Water Resources and Economics 39 (2022) 100202

Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: www.elsevier.com/locate/wre

The Environmental Kuznets Curve at the thermoelectricity-water nexus: Empirical evidence from Spain

Diego Sesma-Martín [a], [b], [*], Miguel Puente-Ajovín [c], [d]

[a] Department of Economics and Business, University of La Rioja, Quintiliano Building, 26004, Logroño, Spain
[b] Institute for Advanced Research in Business and Economics (INARBE), Universidad Pública de Navarra (UPNA), Jerónimo de Ayanz Centre, Arrosadia Campus, 31006, Pamplona, Spain
[c] Department of Economic Analysis, Faculty of Social Sciences and Humanities. University of Zaragoza, 4 Atarazanas St., 44003 Teruel, Spain
[d] Instituto Universitario de Investigación en Empleo, Sociedad Digital y Sostenibilidad (IEDIS), Spain

ARTICLE INFO

Keywords:
Water withdrawal
Thermal power generation
Economic growth
Environmental Kuznets curve
Spain

ABSTRACT

Energy and water are essential resources for ensuring economic growth. Both sectors are closely interrelated. Electricity generation is one of the most water-intensive activities worldwide and the cooling of thermoelectric power stations represents one of the largest uses of water within the energy sector. This study provides evidence on the existence of an Environmental Kuznets Curve (EKC) for water withdrawal at the thermoelectricity sector in Spain, one of the most arid countries in Europe, for the period 1970–2019, using the ARDL model. Our results show a direct relationship between per capita income and water withdrawal until an estimated turning point is reached. In the Spanish case, further development has led to a reduction in water needs for the following reasons: 1) the use of less water-intensive cooling systems, 2) changes in generation technology.

1. Introduction

Water and energy are drivers of growth. Water, the most critical resource globally, represents an essential input in practically all economic activities -agriculture, industry, energy, recreational, etc [1]. Extensive research has also shown the importance of energy in promoting economic growth [2]. In turn, the energy sector is the second thirstiest sector worldwide, accounting for about 10% of water withdrawals and 3% of water consumption globally [3]. Water and energy systems are intrinsically linked and their potential implications for economic growth seem indisputable.

Energy and water sectors are closely interrelated. On the one hand, energy is used at each stage of the cycle of water supply, treatment, and disposal. On the other hand, water is necessary for the extraction, refining and transformation of fuels, transport and storage, and electricity generation [4]. Consequently, the water-energy nexus, as it is known in the literature, is receiving increasing attention from researchers and practitioners [5–8]. Within the energy sector, electricity generation is the activity that involves the largest volumes of water. Approximately, 88% of global power generation is water intensive [9]. In addition to hydropower plants, thermoelectric power stations (fueled by coal, fuel oil, natural gas, or uranium) require significant volumes of water. In 2010, nearly 80% of the world's electricity was still generated in thermoelectric power plants. Moreover, thermal power generation was responsible for almost one half of all water withdrawals in the US and in various European countries [10,11]. Unlike hydropower plants,

---

[*] Corresponding author. Department of Economics and Business, University of La Rioja, Quintiliano Building, 26004, Logroño, Spain.
E-mail address: diego.sesmam@unirioja.es (D. Sesma-Martín).

https://doi.org/10.1016/j.wre.2022.100202
Received 10 August 2021; Received in revised form 29 April 2022; Accepted 2 May 2022

thermoelectric facilities boil water to create steam to spin turbines that generate electricity. Later, the steam that has passed through the turbine is cooled to water before it can be reused to produce more electricity. Cooling is the stage that requires the largest amounts of water within the electricity generation process [12]. Water shortages are already affecting many regions worldwide and many power plants are being forced to shut down due to lack of water [13–15]. Securing the supply of water and electricity is essential to the progress of economies. Therefore, it is a key question to explore the relationship between economic growth and pressure on water resources.

The relationship between economic growth and the environment is complex. Pioneering work on such relationship emerged in the 1990s based on the initial idea of the Kuznets Curve [16–19]. Since then, the Environmental Kuznets Curve (EKC) has become one of the most discussed topics among environmental economists in recent years [20–23]. The EKC, so called because of its similarity to the relationship that economist Simon Kuznets previously established between economic growth and inequality in income distribution [24], suggests that there is an inverted U-shaped relationship in which environmental pressure increases as economic growth does. Then, when a certain level of per capita income is reached (namely, the turning point), the environmental pressure decreases [25]. According to the theoretical underpinnings of this hypothesis, industrialization and agricultural modernization may initially explain the increase in environmental pressure. By contrast, factors that could explain the subsequent turndown include: 1) positive income elasticities for environmental quality; 2) changes in the composition of consumption and production; 3) increasing levels of education and environmental awareness; 4) more open political systems; 5) the presence of increasing returns of scale in the energy production system [21,26,27].

