK,ISR,LVA,LUX,MLT,NZL,PAN,SWE,CHE,URY

POP, large population; *AFF*, affluent countries; *IND*, highly industrialized; *URB*, highly urbanized; *EI*, high level of energy intensity; *DEM*, high level of democracy

Table 9 Configurational conditions for high-carbon development

	Pathways			
	H1	H2	H3	H4
Conditions				
Large population	⊚	⊚		●
Affluent	⊚			⊚
Highly industrialized			●	●
Highly urbanized		●	●	⊚
High intensity of energy use	●	●	●	
High level of democracy			⊚	⊚
Consistency	0.880	0.903	0.939	0.822
Raw coverage	0.432	0.319	0.309	0.290
Unique coverage	0.137	0.013	0.042	0.092
Solution consistency	0.851			
Solution coverage	0.660			

● means the presence of this condition, while ⊚ means the absence of this condition. The threshold of consistency is 0.8 and the threshold of frequency is 3

consistency score (0.851) is moderately higher than the threshold, while the coverage score is relatively high, i.e. 0.66, referring that it can explain nearly 70% of sample countries featuring high-carbon development. More specifically, pathways H1 and H2 occur in countries with small size of population, while pathway H4 happens in the countries with large population. For those small countries with high energy intensity, high-carbon development tends to take place when they are economically backward, e.g. Moldova, Kyrgyzstan, and Mongolia, or highly urbanized, e.g. Bahrain, Oman, and Bulgaria. For those large, industrialized countries, as pathway H4 indicates, economic underdevelopment, lack of democracy and low level of urbanization combine to produce high-carbon development, such as Egypt, China, and Vietnam. Quite different from these three pathways, pathway H3 claims that high-carbon development tends to occur in those non-democratic countries with high level of industrialization, urbanization and energy intensity, regardless of what level of population size and wealth they are at. Typical countries meeting pathway H3 are Bahrain, Belarus, Oman, Russia etc. In terms of coverage, pathway H1 has the highest scores of raw coverage (0.432) and unique coverage (0.137), meaning that this configuration of conditions is most supported by empirical data. However, the other three pathways are also empirically important, as they cover about 30% of countries that develop in a carbon-intensive mode.

A comparison of results from MRA and fsQCA

Based on the cross-sectional data from 136 countries, MRA and fsQCA produce quite different results. The regression analysis of raw data shows that economic development, energy intensity and democracy are most important predictors of national carbon intensity, while the fuzzy set analysis of calibrated data claims that none of them can by itself consistently lead to low-carbon development. In fact, single condition tests show that the consistency scores of all six conditions are below the threshold of 0.8 (Ragin 2009; Greckhamer et al. 2013), indicating there is not enough evidence to establish the subset relations between each of them and the outcome of interest. But some combinations of these conditions can well exceed the consistency threshold. For example, Table 7 shows that there are two pathways with consistency score higher than 0.9, which suggests that countries sharing these configurational conditions are almost members of the set of low-carbon development. In addition, QCA attempts to reveal causal asymmetry. Evidence shows that the pathways to high-carbon development are not just the reverse of pathways to low-carbon development.

Both MRA and fsQCA have a moderate fit for the sample data, which suggests the results of them should be used with caution. Specifically, MRA adopts *R* square or adjusted *R* square to assess model efficiency, while fsQCA uses coverage to evaluate the degree of empirical support for the pathways. However, as Ragin (2008, p. 55) has argued, “coverage gauges only empirical importance, not theoretical importance. A sufficient relation may be quite ‘rare’ from the empirical point of view (and thus exhibit low coverage), but it still could be centrally relevant to the theory”. In the current study, the identified pathways may shed some new lights on the determinants of carbon intensity. For example, there has been a recurring debate on the relationship between urbanization and carbon emissions. The fsQCA results show that a high level of urbanization, when combined with different sets of contextual conditions, can lead to opposite effects on the level of carbon intensity. As a theory-guided and case-based method, fsQCA pays more attention to the dialogue between theoretical proposition and empirical evidence.

Therefore, it is of great value to combine MRA and fsQCA in exploring the complexity of social phenomena. While MRA presents the net effect of each factor on carbon intensity, fsQCA shows which configurations of conditions are sufficient for low (or high)-carbon development. To put it simply, they are complementary rather than conflicting in methodology (Vis 2012).

Discussion

It is worth further discussing the above findings. First, no single condition by itself can sufficiently lead to low (or high)-carbon development. However, there are multiple pathways to the outcome of interest (or the opposite), each with its own configuration of conditions. More specifically, low-carbon development occurs most often in those affluent, highly urbanized and democratic countries with low intensity of energy use, while high-carbon development appears most often in those small, poor countries with high intensity of energy use. An interesting point here is that the pathways to low-carbon development are not just the reverse of the pathways to high-carbon development. This asymmetric phenomenon in causal relations, however, is often overlooked by the prior studies.

