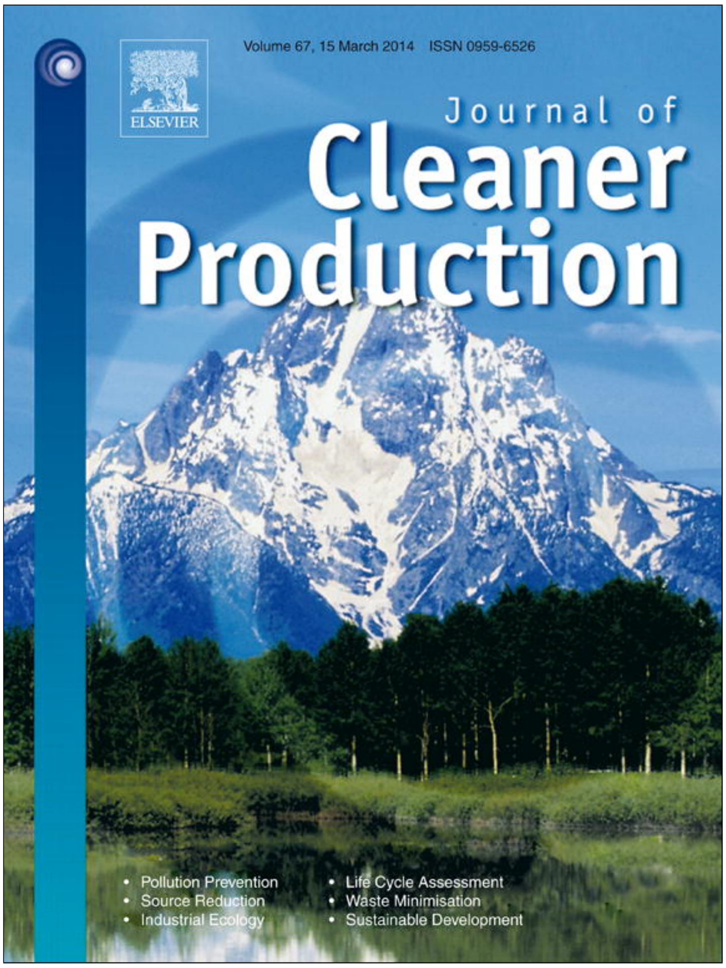
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Review

A meta-analysis investigation of the direction of the energy-GDP causal relationship: implications for the growth-degrowth dialogue

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A B S T R A C T

The complex relation between energy use and the economic process has long attracted attention. Issues such as the scarcity of energy resources, energy theory of value, degrowth and a-growth approaches are closely related to the relationship between energy and development. The present study traces the implications of the Energy-GDP causality dialogue for the context of the growth-degrowth debate, where the energy-development link plays a decisive role. In that context, the present research investigates the possible existence of a fundamental "macro" direction of causality between energy use and economic growth that is not influenced by study-specific characteristics and events. Towards this objective, we perform a meta-analysis that takes into account 158 studies on causality between energy and GDP, covering the period 1978–2011. This is the first time, to our knowledge, that meta-analysis has been applied to investigate the direction of the energy and GDP causal relationship. The meta-analysis results neither support the existence of a fundamental "macro" direction, nor the so-called "neutrality hypothesis (E ≠ GDP)" in the causal relationship between energy consumption and economic growth.

1. Introduction

The contemporary debate on growth, a-growth and degrowth (van Griethuysen, 2010; van den Bergh, 2011; Kallis, 2011; Kallis et al., 2012; Victor, 2012) represents, in fact, an update of the long-standing dialogue over the scarcity of natural resources at the aggregate level, and constraints on economic process and growth (D'Alessandro et al., 2010). The inevitable limits on growth imposed by the scarcity of natural resources – as delineated in the early works of Georgescu-Roegen (1971, 1977) and Meadows et al. (1972) – are reiterated in modern degrowth approaches (Borowy, 2013; Infante Amate and de Molina, 2013; Lietaert, 2010; Research and Degrowth, 2010). The steady state economy (Daly, 1974, 1996), as a "remedy" for scarcity and environmental degradation, inspired a-growth (van den Bergh, 2011) and degrowth approaches (Kerschner, 2010; O'Neill, 2012; Schneider et al., 2010). On the other hand, optimistic approaches which are based on the expectation of continual technological advance and the possibility of substitution of natural inputs with man-made capital (Solow, 1956, 1957) support the continuation of current growth trends (Baumol, 1986; Solow, 1974, 1978, 1993, 1997). Results from this debate may have direct implications for sustainability science, as the availability of natural resources is regarded as one of the conditions for sustainable development (Bithas, 2008; Bithas and Nijkamp, 2008; Howarth, 2007; Hueting, 2010; Spangenberg, 2010). Nowadays, it should be possible for the various theoretical approaches to be placed on a sounder basis as empirical evidence becomes available. Two aspects of contemporary empirical analysis stand out as crucial for the growth-degrowth dialogue: decoupling natural resources use from GDP growth (Bithas and Kalimeris, 2013; Cleveland et al., 1984; Krausmann et al., 2009; Fiorito, 2013) and the direction of the causal relationship between energy use and economic growth.

The present study attempts to trace the existence of a "macro"[1] direction in the findings on energy-GDP causality and attempts to identify the factors that determine this "macro" direction. In addition, the implications of a macro direction of the E-GDP causality nexus on the energy scarcity and growth-degrowth debate will be investigated. The present research carries out meta-analyses

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[1] As "macro" direction, on the Energy-GDP causality nexus, we define the existence of a prevailing direction that holds in the vast majority of cases and is not influenced by the case-specific characteristics of each case study.

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for the first time in the history of the causality dialogue, employing two different methodologies: Rough Set Data Analysis (RSDA) and multinomial logistic regression.

Clearly, energy (exergy), as the only source of "useful work", is indispensable for the economic process (Warr et al., 2010). Natural resource economists and practitioners place the energy issue at the core of contemporary economic analysis and policy (Bentley, 2002; D'Alessandro et al., 2010). The literature on causality results in four different estimates of the direction of causality: from energy (E) to GDP, from GDP to E, bi-directional causality, and no causality in either direction (Ozturk, 2010; Payne, 2010). If the causality tends to run from GDP to E, or if there is no causal relation between the two, then there might be substantial potential for further growth. In this context, energy scarcity does not impose a severe constraint on prospects for economic growth (Ang, 2007; Ghosh, 2002; Soytas et al., 2007). The energy use which is induced by growth can be adjusted within the limits of energy availability. The aggregate output of the economic process could be oriented towards less energy-intensive goods and technological advance could decouple economic process from energy constraints. Causality running from GDP to E implies further potential for the effective use of energy and restructuring of the economy towards less energy-intensive sectors. On the contrary, if the direction of causality from E to GDP prevails, then limited energy resources will impose serious constraints on growth potentials (Magazzino, 2011; Wolde-Rufael, 2010a). Involuntary degrowth will be the inevitable result of the exploitation of current energy resources unless new "promethean" technologies emerge and new energy resources become available in an economically viable way (Georgescu-Roegen, 1976, 1984).