The existing literature on the EKC and water pressure tends to consider water consumption (that is, the part of the freshwater withdrawn which is not returned to the original water body due to evaporation) as a relevant variable. Nevertheless, in this paper we focus on water withdrawal (i.e., the total amount of water removed from the ground or diverted from a water source) for the cooling of thermal power plants during the electricity generation process. In a context of climate change with increasing water scarcity, minimizing the amount of water that makes a process possible may become more important than minimizing the volume of water consumed. Although the quantity of water withdrawn is subsequently returned to the aquatic environment, the water withdrawn is no longer available at the precise place and time for other uses. Thus, the economic notion of ‘opportunity cost’ becomes particularly important here. Likewise, water withdrawal provides an idea of the volumes of water we initially need to run a thermoelectric power plant. If such volumes are not available initially, the power plant may not operate properly [28].

The implementation of the different electricity generation technologies in Spain is crucial to understand the evolution of water requirements in the long term. Until the 1960s, hydroelectricity remained the major contributor to Spanish electricity generation. The economic miracle of the 1960s and early 1970s required more energy input. In terms of electricity, this resulted in the expansion of the Spanish thermoelectric fleet with the commissioning of new thermal power plants (coal and fuel oil) and the beginning of nuclear generation with the opening of the first generation of nuclear power plants. With the turn of the century, natural gas combined-cycle, wind and solar power, and biomass joined to the electricity mix. Fig. 1 shows the complete picture. In terms of water use, the percentage of electricity generation that depends on water has declined over the last two decades due to the shift towards renewable energy sources. However, at present, more than 60% of the Spanish electricity generation still depends on the availability of fresh water. The increasing adoption of less thirsty cooling technologies has also had important implications in this respect [29].

This paper aims to evaluate the validity of the EKC for water withdrawals from thermoelectricity generation in Spain, the most arid country in Europe, for the period 1970–2019. Thermoelectric sector has represented the most important contributor to the Spanish electricity generation over the second half of the 20th century in Spain. Likewise, although the share of thermoelectricity generation that still depends on the availability of fresh water remains significant, there is an absence of studies analysing its relationship with economic growth. In this regard, we aim at checking whether economic growth is environmentally beneficial. In other words, whether pressure on water resources is reduced as income increases or the lack of water availability could hinder economic growth. To do so, we

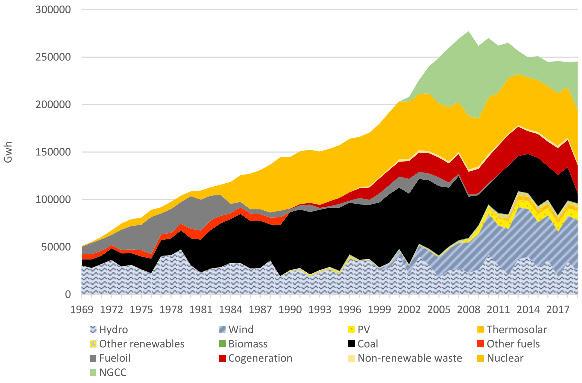


Fig. 1. Evolution of Spanish electricity generation by technology (1969–2019).

Note: NGCC means natural gas combined cycle; PV means photovoltaic solar. Source: own elaboration based on UNESA annual reports (1969–1990) and data from Red Eléctrica de España from 1990 onwards. Peninsular system only (excludes Balearic and Canary Islands, and the autonomous cities of Ceuta and Melilla). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

follow the autoregressive distributed lag (ARDL) bounds cointegration technique by using data of cooling water withdrawal from all those thermoelectric power plants using fresh water.

The rest of the paper is organized as follows. Section 2 presents a vast body of both international and national research addressing the EKC. Section 3 explains the data used and the methodology followed to perform the analysis. Section 4 shows the results. Finally, Sections 5 presents the discussion and main conclusions.

Table 1
Classification of thermoelectric power plants in Spain by type of generation technology and cooling system.