Second, the role of single factor has to be understood in combination with other factors. On the one hand, the same factor may show a quite different role in different contexts. For example, there are three pathways (L1, H2 and H3) containing the presence of "highly urbanized". While pathway L1 achieves low-carbon development, the latter two lead to the opposite outcome. That is to say, the impact of urbanization on carbon intensity tends to be contingent upon the national context. On the other hand, different factors, under certain conditions, may play an equivalent role in reducing carbon intensity. For instance, pathways L1 and L2 show that, for those affluent, democratic countries with low energy intensity, low-carbon development can be achieved by promoting urbanization or keeping small population. As such, high level of urbanization tends to be equivalent to the role of small population in this specific context. This finding shows that it is important for countries with large population to promote urbanization if they attempt to control carbon intensity like those countries with small population.

Third, this study integrates democracy into traditional IPAT model, finding that high level of democracy is an insufficient but necessary part of a condition that is unnecessary but sufficient (i.e. INUS condition) for low-carbon development. However, high level of democracy tends to be invalid in some specific contexts to reduce national carbon intensity. For example, pathway L1 suggests that those small, poor countries with high intensity of energy use will step into a carbon-intensive development mode at whatever level of democracy. Therefore, the carbon mitigation effect of democracy tends to be contingent upon the national context.

Conclusion and policy implications

This study examines the configurational conditions of national carbon intensity with the cross-sectional data from 136 countries. By constructing a configurational analytical framework integrating six factors, i.e. population, affluence, industrial structure, energy intensity, urbanization rate and political regime, this study attempts to capture the complex interactions among these potential determinants. Beyond traditional regression analysis, a new method called fsQCA is adopted as it is able to show what combinations of them can lead to low-carbon development or the opposite, not just identifying the net effect of each condition on carbon intensity. Results show that there are two pathways to low-carbon development but four pathways to the opposite. Furthermore, the most common pathway to low-carbon development happens in those affluent, highly urbanized and democratic countries with low intensity of energy use, while the most common pathway to high-carbon development occurs in those small, poor countries with high intensity of energy use.

This study offers some valuable implications for the policymakers. First, to reduce national carbon intensity, policymakers should take a configurational perspective and pay more attention to the combined effects of various conditions. Low-carbon development is most likely due to some specific configurations of multiple conditions rather than any one of them. In other words, it may be useless if policymakers invest in some conditions while ignoring some others. Second, the experiences of most countries show that there are two pathways to low-carbon development. One of them only applies to the countries with small population, suggesting that carbon intensity in those small countries can be reduced by promoting economic growth and democratization while lowering the intensity of energy use. However, the other one, with more empirical importance, can give enlightenment to all countries regardless their sizes of population. This pathway not only requires promoting economic growth and democratization while lowering energy intensity but also demands a high level of urbanization rate. Therefore, policymakers should take the size of population into consideration when making efforts to reduce carbon intensity. Particularly, urbanization is an essential part of configuration that can lead to low-carbon development in those countries with large population. Third, there are also four pathways to high-carbon development and policymakers should avoid these combinations of conditions if possible. Likewise, the configurational conditions for high-carbon development are different between countries with different levels of population size. Note that high-carbon development is most likely to happen if those countries with small size of population are backward in economy while intensive in energy use. Additionally, in some specific national contexts, i.e. highly industrialized, highly urbanized, energy-intensive and non-democratic, high-carbon development tends to occur regardless of the levels of population and economy.

Some limitations in this study need to be emphasized. First, researchers should not make strong causal claims about the fsQCA results. The interpretation of necessity or sufficiency is just what the data tell us functionally on the laws of Boolean algebra. In other words, fsQCA does not attempt to "prove" causation but to find out possible causal relations which are supported by empirical data. Second, this study lacks a detailed explanation of the potential mechanisms through which these configurations lead to low (or high)-carbon development. It requires more field investigations, including within-case and cross-case studies, to find out how these configurations work. Third, as a cross-sectional analysis, this study does not embrace temporal dimension in the process of causal inference. Recently, the traditional QCA approach has been extended by taking the role of time into consideration. For example, some researchers have developed a panel data set-theoretical method to assess the consistency and coverage both cross-sectionally and across time (Garcia-Castro and Ariño 2016). By employing a longitudinal set-theoretical approach, future studies may be able to get a more precise and robust understanding of the conditions of national carbon intensity.

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Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest.

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