The paper is organized as follows: Section 2 reviews the relevant literature on the energy-GDP growth causal relationship, extending previous surveys of the literature to cover the period from 1978 to 2011; Section 3 presents the methodological framework; Section 4 presents the results of meta-analysis by rough set analysis; Section 5 presents the results of meta-analysis by multinomial logistic regression analysis of the same dataset; finally, Sections 6 and 7 consist of further discussion of the results and the overall concluding remarks, respectively.

2. The causality debate between energy consumption and economic growth

There has been a growing literature over the last three decades concerning the issue of the causal relationship between energy consumption and economic growth measured in terms of GDP. This ongoing debate has produced at least 172 research papers so far. These encompass a wide variety of approaches. They focus on different countries, groups of countries or even parts of a country, and employ various econometric methodologies, time periods and proxy variables. In more detail, the four possible findings regarding the direction of the causal relationship between energy consumption and economic growth, already introduced above, are as follows (Ozturk, 2010; Payne, 2010):

- **Neutrality hypothesis or no causality (E $\neq$ GDP):** no causal relation exists between GDP growth and energy consumption. This implies that energy consumption is not correlated with GDP growth and it follows that energy scarcity and conservative policies in relation to energy use do not affect economic growth (Ozturk, 2010). The "*neutrality hypothesis*" has been documented by Akarca and Long (1980), Yu and Hwang (1984), Yu and Choi (1985), Erol and Yu (1987), Yu and Jin (1992), Cheng (1996), Glasure and Lee (1997), Fatai et al. (2002), Soytas and Sari (2003), Altinay and Karagol (2004), Soytas and Sari (2006a), Jobert and Karanfil (2007), Lee (2006), Soytas et al. (2007), Halicioglu (2009), Payne (2009), Soytas and Sari (2009), Acaravci and Ozturk (2010), Payne and Taylor (2010) and Payne (2011a).
- **Conservation hypothesis (GDP $\rightarrow$ E):** unidirectional causality running from GDP growth to energy consumption. This hypothesis implies that GDP growth causes energy consumption. It suggests that an economy that functions in such a causal relationship is less energy dependent; consequently, any conservation policies concerning energy consumption will have little or no adverse effect on economic growth (Ozturk, 2010). The "*conservation hypothesis*" has empirical support in findings of Kraft and Kraft (1978), Abosedra and Baghestani (1989), Cheng and Lai (1997), Cheng (1998, 1999), Soytas et al. (2001), Aqeel and Butt (2001), Soytas and Sari (2003), Narayan and Smyth (2005), Al-Iriani (2006), Lee (2006), Yoo and Kim (2006), Zachariadis (2007), Mozumder and Marathe (2007), Zamani (2007), Mehrara (2007), Lise and Van Montfort (2007), Lee and Chang (2007b), Ang (2008), Karanfil (2008), Hu and Lin (2008), Zhang and Cheng (2009), Ghosh (2009), Narayan and Smyth (2009), Chang (2010), Ozturk et al. (2010), Lean and Smyth (2010) and Kumar (2011).
- **Growth hypothesis (E $\rightarrow$ GDP)**: unidirectional causality running from energy consumption to GDP. It implies that energy consumption causes GDP growth. The "*growth hypothesis*" suggests that the availability of abundant cheap energy sources promotes economic growth. In that sense, while increases in energy consumption may contribute to further economic growth, reductions in energy consumption may have negative effects on growth (Ozturk, 2010). The "*growth hypothesis*" is supported by empirical findings of Ramcharran (1990), Stern (1993), Masih and Masih (1996, 1998), Glasure and Lee (1997), Stern (2000), Asafu-Adjaye (2000), Soytas and Sari (2003), Morimoto and Hope (2004), Wolde-Rufael (2004), Thoma (2004), Lee (2005), Lee and Chang (2005), Soytas and Sari (2006b), Lee (2006), Ang (2007), Lee and Chang (2007a), Narayan and Singh (2007), Soytas and Sari (2007), Yuan et al. (2007), Lee and Chang, 2008; Narayan and Smyth (2008), Abosedra et al. (2009), Akinlo (2009), Apergis and Payne (2009a, 2009b), Odhiambo (2009b), Chang (2010), Tsani (2010), Warr and Ayres (2010), Wolde-Rufael (2010a), Magazzino (2011), Payne (2011b), Asghar and Rahat (2011), Fotros and Maabudi (2011), Heo et al. (2011), Alam et al. (2011), Tiwari (2011), Yin and Wang (2011) and Arifin and Syahruddin (2011).
- **Feedback hypothesis (E $\leftrightarrow$ GDP) or bi-directional causality**: a bi-directional causality flows between GDP and energy consumption. Both energy consumption and GDP growth trigger each other. The "*feedback hypothesis*" is documented by Hwang and Gum (1991), Ebohon (1996), Masih and Masih (1996, 1997), Asafu-Adjaye (2000), Yang (2000), Hondroyiannis et al. (2002), Glasure (2002), Soytas and Sari (2003), Paul and Bhattacharya (2004), Oh and Lee (2004), Ghali and El-Sakka (2004), Han et al. (2004), Lee (2006), Soytas and Sari (2006b), Yoo (2006a, 2006b, 2006c), Zou and Chau (2006), Climent and Pardo (2007), Francis et al. (2007), Ho and Siu (2007), Mahadevan and Asafu-Adjaye (2007), Zachariadis and Pashourtidou (2007), Lee et al. (2008), Yuan et al. (2008), Erdal et al. (2008), Tang (2008), Odhiambo (2009a), Belloumi (2009), Mishra et al. (2009b), Apergis and Payne (2010a, 2010b), Belke et al. (2011), Shuyun and Donghu (2011), Kouakou (2011) and Kahsai et al. (2012).

The empirical findings on the energy consumption-economic growth nexus consist of a variety of often conflicting results; nothing approaching a consensus has emerged in the literature. This raises important questions concerning the appropriateness of the chosen methodology and the selected variables (Beaudreau, 2010).

The main purpose of the present paper is to cast light on the importance of the questions and criticism raised by Beaudreau (2010) as well as other researchers (Karanfil, 2009; Mehrara, 2007), by carrying out a systematic review of the empirical literature. We extend previous surveys of the literature on the energy-GDP growth causal relationship to cover the period 1978–2011. Our review is based on two previous literature surveys of the energy-GDP causality debate (Ozturk, 2010; Payne, 2010) as well as on additional effort by the authors to bring the survey up to 2011. The literature survey revealed 172 studies. We augment the narrative review by means of a meta-analysis in which the causality direction found by each case study is related to the study's micro characteristics. In fact, two meta-analyses, employing different methodologies, are carried out: one is Rough Set Data Analysis and the other is multinomial logistic regression. According to Glass (1976), the meta-analysis method can be described as the statistical analysis of the results of a large collection of analyses for the purpose of integrating their findings (analysis of analyses). To put it differently, the basic purpose of meta-analysis is to provide the same methodological rigour to a literature review that is required of experimental research. A meta-analysis establishes the presence of an effect and can be a valuable tool for resolving differences in a debate or determining important moderators of an effect (DeCoster, 2004).