Power Plant	Technology	Installed Capacity (MW)	Cooling System	Operating Period
Almaraz 1,2	Nuclear	1049.43 (1)	OT	1983-present (1)
		1044.45 (2)		1984-present (2)
Ascó 1,2	Nuclear	1032.50 (1)	CT	1984-present (1)
		1027.20 (2)		1986-present (2)
Cofrentes	Nuclear	1092.02	CT	1985-present
Santa María de Garoña	Nuclear	466	OT	1971–2017
Trillo 1	Nuclear	1066	CT	1988-present
José Cabrera (Zorita)	Nuclear	160	OT	1968–2006
Aliaga	Coal	45	CT	1952–1982
Andorra (Teruel)	Coal	1101.40	CT	1981–2020
Anllares	Coal	365.20	Partial OT with CT	1982–2018
U.P.T. As Pontes	Coal	1468	CT	1976-present
Compostilla 1	Coal	141	OT	1949–1973
Compostilla 2,3,4,5	Coal	148 (1)		
		323 (2)	OT (2,3)	1972–2020 (2,3)
		341 (3)	CT (4,5)	1984–2020 (4,5)
		341 (4)		
Escatrón	Coal	172.50	OT	1953–2011
Fígols	Coal	14.4	OT	1931–1971
Lada	Coal	358	CT	1949–2020
La Robla 1,2	Coal	284 (1)	Partial OT with CT	1971–2020 (1)
		371 (2)		1984–2020 (2)
Meirama	Coal	557	CT	1980–2020
Narcea 1,2,3	Coal	65(1)	OT (1,2)	1965–2020 (1)
		154 (2)	CT (3)	1969–2020 (2)
		350 (3)		1984–2020 (3)
Puente Nuevo 1,2	Coal	(1,2)	CT	1966–2020 (1,2)
Puertollano (CSE, ENECO)	Coal	221	CT	1972–2013
Puertollano (ENCASO, ENP, REP)	Coal	50	CT	1951–1993
Serchs (Cercs)	Coal	162	CT	1971–2011
Soto de Ribera 1,2,3	Coal	67 (1)	CT	1962–2007 (1)
		254 (2)		1967–2015 (2)
		350 (3)		1984-present (3)
Ujo	Coal	24.9	OT	1923–1970
Velilla del Río Carrión 1,2	Coal	155 (1)	OT (1)	1964–2020 (1)
		360,7 (2)	CT (2)	1984–2020 (2)
Aceca 1,2	Fueloil-Gas	629	CT	1969–2012
Guadaira	Fueloil	n/a	CT	n/a –1977
Elcogas	IGCC	335	CT	1996–2015
Aceca 3,4	NGCC	392 (3)	CT	2005-present (3)
		379 (4)		2006-present (4)
Arcos 1,2,3	NGCC	395,6 (1)	CT	2005-present (1,2,3)
		379,4 (2)		
		837,8 (3)		
Arrúbal	NGCC	800	CT	2005-present
As Pontes	NGCC	800	CT	2008-present
Castejón 1,3	NGCC	429,2 (1)	CT	2002-present (1)
		418,5 (3)		2008-present (3)
Castejón 2	NGCC	400	CT	2003-present
Escatrón	NGCC	818	CT	2011-present
Escatrón Peaker	NGCC	275	CT	2007-present
Soto de Ribera 4,5	NGCC	432 (4)	CT	2008-present (4)
		434 (5)		2010-present (5)

Source: own elaboration. Notes: n/a = not available; CT = cooling tower; OT = once-through; IGCC = integrated gasification combined cycle; NGCC = natural gas combined cycle; Anllares and La Robla 1,2 use mixed cooling systems. Since we lack information on what percentage of electricity is generated from each (that is, once-through or cooling tower), we assumed that both power plants use once-through cooling systems throughout the entire period. This may slightly overestimate our calculations of water withdrawal. The numbers in parentheses refer to the generating group of each power plant.

2. Literature review

The origins of the Kuznets Curve date back to the mid-20th century, when the economist Simon Kuznets published "Economic growth and income inequality" [24]. This work concluded that the variables inequality and economic growth follow an inverted U-shaped relationship. Initially, the growth of the economy leads to greater inequality. However, there is a level of per capita income that results in a trend change from which any increase in income translates into less inequality. Later, other authors developed new approaches based on Kuznets' initial idea by including environmental quality variables and resulting in the so-called Environmental Kuznets Curve (EKC) [30,31]. The EKC has been widely criticised. Evidence has shown that the existence of the EKC is not always fulfilled as it depends on a variety of factors, such as the type of pollutant or the geographical region under consideration [25,32,33].

A significant body of international literature has sought to validate the EKC hypothesis for air pollution [26,34–38], sandy desertification [39], and deforestation [40] among others. By contrast, existing studies on the relationship between economic growth and water use are more limited and tend to consider all uses of water for a wide range of countries. For example [41], made use of the dataset provided by Ref. [42] to assess the existence of the EKC for water use. Cole concluded that water use may benefit from composition and technique effects, although there is no certainty that this will occur in developing countries. [43] analysed the relationship between per capita water use and per capita income for 65 countries, over the period 1962–2008. These authors made use of not only traditional panel data models, but also a Panel Smooth Transition Regression (PSTR) approach. They found a negative association between per capita income and per capita water withdrawal, regardless of the model used. Additionally, their findings pointed to a particular EKC with a decreasing part that dominates the link between both variables from 1960 to the present. [44] addressed freshwater use as a function of economic development. The author found some support for the existence of an EKC, but results were highly dependent on the choice of datasets and statistical technique. Likewise, results were also sector-specific and the EKC curves proved to be poor indicators of country performance. However, only some isolated studies have attempted to assess the validity of the EKC for the energy sector. For example [45], investigated the relationship between hydropower energy consumption, ecological footprint, and economic growth for Brazil, China, Canada, India, Norway, and the US. Authors concluded that the EKC hypothesis is not valid for these countries.

In the case of Spain [46], analysed trends in annual emissions of six relevant air pollutants -carbon dioxide, methane, nitrous oxide, sulphur dioxide, nitrogen oxides, and non-methanic volatile organic compounds- from 1980 to 1996. Authors found no correlation between higher income levels and lower emissions, except for SO2, whose evolution could be compatible with the EKC hypothesis. [47] also evaluated the relationship between income growth and atmospheric pollution in Spain by considering additional emission gases (namely, the six greenhouse gases and three gases associated with local and regional environmental problems). In this case, the authors renounced to prove the existence of an EKC in Spain. They contributed to the EKC debate from two perspectives: 1) by conducting a structural decomposition analysis to examine the contribution of several factors involved in economic dynamics to the evolution of atmospheric emissions and 2) by analysing the emissions associated with the consumption patterns of different groups of households according to their expenditure levels. [48] tested the EKC for the Spanish economy by making use of cointegration tests that allow for the identification of structural breaks. These authors found not only linear cointegration with two breaks in 1941 and 1967, but also a long-run elasticity between CO_2 and income decreasing over time. More recently, other authors such as Balaguer and Cantavella modelled the EKC for Spain by exploiting long time series (1874–2011) and by using real oil prices as indicator of fuel consumption. The authors supported the EKC hypothesis through an autoregressive distributed lag (ARDL) model [49].

To our knowledge, this is the first analysis on the relationship between economic growth and water pressure resulting from thermoelectricity generation. This article aims to fill the gap in the literature on the water-energy nexus through a case study of the thermoelectric sector, the most important contributor to the Spanish electricity generation over the second half of the 20th century. This study may be of relevance when making policy recommendations on water and energy in a country that suffers from water availability problems. Does economic growth really have a positive impact on water withdrawal in a particularly thirsty sector such as thermoelectricity? Are only technological variables causing the decline in water withdrawal?

Table 2
Water factors by electricity generation technology and cooling system from the international literature.

Technology	Water Withdrawal (m3/MWh)	
	Once-through	Cooling tower
Coal	137,60	3,80
NGCC	43,08	0,97
Nuclear	167,88	4,17
Fueloil-Gas	85,9	0,95
IGCC	–	0,86

Source: own elaboration from Refs. [52,53].

3. Data and methodology

3.1. Data sources

To test the EKC hypothesis in the context of the water-thermoelectricity nexus in Spain, we identified all thermoelectric power plants operating in Spain (peninsula only) between 1970 and 2019, and using fresh water for cooling. We focus on the operational stage of the facilities, i.e., on the electricity generation process. Our database included a total of 8 nuclear reactors (grouped in 6 plants), 19 coal plants, 1 fuel oil-gas plant, 1 fuel oil plant, 1 integrated gasification combined cycle power plant, and 9 natural gas combined cycle facilities. We excluded from the analysis those power plants cooling with sea water, gas, and air. Table 1 shows the classification of the power plants mentioned by type of generation technology and cooling system. We collected data on electricity generation in Spain for the period 1970–2019 from the annual reports of UNESA [50] and Red Eléctrica de España [51]. Regarding data on water withdrawal, the international literature provides technical factors for different generation technologies and cooling systems [52,53]. Table 2 presents a summary of the water factors used in the subsequent analysis. Finally, annual real per capita income (constant prices of 2010) data comes from the Spanish National Institute of Statistics (www.ine.es).

The following two sections explain the methodology used to estimate water withdrawal from the thermoelectric generation process and to test the validity of the related EKC in Spain.

3.2. Estimated water withdrawal

Two highlighted concepts emerge when estimating water used for electricity generation: water withdrawal and water consumption. The US Geological Survey (USGS) defines water withdrawal as the amount of water removed from the ground or diverted from a water source for use. By contrast, water consumption refers to the amount of water withdrawn that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment [54]. Cooling is the stage that entails the largest volumes of water within the electricity generation process. Cooling systems are classified into two categories: dry cooling and wet cooling. In turn, wet cooling technologies are subdivided into two types: once-through and cooling towers. Once through systems remove water from a nearby source (i.e., river, lake, aquifer, or sea), circulate it through a steam condenser, and discharge the resulting warmer water into the original water body. Conversely, cooling towers withdraw water and circulate it within the system, while air is forced through the circulating water flows. The waste heat from the cooling water is eventually expelled into the atmosphere through the tower. These systems present differences in quantitative impacts on water resources due to their different functioning. Whilst once-through cooling systems result in higher water withdrawal, cooling towers involve higher water consumption [55]. Consequently, the type of fuel, power generation technology, and cooling system are the factors that determine the water requirements of a thermoelectric power plant [56].