From the above, it appears that the findings in the literature on the relationship between energy consumption and economic growth could hardly be further from providing a consensus, as they support the four possible conclusions regarding the causality direction with almost equal frequencies. Meta-analysis aims at bringing some order to this chaos, by ascertaining whether the four findings are related in any degree to the characteristics of the studies. For example, does a particular econometric method tend to lead with relatively high probability to one particular conclusion about causality?

The attributes of studies that were selected for the meta-analysis as ones that potentially might influence conclusions, and also could generally be extracted from the published papers, were the following:

- *The time period examined*. Whereas some studies investigate a very short period of time, up to 10 years (Abosedra et al., 2009; Sari et al., 2008), others examine a period between 10 and 40 years (Chang et al., 2001; Chontanawat et al., 2006, 2008; Erol and Yu, 1987; Kraft and Kraft, 1978), and several studies are based on a period of 40 years or more (Aqeel and Butt, 2001; Cheng, 1999; Soytas and Sari, 2003; Stern, 1993; Yin and Wang, 2011). There is also a study that investigates different time regimes within a country (Fallahi, 2011). Zachariadis (2007) criticizes the use of small samples as it may be associated with the well-known loss of power of econometric tests. In this sense, we assume that the length of the time period might have an important influence on the final results.
- *The classification of countries studied*. Countries may be classified according to their economic development status (Acaravci and Ozturk, 2010; Apergis and Payne, 2010a; Belke et al., 2011; Chiou-Wei et al., 2008; Costantini and Martini, 2010; Huang et al., 2008; Jinke et al., 2008; Lee and Chang, 2007a; Ozturk et al., 2010; Soytas and Sari, 2006b; Zachariadis, 2007; Huang et al., 2008), geographical criteria (Chang et al., 2011; Esso, 2010; Francis et al., 2007; Kahsai et al., 2012; Kumar, 2011; Lee and Chang, 2008; Lee et al., 2008; Mishra et al., 2009a, 2009b; Narayan and Smyth, 2009; Wolde-Rufael, 2006, 2009; Yoo and Kwak, 2010), their energy imports and exports profile (Eggoh et al., 2011; Mahadevan and Asafu-Adjaye, 2007; Squalli, 2007) or other country classifications and trade agreements among countries (Al-Iriani, 2006; Apergis and Payne, 2009c, 2010c). There are also studies referring to a former (USSR) union of countries (Reynolds and Kolodziej, 2008), while a few others scrutinize separate parts (cities) or economic sectors (e.g. industry) of a country (Halicioglu, 2007; Ho and Siu, 2007; Soytas and Sari, 2007; Thoma, 2004; Wolde-Rufael, 2004; Yanqin, 2011; Zhixin and Xin, 2011).
- *Methodology*. A broad variety of methodological approaches has been implemented in order to reveal the causality between energy consumption and economic growth, and in which direction it operates. These approaches can be classified into three broad classes (Beaudreau, 2010): early tests, cointegration tests and post-cointegration tests. Since the very beginning of the causality debate until the late 1990s, most studies (Abosedra and Baghestani, 1989; Cheng, 1997; Erol and Yu, 1987; Kraft and Kraft, 1978; Nachane et al., 1988; Stern, 1993; Yu and Hwang, 1984) utilized a methodology based on both Granger (Granger, 1969) and Sims (Sims, 1972) causality econometric tests, including the modified Engle-Granger causality test (Engle and Granger, 1987) and Hsiao's Granger causality test (Hsiao, 1981). From the mid-1990s, the causality debate was enhanced by new methodological approaches (Johansen and Juselius, 1990) based on the cointegration method (Cheng, 1999; Masih and Masih, 1996; Stern, 2000; Yoo, 2005; Yuan et al., 2007) and other alternatives such as Toda and Yamamoto (1995) causality tests (Fatai et al., 2002; Wolde-Rufael, 2005), Pedroni (1999) panel cointegration (Costantini and Martini, 2010; Lee, 2005; Mahadevan and Asafu-Adjaye, 2007), ARDL (Pesaran et al., 2001; Sari et al., 2008; Shin and Smith, 2001) bounds test (Akinlo, 2008; Ghosh, 2009; Fatai et al., 2004; Ozturk and Acaravci, 2010, 2011; Zachariadis, 2007) and at least 12 other methods (Asghar and Rahat, 2011; Belke et al., 2011; Chiou-Wei et al., 2008; Fallahi, 2011; Hu and Lin, 2008; Narayan and Prasad, 2008; Thoma, 2004).
- *The energy source*. Various energy inputs have been examined in the energy-GDP causality debate. We can divide the literature into groups of studies estimating energy input contributions from fossil fuels at an aggregate and disaggregate level (Bowden and Payne, 2009; Narayan and Wong, 2009; Reynolds and Kolodziej, 2008; Yoo, 2006a; Wolde-Rufael, 2010b; Zou and Chau, 2006), electricity consumption or production (Akinlo, 2009; Altinay and Karagol, 2005; Chen et al., 2007; Ghosh, 2002; Jinke et al., 2008; Jumbe, 2004; Murray and Nan, 1996; Ramcharran, 1990; Shiu and Lam, 2004; Thoma, 2004; Yoo and Kim, 2006; Zachariadis and Pashourtidou, 2007), nuclear energy consumption or production (Heo et al., 2011; Payne and Taylor, 2010; Wolde-Rufael, 2010a; Yoo and Jung, 2005), and renewable energy consumption or production (Apergis and Payne, 2011, 2012, 2012; Bithas and Banti, 2002; Payne, 2011b; Tiwari, 2011), as well as an exergy approach (Warr and Ayres, 2010) and the use of the divisia index of quality weighted energy consumption (Stern, 1993, 2000; Zarnikau, 1997).

3. The methodological framework

3.1. The database construction

According to Hawcroft and Milfont (2010), the procedure of meta-analysis can be described in brief as: (1) a search for studies; (2) selection of studies that meet the criteria for inclusion in the meta-analysis; and (3) coding the attributes of eligible studies. These steps result in the construction of the database for the meta-analysis.

Firstly, the literature review process followed the procedure described thoroughly by Seuring and Müller (2008). Secondly, we excluded some studies from the initial sample of 172 studies. Among those excluded were literature reviews (Ozturk, 2010; Payne, 2010), special points of view (Beaudreau, 2010; Karanfil, 2009) and a few studies that failed to provide essential input for the requisite categories (Adams and Shachmurove, 2008; Carrion-i-Silvestre et al., 2005; De Janosi and Grayson, 1992; Duro et al., 2010; Ferguson et al., 2000; Holtedahl and Joutz, 2004; Huang, 1993; Mishra et al., 2009a; Narayan et al., 2010; Sari and Soytas, 2007; Wolde-Rufael, 2010b; Yoo and Lee, 2010; Yu et al., 1988), or lacked accessibility to further details beyond the study's abstract. We excluded studies that examined other key variables such as causality between employment and GDP, employment and energy consumption, energy intensity and so on. However, studies at least partially examining the energy-GDP nexus, or focusing on an industry sector and relevant industrial production as a part of the specified country's economy instead of GDP (Feng et al., 2009; Fotros and Maabudi, 2011; Halicioglu, 2007; Hondroyiannis et al., 2002; Narayan et al., 2007; Sari et al., 2008; Thoma, 2004; Ziramba, 2009), were included in our meta-analysis.

A small number of earlier studies employ GNP instead of GDP. We included these studies without distinction from the large majority that examine GDP. Nevertheless, it should be mentioned that the use of GDP as an aggregate indicator of economic process has been severely criticized for obscuring crucial attributes of real-world economic production (Daly, 2013; van den Bergh, 2010); hence, the exclusive use of this indicator by the vast majority of the studies within the causality debate may have further implications affecting the result of directionality.

Studies that estimate causality for a group of countries are separated into their component countries whenever possible. This procedure of separating countries led to 686 cases with complete data, representing the 158 published studies. The great majority of these studies (135, 85.4%) were published from 2000 onwards (derived cases: 606, 88.3%). Sixteen studies (10.1%) were published in the 1990s (derived cases: 50, 7.3%) and six studies (3.8%) in the 1980s (derived cases: 29, 4.2%), with just one from the 1970s (0.6%). Ranking studies according the journal in which they were published reveals that almost 57% of the 158 studies appeared in *Energy Economics* (52 studies, 32.9%) and *Energy Policy* (38 studies, 24.1%). A further 17.7% was published in various other high impact-factor[2] journals such as *Applied Energy* (8, 5.1%), *Journal of Policy Modeling* (8, 5.1%), *Energy* (5, 3.2%), *Ecological Economics* (4, 2.5%) and *Applied Economics* (3, 1.9%). The remaining 21% of the studies included in the meta-analysis were published in 17 other journals, while a small number of published working papers (3, 1.9%) and papers published in peer-reviewed conference proceedings (4, 2.5%) complete the dataset.

Some studies included both short-run and long-run causal relationship implications (Alam et al., 2011; Apergis and Payne, 2009c, 2010c; Belloumi, 2009; Ciarreta and Zarraga, 2009; Magazzino, 2011; Narayan et al., 2010; Ozturk and Acaravci, 2011; Zhixin and Xin, 2011) and in these cases we used only the short-run results as we did not aim to distinguish between short-run and long-run causality results in the meta-analysis. The growth hypothesis (E → GDP) was supported by 193 cases (28.1%), the conservation hypothesis (GDP → E) by 163 (23.8%), the feedback hypothesis (E ↔ GDP) by 175 (25.5%) and the neutrality hypothesis or no causality (E ≠ GDP) by 155 (22.6%).

[2] For the "impact factor (IF)", we explicitly use the latest 5-year Impact Factor (2012), according to Journal Citation Reports, published by Thomson Reuters. Because of changes in a journal's IF, examination of any relationship between the results of studies and the journal's IF remains rather a hard task.

3.2. Coding of study attributes

The year of publication attribute was coded according to the date of publication, as: 1970s; 1980s; 1990s; and 2000–2011.

The length of the study period was grouped into ten-year periods: less than 10 years; 10–19 years; 20–29 years; 30–39 years; 40 years or more.

The level of economic development of the country under study was coded as: G7 member; OECD member (excluding G7); high developing non-OECD members; and other non-OECD countries. A separate category was used for studies that examined only part of a country (city or region) or an economic sector of a country.

The categorization of *econometric methodology* follows the general lines of Payne (2010). Six categories were distinguished, which can be labeled briefly as: Sims and Engle-Granger causality; Johansen-Juselius; Toda-Yamamoto causality; Pedroni panel cointegration; ARDL bounds test; and other methods.

The energy types examined in the causality debate are recorded in nine categories: total fossil fuels consumption (coal, oil, and natural gas); electricity consumption (or production); energy consumption per capita (primary or electricity, etc.); total energy consumption (primary fuels plus electricity); oil or petroleum consumption (or production); coal consumption (or production); natural gas consumption (or production); nuclear energy consumption (or production); and renewable energy consumption.

The energy measurement unit is a crucial issue in the relationship between energy consumption and economic growth (Cleveland et al., 1984; Kaufmann, 1992; Warr et al., 2010; Stern, 2011). However, a substantial number of studies avoid giving a clear definition of the energy measurement unit (Cheng and Lai, 1997; Masih and Masih, 1996; Wolde-Rufael, 2004). Our classification of the energy measurement methods used in the causality debate is into nine distinct types: Btu's; oil equivalent; electricity (watts); coal equivalent; exergy; crude quantity; Devisia Index; Joules; and not defined, for those studies that do not specify the unit of energy measurement.

An attribute "*One or more countries*" was included to cater for those studies of more than one country that could not be broken down into results for the individual component countries. It thus includes two categories: single country, if the estimated causality direction referred to a single country; and group of countries, if the estimated causality direction referred to an overall group of countries that could not be separated.

Finally, the dependent variable "*Causality direction*" was coded into four distinct categories: the *growth hypothesis* E → GDP; the *conservation hypothesis* E ← GDP; the *bi-directional hypothesis* E ↔ GDP; and the *neutrality hypothesis* E ≠ GDP.

The 686x7 data matrix consisting of the six numerically coded attributes and the outcome of each study is available on-line as supplementary material. Table 1 shows the frequencies of the categories of each attribute in the total sample of 686 studies.

The associations between each attribute and the outcome variable, that is, the causality findings, are shown in Tables 2 and 3. Chi-squared tests show that every attribute is statistically significantly associated with the outcome, with the exception of the attribute "single country versus group of countries" ($P = 0.17$; P is at most 0.023 for the other attributes). Examples of the many features that can be seen in these tables include: an increased proportion of neutral results (E ≠ GDP) in longer-term studies (duration 40 years or more) but fewer in studies of high-developing non-OECD countries and in studies of groups of countries; relatively more E → GDP results using the Pedroni panel cointegration methodology; and relatively fewer GDP → E findings when the study measured energy in oil equivalent. However, these findings are not independent of each other, because there are also strong

Table 1
Frequencies of attributes recorded for the meta-analysis of 686 cases from 158 studies of the relationship between energy consumption and economic growth.