To estimate the operational water withdrawal of the Spanish thermoelectric power plants we followed the methodology used in Ref. [57]. Once the technical water factors per power plant were identified, the operational water withdrawal of a single power plant n in year t was estimated by multiplying the corresponding intensity factor (WWF), measured in m^3/MWh, and the electricity generated (EG) in MWh. Formally:

$$WW_t^n = WWF_t^n \cdot EG_t^n \tag{1}$$

Thus, for a given year, the total water withdrawal is:

$$\text{Total}\ \ WW_t = \sum_{n=1}^{N}\left(WWF_t^n \cdot EG_t^n\right) \tag{2}$$

3.3. Testing the validity of the EKC

Once the water withdrawal from thermal power plants has been estimated, we can analyze their relationship to per capita income. The availability of reliable data allows us to analyze the possible existence of the EKC relationship between 1970 and 2019.

To test the validity of the EKC hypothesis we have as our goal the estimation of a log linear quadratic function that analyzes the relation between water withdrawal and real per capita income. In addition to the possible non-linear effects of per capita income over water withdrawal, we also incorporated in the equation several variables to account for the electricity mix. By introducing the share of electricity generated by the different types of thermoelectric plants and the shares of the electricity generated using each cooling system we can more reliably estimate the existence of the relationship over time. Also, by including the total thermoelectricity generation we can estimate the effect on water withdrawal from a higher demand for electricity. Using these variables, we can control for the size and the structure of the thermoelectric sector so that real per capita income level can be used as a proxy of the level of development in Spain.

$$\mathrm{Ln}(WW_t) = \beta_0 + \beta_1 \ln(y_t) + \beta_2 ln(y_t)^2 + \beta_3 \ln(e_t) + \beta_4 N_t + \beta_5 C_t + \beta_6 F_t + \beta_7 T_t + \beta_8 trend + \varepsilon_t \tag{3}$$

where WW_t is water withdrawal, y_t is per capita real income, e_t is the total electricity generated in the power plants. The share of electricity generated in nuclear power plants is denoted by N_t. The shares of electricity generated in thermal power stations fueled by coal and fuel oil are denoted by C_t,F_t, respectively. T_t is the share of electricity generated using cooling towers as a cooling system. ε_t is the regression error term. Since the sum of total shares of both power plants and cooling systems is 100%, both combined-cycle power plants and once-through cooling are excluded to avoid multicollinearity.

β_1 is expected to be positive whereas, under the EKC hypotheses, β_2 should be negative. In that case, the relationship between real income per capita and water withdrawal will be positive (negative) for any value of the real per capita income that is lower (greater) than a certain turning point. This turning point can be obtained calculating the local maximum: $\frac{\beta_1}{-2\beta_2}$. As we are dealing with a long-run relationship, first we must acknowledge the possibility of a spurious relationship between the variables as they are usually non-stationary.

Different approaches exist to deal with this problem, mainly a methodology based on the residuals by Ref. [58]; the maximum likelihood-based approach used by Ref. [59]; and [60]. We use the later, known as the autoregressive distributed lag (ARDL) for the cointegration analysis. This approach does not require the same order of integration for all variables, but they have to be either I(0) or I (1) as I(2) will make the results unreliable.

In order to begin the analysis, we employ the Augmented Dickey Fuller (ADF) and Phillips Perron (PP) tests to analyze the presence of unit roots in each variable. This step is important to be sure that we are not dealing with I(2) variables. The results are presented in Supplementary Table 1.

At the 10% level of significance we reject the hypothesis of I(2) for all variables considered, both using the Augmented Dickey-Fuller test (ADF), and the Phillips-Perron test. The variables C and F are not I(1) in the ADF test as they are stationary in levels, which implies that we have different degrees of integration over the variables. For this, we believe the ARDL technique is the best procedure for analyzing the EKC relationship.

The analysis of the long-run relationship using the ARDL methodology is based on the estimation of equation (4):

$$\begin{aligned}\Delta ln(WW_t) = \beta_0 &+ \sum_{i=1}^{p}\beta_{1i}\Delta ln(WW_{t-i}) + \sum_{i=0}^{p}\beta_{2i}\Delta ln(y_{t-i}) + \sum_{i=0}^{p}\beta_{3i}\Delta ln(y_{t-i})^2 + \sum_{i=0}^{p}\beta_{4i}\Delta ln(e_{t-i}) + \sum_{i=0}^{p}\beta_{5i}\Delta N_{t-i} + \sum_{i=0}^{p}\beta_{6i}\Delta C_{t-i} \\ &+ \sum_{i=0}^{p}\beta_{7i}\Delta F_{t-i} + \sum_{i=0}^{p}\beta_{8i}\Delta T_{t-i} + \beta_9 trend + \theta ECT_{t-1}\end{aligned} \tag{4}$$

where ECT_{t-1} is the error correction term, and represents the error obtained from the long-run relation, if it exists, estimated with equation (3). In this context, θ shows the speed of adjustment respect to the long-run equilibrium. This parameter should be between 0 and -1 to have convergence between the short run and the long run.