	Total number of cases	*n*	%
		686	100
Length of study period (years)[a]	<10	5	0.7
	10–19	8	1.2
	20–29	191	27.8
	30–39	353	51.5
	40+	127	18.5
Economic development of study country	G7	121	17.6
	Other OECD	163	23.8
	Non-OECD high development	148	21.6
	Other non-OECD	245	35.7
	Region of country	9	1.3
One or more countries	Single country	637	92.9
	Group of countries	49	7.1
Econometric methodology	Sims & amp; Engle-Granger	207	30.2
	Johansen-Juselius	189	27.6
	Toda-Yamamoto	116	16.9
	Pedroni	52	7.6
	ARDL bounds test	52	7.6
	Other	70	10.2
Energy input source	Energy per capita	272	39.7
	Total energy	214	31.2
	Electricity	139	20.3
	Coal	22	3.2
	Oil	14	2.0
	Gas	13	1.9
	Other[b]	12	1.7
Energy measurement method	Oil equivalent	357	52.0
	Electricity	168	24.5
	Btu	49	7.1
	Coal equivalent	25	3.6
	Crude quantity	12	1.7
	Other[c]	8	1.2
	Undefined	67	9.8

[a] Not defined in 2 cases.
[b] Nuclear 5, renewables 4, total fossil fuels 3.
[c] Devisia index 5, Joule 2, exergy 1.

associations between the attributes. For one example, studies in G7 countries tend to be longer term than in others: 49% cover at least 40 years, compared to 12% of studies in other countries. For another example, the Sims or Engle-Granger methodologies have been employed in 48% of studies that measured energy as energy per capita, compared to 19% of studies using other measurement methods. Because of these associations, it is desirable to carry out multivariate analyses that consider all attributes simultaneously.

4. Rough Set Data Analysis (RSDA)

4.1. The method

Rough Set Data Analysis (RSDA) is an operational research method applied to conceive and evaluate quantitative data and qualitative characteristics. It can identify causal relationships and express them through decision rules. The attributes and characteristics of different objects (cases) are analyzed and classified. The attributes are related to the decision variable (dependent variable) through decision rules reflecting rigorous causal relationships. The mathematical background of RSDA is presented in full in the relevant literature (Duntsch and Gunther, 1998; Pawlak, 1982, 1991; Slowinski, 1993). RSDA theory takes for granted the existence of a finite set of objects for which some information is known in terms of factual (qualitative or numerical) knowledge of a class of attributes (features, characteristics) (Bithas and Nijkamp, 1997a, 1997b). The rough set model is intended to be a structural, non-numerical method of information analysis, thus its quantitative aspects are of secondary interest (Duntsch and Gunther, 1998). As a result, RSDA can classify the attributes of objects-cases and determine the most important ones. We selected RSDA mainly because it is a simplified method used to discover information overlooked by other methods, to preprocess the data for further analysis and to strengthen results found previously by other methods (Rupp, 2005). RSDA has been developed as an alternative data analysis tool by Pawlak (1982, 1991) and further developed by Slowinski (1993). We carried out our analyses using the Rosetta Rough Set Toolkit (Øhrn and Komorowski, 1997; Komorowski et al., 2002) which offers a wide range of ready-to-apply statistical tools and filters.

4.2. RSDA results

RSDA application obtains preliminary information from the decision table (that is, the data matrix described above) by generating decision rules. Decision rules are expressed as conditional statements ('if then'), in which the 'if' conditions specify the initial conditions, while the 'then' inference statements indicate the logically

Table 2
Causality result of analysis in relation to length of study period, characteristics of study country, and econometric methodology employed. Percentages sum to 100 within each row.

		Causality result							
		E → GDP		GDP → E		E ↔ GDP		E ≠ GDP	
		n	%	*n*	%	*n*	%	*n*	%
Length of study period (years)	<20	4	30.8	4	30.8	4	30.8	1	7.7
	20–29	60	31.4	50	26.2	37	19.4	44	23.0
	30–39	93	26.3	89	25.2	103	29.2	68	19.3
	40+	35	27.6	20	15.7	30	23.6	42	33.1
Economic development of study country	G7	25	20.7	25	20.7	33	27.3	38	31.4
	OECD	43	26.4	35	21.5	41	25.2	44	27.0
	High development	49	33.1	34	23.0	45	30.4	20	13.5
	Non-OECD	72	29.4	67	27.3	56	22.9	50	20.4
	Region	4	44.4	2	22.2	0	0.0	3	33.3
One or more countries	Single country	177	27.8	148	23.2	162	25.4	150	23.5
	Group of countries	16	32.7	15	30.6	13	26.5	5	10.2
Econometric methodology	Sims & Engle-Granger	46	22.2	43	20.8	60	29.0	58	28.0
	Johansen-Juselius	59	31.2	36	19.0	70	37.0	24	12.7
	Toda-Yamamoto	31	26.7	38	32.8	8	6.9	39	33.6
	Pedroni	26	50.0	10	19.2	15	28.8	1	1.9
	ARDL bounds test	11	21.2	19	36.5	13	25.0	9	17.3
	Other	20	28.6	17	24.3	9	12.9	24	34.3

Table 3
Causality results in relation to energy source and energy measurement employed in study. Percentages sum to 100 within each row.

		Causality result							
		E → GDP		GDP → E		E ↔ GDP		E ≠ GDP	
		n	%	*n*	%	*n*	%	*n*	%
Energy input source	Electricity	39	28.1	37	26.6	23	16.5	40	28.8
	Energy per capita	68	25.0	61	22.4	95	34.9	48	17.6
	Total energy	71	33.2	50	23.4	46	21.5	47	22.0
	Oil	4	28.6	3	21.4	4	28.6	3	21.4
	Coal	3	13.6	6	27.3	4	18.2	9	40.9
	Gas	2	15.4	4	30.8	1	7.7	6	46.2
	Other	6	50.0	2	16.7	2	16.7	2	16.7
Energy measurement	Btu	6	12.2	19	38.8	5	10.2	19	38.8
	Oil equivalent	105	29.4	78	21.8	110	30.8	64	17.9
	Electricity	51	30.4	45	26.8	28	16.7	44	26.2
	Coal equivalent	4	16.0	5	20.0	7	28.0	9	36.0
	Crude quantity	2	16.7	5	41.7	3	25.0	2	16.7
	Other	4	50.0	1	12.5	3	37.5	0	0.0
	Undefined	21	31.3	10	14.9	19	28.4	17	25.4

valid conclusions. In this way, RSDA can be used as a tool for conditional transferability of the results from case studies to a new situation. A decision rule is thus an implication relationship between the description of the attributes and the decision attribute (causality direction). A rule is exact if the combination of the values of the attributes in that rule implies only one single combination of the values of the decision attributes, whereas an approximate rule only states that more than one combination of values of the decision attributes correspond to the same values of the attributes (Bithas and Nijkamp, 1997a, 1997b). A complete description of the rule generation procedure can be found in the relevant literature (Kusiak, 2001; Øhrn and Komorowski, 1997; Rupp, 2005; Pawlak, 1991).

In the present study, 235 rules were generated from the decision table. Very few of these rules were exact. An example of a rule is:

If A2 (5) AND A4 (3) AND A5(4) AND A6 (9) then decision for causality: => *D* (1)

Support = 3
Coverage = *0.004373*
Accuracy = *100%*

The interpretation of this rule is: if attribute A2 "*Length of study period*" takes the value (5) "*More than 40 years*", and attribute A4 "*Econometric methodology*" takes the value (3) "*Toda-Yamamoto*", and attribute A5 "*Energy input source*" takes the value (4) "*Total energy consumption*", and attribute A6 "*Energy measurement*" takes the value (9) "*Not defined*", then the causality direction is *D*(1), thus "*E* → *GDP*". For this rule, the conditional attributes have a support of 3 objects from the total of 686 objects (support = 3), which accounts for 0.43% of the total objects in the decision table (coverage = 0.004373) and 100% of these 3 objects (Accuracy = 100%) have a decision value = D(1). In general, only rules with relatively high support (hence, higher coverage) and high accuracy should be considered (Kusiak, 2001). To continue with the previous example, despite the fact that this rule presents the highest possible level of accuracy (100%), it fails as far as both support and coverage levels are concerned. To put it differently, it applies to too few cases to be able to offer a useful description relative to the dataset as a whole.

Once preliminary results have been obtained, validation techniques ensure that the knowledge obtained by rules is interpretable in functional relationships. A further filtering procedure is performed in order to find the rules that are accurate representations of the dataset. The filtering procedure is a practical sorting of rules according to their quantitative aspects (accuracy, coverage, etc) in order to reveal the most significant ones. The great majority of the rules obtained in this way failed to fulfill the prerequisites of high support and high accuracy, for every alternative combination of statistical methods and filtering techniques that was applied. The procedure always resulted in large numbers of approximate rules with high accuracy but low support (few objects), and with low accuracy in combinations with higher support. Under these circumstances, it is impossible to choose accurately and consistently between generated rules. In conclusion, RSDA failed to provide concrete and effective results concerning the direction of causality.

5. Multinomial logistic regression analysis and results

Logistic regression analysis has become the standard statistical model for examining the influence of various factors on a dichotomous outcome in a regression framework. It estimates the probability of the occurrence of the outcome category of interest by modeling the relationship between one or more independent (explanatory) variables and the log odds (logit) of the dichotomous outcome. In the present study, the dependent variable is the causality direction result, which is not dichotomous but consists of four categories. We therefore apply the multinomial logistic regression model (Agresti, 1996). This analysis fits simultaneously three models, holding one outcome category as reference category and comparing each of the other three categories to it. Hence, choosing E ≠ GDP as reference category, the three regression models that are fitted are:

1. *E* → *GDP compared to E* ≠ *GDP*
2. *GDP* → *E compared to E* ≠ *GDP*
3. *E* ↔ *GDP compared to E* ≠ *GDP*

If π_j is the probability that the causality result is the category $j = 1, 2, 3, 4$, then these regression models are of the logit form:

$$\log\frac{\pi_j}{\pi_4} = \alpha_j + \beta_{1j}x_1 + \beta_{2j}x_2 + ... + \beta_{pj}x_p$$

for $j = 1, 2, 3$, where the constants α_j and regression parameters β_{ij} are to be estimated from the data by the method of maximum likelihood. Because all our explanatory variables are categorical, every independent variable x_i will be replaced by a set of dummy variables. For each of the attributes we must also set a reference category. For example, for the attribute "*Econometric methodology*" we chose the subcategory "*others*". The choice of reference category

Table 4
Multinomial logistic regression results: rate ratios with their 95% confidence intervals.

Attribute	Categories	Rate ratio and 95% CI versus E≠GDP		
		E → GDP	GDP → E	E ↔ GDP
Econometric methodology	Sims & E-G	1.14 (0.53 – 2.43)	1.12 (0.51 – 2.44)	2.46 (1.01 – 5.98)
	Johansen-Juselius	4.34 (1.90 – 9.94)	2.39 (1.00 – 5.72)	8.80 (3.40 – 22.8)
	Toda-Yamamoto	0.99 (0.44 – 2.22)	1.55 (0.70 – 3.43)	0.53 (0.17 – 1.60)
	Pedroni	35.5 (4.29 – 293)	14.0 (1.60 – 123)	33.0 (3.69 – 295)
	ARDL	1.95 (0.66 – 5.78)	3.14 (1.13 – 8.75)	4.70 (1.46 – 15.1)
	Other[a]	1	1	1
Energy measurement	Btu	0.18 (0.06 – 0.58)	1.28 (0.45 – 3.61)	0.13 (0.04 – 0.47)
	Oil equivalent	0.96 (0.45 – 2.05)	1.74 (0.73 – 4.16)	1.00 (0.46 – 2.21)
	Electricity	0.87 (0.38 – 2.00)	1.60 (0.63 – 4.03)	0.52 (0.21 – 1.27)
	Other[b]	0.39 (0.12 – 1.27)	1.16 (0.34 – 4.01)	0.47 (0.15 – 1.49)
	Undefined[a]	1	1	1

[a] Reference category.
[b] Including coal equivalent.

does not affect the overall statistical significance of an attribute, nor the estimates of the probabilities π_j derived from the fitted model.

Likelihood ratio tests in the analysis that regressed causality results against sets of dummy variables representing all six attributes identified two attributes as statistically significant: "*Econometric methodology*" ($P < 0.001$) and "*Energy measurement*" ($P = 0.016$). Each of the other attributes had $P > 0.1$. The analysis was repeated using only these two attributes as explanatory variables in order to obtain the final results for presentation. Estimates are shown in Table 4. Results are expressed in terms of the rate ratio $exp(b_{ij})$, where b_{ij} is the estimate of a regression coefficient β_{ij}. This gives the multiplicative effect of the corresponding dummy variable on the probability ratio π_j/π_4. A rate ratio (RR) greater than unity indicates that membership of the attribute category indexed by this dummy variable increases the probability of outcome j compared to the reference category E ≠ GDP. RR < 1 indicates a reduced probability of outcome j compared to the reference category and RR = 1 indicates that there is no differentiation in outcomes between membership of this attribute category and the reference category.

In interpreting the results of Table 4, we concentrate on those rate ratios for which the confidence interval does not include the value unity (so that RR ≠ 1 is supported). In the case of *energy measurement*, the differentiation appears to be between measurement in Btu's and the other categories. Studies in which energy was measured in Btu's have a reduced probability of demonstrating E → GDP or E ↔ GDP, but an increased probability of finding GDP → E, compared to the neutrality hypothesis (see also Table 3). From cross-tabulations between the attributes (data not shown), these studies are commonly of 30–39 years duration (65.3%), conducted among G7 countries (38.8%) or other OECD members (46.9%), and often analyze total energy (57.1%). For the *econometric methodology* attribute, three methodologies – Johansen-Juselius, Pedroni and ARDL – all have increased probabilities of demonstrating any other causality result than the neutrality hypothesis, compared to the Sims and Engle-Granger, Toda-Yamamoto and other methodologies (see also Table 3). Some of these effects seem to be very strong, although the extremely wide confidence intervals make it difficult to make precise statements. This lack of precision is due to low numbers of cases in certain combinations of data: for example, only one of the 52 studies using the Pedroni methodology concluded in favor of the neutrality hypothesis (Table 3).