For the estimation of equation (4), the optimal lag structure of the variables must be selected using information criteria, such as the Bayesian Information Criterion (BIC) and the Akaike Information Criterion (AIC). Supplementary Table 2 shows the lag structure that offers the lower (best) value of both the BIC and AIC. For the analysis of the model, we have chosen the lag structure selected as the preferred model by the BIC (2,2,2,0,2,2,2,0), although in section 4.2 we do the same analysis for the other three preferred models to see how robust the results are.

4. Results

4.1. ARDL estimation

We use Stata to perform the estimation procedure and select the top ARDL model selected by the BIC criteria (2, 2, 2, 0, 2, 2, 2, 0). Table 3 shows the estimated parameters of the long run relationship (equation (3)) and Table 4 shows the estimated error correction model (equation (4)), with both short-run coefficients and the adjustment speed.

The estimated coefficients show the presence of a non-linear relationship between the income per capita level and the total water withdrawals. The negative coefficient of $ln^2(y)$ shows that there is a turning point from which a greater income per capital level will decrease the endogenous variable. As is expected, a 1% increase in the amount of energy generated will increase the amount of total water withdrawals in 0.96% (close to a constant proportional relationship). The share of energy generated from both nuclear and coal power plants shows an increase in the amount of total water withdrawal as we could expect looking to the coefficients of water requirements that are shown in Table 2. For the same reason, the share of energy generated from fueloil and the share of energy generated with cooling towers shows a decrease in the total water withdrawal. These results are in line with the coefficients associated

Table 3
Long run coefficients.

Variables	Coefficients	Std. error	t-Statistics	P-value
$\ln(y)$	6.7241	1.8755	3.59	0.001***
$\ln^2(y)$	−0.3366	0.0948	−3.55	0.001***
$\ln(e)$	0.9604	0.0136	70.38	0.000***
N	0.0008	0.0004	1.89	0.070*
C	0.0012	0.0004	2.75	0.01***
F	−0.0072	0.0011	−6.50	0.000***
T	−0.0232	0.0004	−47.71	0.000***
trend	−0.0016	0.0006	−2.53	0.017**

Table 4
Error correction model.

Variables	Coefficients	Std. error	t-Statistics	P-value
Δ ln(WW)	0.0515	0.0147	3.50	0.002***
$\Delta \ln(y)$	5.6333	4.5640	1.23	0.228
$\Delta \ln(y)(-1)$	−5.6612	3.1638	−1.79	0.085
$\Delta ln^2(y)$	−0.2826	0.2319	−1.22	0.234
$\Delta ln^2(y)(-1)$	0.2873	0.1618	1.78	0.087*
Δe	1.0679	0.0116	91.97	0.000***
ΔN	0.0035	0.0006	5.84	0.000***
ΔN(−1)	0.0034	0.0007	4.67	0.000***
ΔC	0.0008	0.0004	1.77	0.088*
ΔC(−1)	0.0018	0.0007	2.75	0.010***
ΔF	−0.0012	0.0008	−1.53	0.138
ΔF(−1)	0.0057	0.0009	6.21	0.000***
ΔT	−0.0258	0.0006	−44.96	0.000***
Constant	−30.4188	10.4315	−2.92	0.007***
ECM(−1)	−1.1119	0.0192	−57.84	0.000***

with the relationship between the energy produced and the water withdrawal needed.

Table 4 shows the estimated coefficients of the error correction model. The most important parameter, the speed of adjustment from the short-run equilibrium to the long-run equilibrium state is slightly below −1 (−1.1119), which shows that it over-corrects itself. Furthermore, a negative and significative coefficient also shows the existence of the long-run estimated model.

We obtained the F-statistic and t-statistic values for the [60] bound. They are compared with the [61] critical values for sample sizes ranging from 30 to 80. The null hypothesis of no level relationship is rejected with the F-statistc = 1234.2 (p.value = 0.000) and the t-statistic = −57.843 (p.value = 0.000). Thus, we can conclude that there is cointegration between our variables.

Supplementary Table 3 shows the diagnostic tests, which reveal the following results:

The Ramsey RESET test has the null hypothesis of no omitted variables in the estimated model and, thus, no misspecification. In our case, the F-statistic shows that the null hypothesis is not rejected (p.value = 0.8476).