The results of the analysis may also be demonstrated by calculating the estimated probabilities of each causality result based on the estimated regression coefficients for energy measurement and econometric methodology. Fig. 1a–e present these probabilities diagrammatically and Table 5 gives the combinations that are the most strongly associated with one particular outcome, in that it occurs with a relatively high fitted probability (>0.4). These combinations account for 212 of the cases (30.9%) but several occur rarely, some in as few as one case. The commonest of these combinations are of oil-equivalent energy measurement with either the Johansen-Juselius methodology (support = 99 cases, 14.4% of the total, with fitted probability 0.423 of the outcome GDP → E) and the Pedroni methodology (support = 44 cases, 6.4% of the total, with fitted probability 0.501 of the outcome E ≠ GDP). These are the strongest results of the analysis. The most frequent combination of all is of the Sims or Engle-Granger methodology with oil-equivalent energy measurement (122 cases, 17.8%), for which the fitted probabilities of the four outcomes are not very different from each other (E → GDP 0.205, GDP → E 0.327, E ↔ GDP 0.241, E ≠ GDP 0.227).

6. Discussion

The present article focuses on the identification of general trends in the direction of the energy-growth causal relationship. The analysis tested the existence (or otherwise) of causal relationships among the selected attributes of the energy-growth nexus which explain the direction of causality. The investigation was based on both statistical methods and on methods of operational research. To this end, we performed a Rough Set Data Analysis (RSDA) and a multinomial logistic regression on a database consisting of 686 cases-sets of results derived from 158 published studies.

The RSDA indicated that there are no accurate rules – causal relationships among the attributes of the economies studied – that determine the causality direction. No solid causal relationships that define the direction of causality could be established. As a result, the direction (or the absence of any direction) of causality cannot be described by a theoretically testable argument. This conclusion is further supported by the findings of multinomial logistic regression; these also failed to define a robust causal relationship between the attributes of case studies and the direction of causality. A weak "rule" – causal relationship – such as the indication that the combination of the "Johansen-Juselius" methodology with "oil-equivalent" energy measurement usually leads to support for the conservation hypothesis (GDP → E), is of marginal importance as it does not lead to a fundamental rational explanation concerning the causality direction. Taking into account the findings of both RSDA and multinomial logistic regression, we are forced to argue that the direction of causality cannot obey a general "macro" rule among the attributes of the energy-economy nexus. In that context, it seems that the way causality runs depends on the specific conditions of each case study and is probably sensitive to the methodology adopted. The meta-analysis results support the argument of Mehrara (2007) who comments on the energy-GDP growth causality debate: "*when it comes to whether energy use is a result of, or a prerequisite for economic*

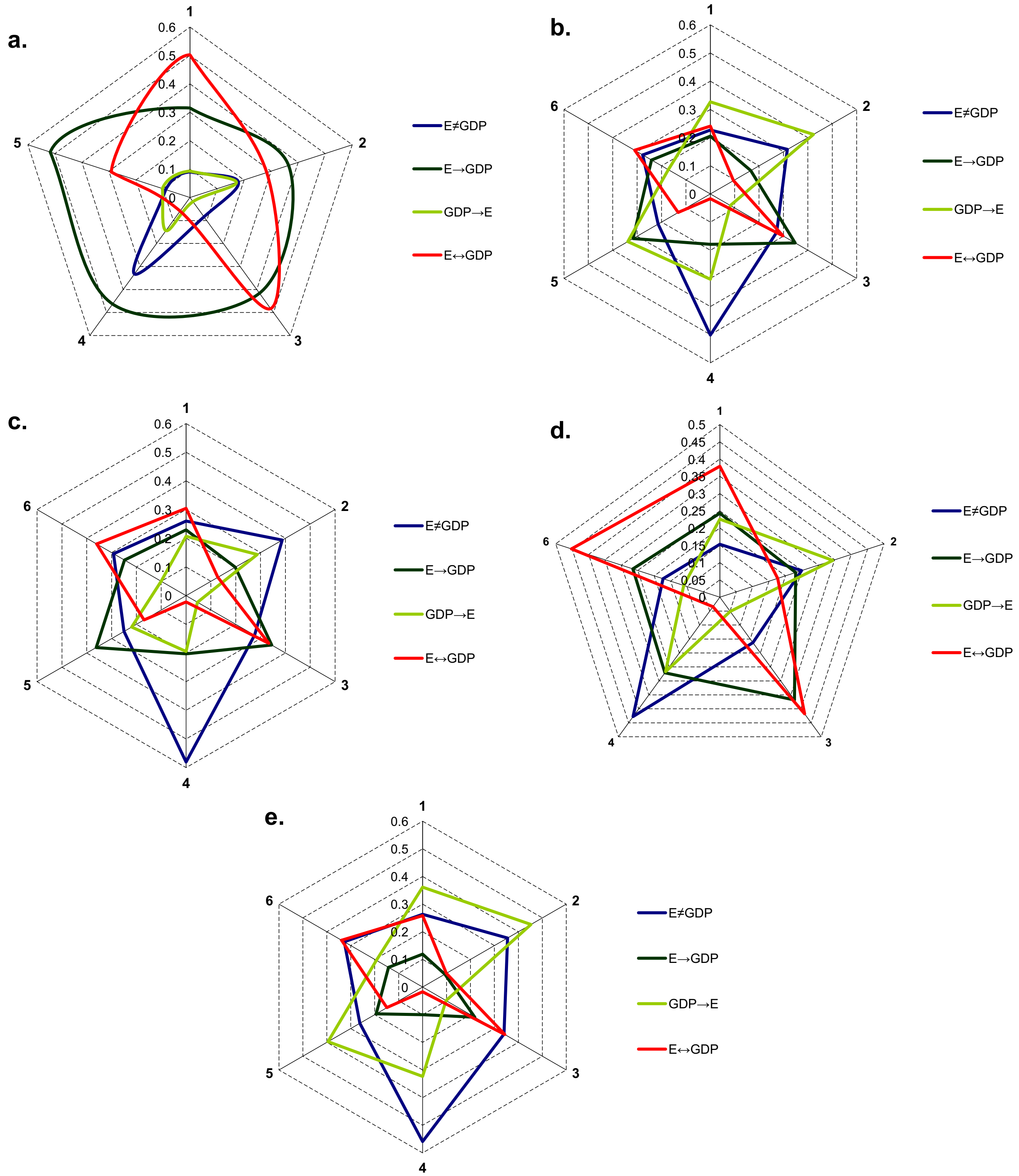

Fig. 1. Representation of Tables 4 and 5 Each radar-type diagram shows the fitted probabilities of each of the four outcomes for each of the six categories of Methodology: (a) for Energy Measurement in Btu's; (b) for Energy Measurement in oil equivalent; (c) for Energy Measurement in Electricity; (d) for Energy Measurement in coal equivalent; (e) for Energy Measurement "not defined". Methodology categories are: (1) Sims & Engle-Granger Causality; (2) Johansen-Juselius for Cointegration; (3) Toda Yamamoto Causality; (4) Pedroni Panel Cointegration; (5) ARDL Bounds test; (6) Others.

growth, there are no clear trends in the literature. Depending on the methodology used, and country and time period studied, the direction of causality between energy consumption and economic variables has remained empirically elusive and controversial".

Nevertheless, empirical analysis in recent years identifies the existence of a fundamental relationship between energy use and economic growth (Bithas and Kalimeris, 2013; Cleveland et al., 1984; Warr et al., 2010). Regardless of the directionality, the most crucial

Table 5
Combinations of attribute categories with the highest fitted probabilities of one outcome from the multinomial logistic regression analysis.

Favored result	Categories of:		Fitted probability	Number of cases	
	Methodology	Energy measurement		*n*	% Of total
E → GDP	Toda-Yamamoto	Btu	0.416	10	1.5
	Pedroni	Btu	0.463	2	0.3
	ARDL	Btu	0.517	8	1.2
GDP → E	Johansen-Juselius	Oil equivalent	0.423	99	14.4
	Johansen-Juselius	Undefined	0.453	13	1.9
E ↔ GDP	Sims	Btu	0.502	16	2.3
	Johansen-Juselius	Btu	0.483	10	1.5
	Toda-Yamamoto	Other	0.418	3	0.4
	Other	Other	0.452	1	0.1
E ≠ GDP	Pedroni	Oil equivalent	0.501	44	6.4
	Pedroni	Electricity	0.580	4	0.6
	Pedroni	Other	0.428	1	0.1
	Pedroni	Undefined	0.559	1	0.1

conclusion of the causality debate so far is, for most authors, that energy is an important determinant of economic growth. The uninterrupted function of the economic process requires substantial energy inputs (Altinay and Karagol, 2005; Ghali and El-Sakka, 2004; Hondroyiannis et al., 2002; Lee, 2006; Soytas et al., 2001; Yuan et al., 2008).

7. Conclusions

Given the demand for designing effective energy policies, the causality debate should offer a coherent understanding of the energy-growth nexus. The direction of causality between energy use and economic growth could be a decisive component of this nexus. Over the last three decades, the ongoing debate on the direction of causality between energy consumption and economic growth – closely following advances in econometric theory, energy economics and environmental economics – has produced a significant amount of scientific literature. However, despite all this research, the state of knowledge still remains quite indeterminate and controversial. The attempt in the present study to examine the concreteness and consistency of the debate's results by means of meta-analysis failed to define a robust macro causality direction and, moreover, failed to identify general factors and causal relationships determining the directionality. Under constraints imposed by the inability to identify a macro direction of causality, the numerous individual case studies may be perceived as influenced by conditions specific to each case and time. On the other hand, the failure of meta-analysis to reveal valid causal relationships defining the directionality at the aggregate level ultimately reflects the contradictory results that the debate itself presents. These contradictions and conflicts within the empirical results have been highlighted by many researchers (Beaudreau, 2010; Mehrara, 2007; Ozturk, 2010). Although progress in econometric methods provides several powerful tools for the analysis and understanding of the energy-economic growth relationship, applied studies using these tools are open to the criticism that many of these studies yield conflicting and even contradictory findings which makes it difficult to draw macro policy implications. As Karanfil (2009) and Ozturk (2010) comment: "*research papers using the same methods with the same variables, just by changing the time period examined, have no further potential to make a contribution to the existing energy–growth literature*". In that context, we may conclude that the directionality is the result of very specific conditions pertaining to each case study and may be influenced strongly by the analytical methods and econometric techniques applied. In the light of this conclusion, policy implications based on the direction of causality should be carefully worded as they are not based on solid theoretically and empirically testable arguments and hence could be sensitive to various factors.

Nevertheless, we argue that the impossibility of determining a general rule governing the directionality between energy and growth cannot question the very fact that growth requires energy and that the efficiency gains induced by technological advances have not alleviated this strong link. In that context, future research on E-GDP causal relationship could benefit by focusing on and investigating the following aspects:

- An effort to bridge three different fields of empirical analysis: the energy-GDP nexus; the decoupling effect; and the Environmental Kuznets Curves (EKC). A historical analysis of a country or a group of countries, in the light of the simultaneous empirical evidence of causal relationship between energy use and GDP growth (the causality investigation) in tandem with energy use intensity per unit of GDP (decoupling effect) and the EKC, could contribute to a fruitful comparison among methodologies and results and lay the foundation for a more integrated and substantial approach to the complex relationship between the use of natural resources and economic growth.
- A step beyond energy measurement in thermal equivalents to a more accurate energy efficiency measurement, such as the "*exergy*" and "*useful work*" approach (Warr and Ayres, 2010; Warr et al., 2010), and the Divisia index adjustment (Stern, 1993, 2000; Zarnikau, 1997) may reveal new empirical evidence, since only 5 out of 158 studies (0.33%) attempted an alternative measurement of energy use in terms of qualitative adjustments.
- In accordance with the previous point, an effort to evaluate and incorporate energy price fluctuations and price elasticities, instead of energy quantities, is absent from the vast majority of studies published within the causality dialogue. In this context, econometric studies examining the relationship between energy prices and the economic process (Hamilton, 1996, 2008) could offer a sound basis for progress in this direction
- As already mentioned in a previous section, the GDP has been the subject of extensive and severe criticism for many years as being an aggregate indicator which masks certain crucial aspects entailed by the economic process (Bithas and Kalimeris, 2013; Daly, 2013; van den Bergh, 2010). In the context of the causality debate, an effort to overcome the shortcomings arising from the use of GDP could be traced in the very few studies (just 7, 4.4%) that examined alternative variables such as percentage value added of an economic sector (Costantini and Martini, 2010; Feng et al., 2009; Sari et al., 2008), or business cycles (Thoma, 2004) instead of GDP. Towards this

direction, a more disaggregated analysis may offer more substantial conclusions.

-Finally, as Payne (2010) proposes, a more robust classification of countries into groups with similar energy consumption patterns together with similar levels of development status could contribute to more coherent empirical estimates.

Beyond its prima facie interest, the analysis and evaluation of those aspects in future research may eventually provide the empirical basis for the – still theoretical – degrowth and a-growth dialogues. The present study could be perceived as a small contribution towards this direction.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2013.12.040

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