Two heteroscedasticity tests have been carried out to test the null hypothesis of a constant variance (homoscedasticity). In our case, both the White test (p.value = 0.727) and the Breusch-Pagan test (p.value = 0.5355) shows that the null hypothesis may not be rejected.

We employ two normality tests with the null hypothesis of a normal distribution in the residuals of the estimated model. The Chi-square test (p.value = 0.9645) and the Shapiro-Wilk test (p.value = 0.740) do not reject the null hypothesis.

Finally, we use the Breusch-Godfrey test with the null hypothesis of no autocorrelation (p.value = 0.3033). In this case, we also can not reject the null hypothesis.

To check the stability of the estimation of both the long run and short run parameters from the ARDL (2, 2, 2, 0, 2, 2, 2, 0), we apply the cumulative (CUSUM) and cumulative sum of squares (CUSUMQ) proposed by Ref. [62].

If the plotted graphs for the CUSUM and CUSUMQ show that the statistic stay within the critical bounds of a 5% level of significance, the null hypotheses, which implies that all coefficients of the regression are stable, cannot be rejected.

Figs. 2 and 3 show that both the CUSUM and CUSUMQ remain within the critical bound of the 5% significance level. Therefore, we conclude that the stability of all coefficients in the ARDL model cannot be rejected.

Once obtained the estimated parameters of the ARDL, we can highlight the following remarks.

The objective of this paper was to analyze the relationship between income per capita levels and water withdrawal from thermoelectricity generation. Fig. 4 shows the non-linear relationship between those two variables, which served as the first motivation to

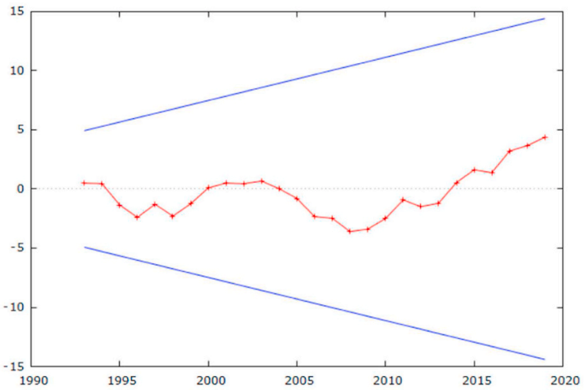


Fig. 2. Cumulative sum (CUSUM) test for stability (5% significance bands).

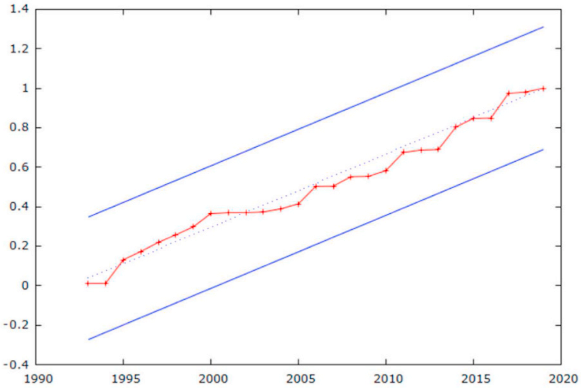


Fig. 3. CUSUM square test for stability (5% significance bands).

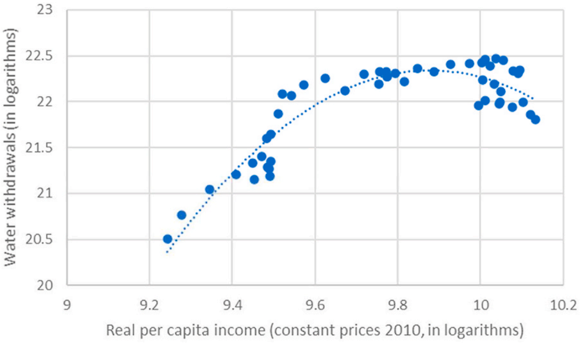


Fig. 4. Fitted values for the estimated EKC relation for total water withdrawals.

try to study if the presence of an EKC was the main factor in the decline of water withdrawal during the later years. It shows the fitted values of water withdrawal (estimated using the previously estimated long-run model, Table 3) in relation to the income per capita levels -we add a simple quadratic polynomial to show the non-linear relationship between the two. Two main reasons explain this point. First, the estimated coefficients in the long run relationship show the presence of a Kuznets Curve between the level of per capita GDP and water withdrawal. As θ_1 is positive and θ_2 is negative, we conclude that a nonlinear relationship exists. We find a positive

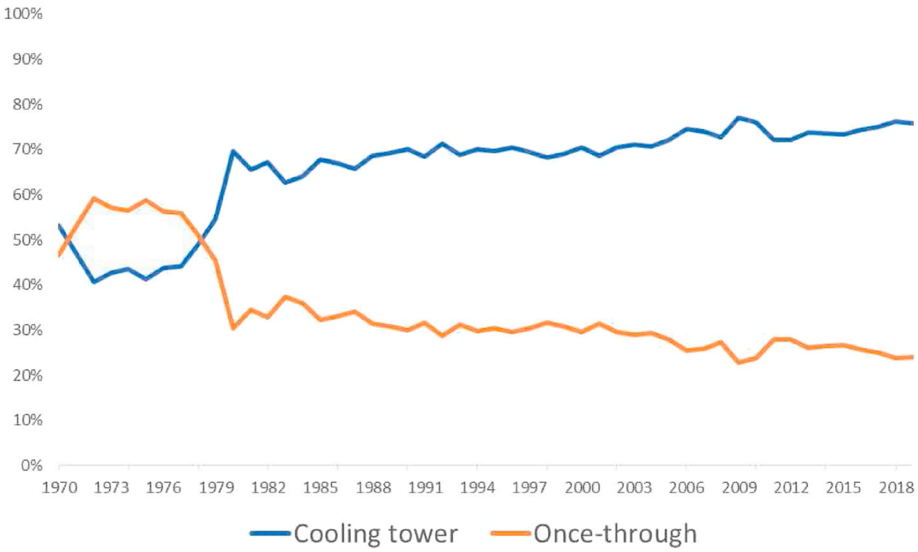


Fig. 5. Percentage of electricity generated by once-through and cooling towers.

relation for low values of the log of per capita GDP that is transformed into a negative relationship for values that are greater than the local maximum $\frac{\theta_1}{-2\theta_2} = 9.9882$, which implies a per capita income level of 21,769 euros (constant prices of 2010). Second, the actual technological change based on the continuous substitution of energy generated from power plants that use a once-through system to the ones based on cooling towers, which need less water withdrawals to obtain the same amount of energy generated. This change can be seen in Fig. 5. This substitution, with the fact that the estimated model concludes that the percentage of energy generated through cooling towers affects negatively to the amount of water withdrawals, seem to explain the decrease in water withdrawals. Other changes in the energy mix like the increase of nuclear power and the decrease of coal power, seem to not directly affect the amount of water withdrawal as the coefficients of both variables are rather similar. This second effect has been studied as one of the main reasons behind the EKC. As countries show a greater level of development, in the presence of increasing returns in the technological link between the production of a product and the pollutant that it creates, we should see this inverted U-shape [21,27].

4.2. *Robustness test*

To check for the robustness of our results, we carried out the same analysis changing the variables considered or the lag structure of the estimated model. In Fig. 6 we show the summary of our results for each model. On the one hand, the coefficient estimated for the square of the income per capital level (in logarithms). On the other hand, whether the ARDL show signs of cointegration and, if it does, if the presence of the Kuznets Curve is also present. We use a specification chart to show the level of robustness of the most important variable for the key purpose of this paper, to see if there is a non-linear relationship between income per capita levels and the total water withdrawals.

Model A is the one already estimated in the previous section. B, C and D models are the ones estimated with the lag structure of the three next preferred models (shown in Supplementary Table 2). For the rest of the models, we have eliminated some key variables, shown in Fig. 6 with a red circle if they are eliminated from the estimated model.

We mainly conclude that the estimated model is quite similar for different configurations of the lag structure. In the four preferred models both for the Akaike and Bayesian information criteria, the coefficients, their significance, and signs are rather similar. All four show that there is a cointegration relationship between the variables and conclude that the Kuznets Curve exists in the relationship between per capita income and water withdrawals.

For models H to J, we eliminate some key variables: the percentage of energy generated through cooling towers, the structure of the different plants in the energy mix, and both. With these changes, the presence of the Kuznets Curve is rejected, although the estimated model has always a worse performance than the original one. We present in Supplementary Table 4 the complete estimated long-run model for each alternative.

5. Conclusions and discussion

This paper provides evidence on the existence of an Environmental Kuznets Curve for water withdrawal at the thermoelectricity sector in Spain for the period 1970–2019. The results show that two main reasons explain the decline of water withdrawal. First, the increase in the share of cooling towers in the Spanish thermoelectric fleet over time. Consequently, there is a significant and negative effect to the total amount of water withdrawals. Second, the presence of an EKC. This implies that there is a turning point from which an increase in the income per capita level decreases the amount of water withdrawal. This effect cannot be explained through the changes in the technological mix, as those variables are already considered in the model. The presence of increasing returns of scale could explain this result. Another potential explanation for the presence of the EKC is that a more developed country could shift from fossil fuels to renewable energies (i.e., solar and wind power), which use less water.

Economic growth has indeed an impact in water withdrawal. However, this impact does not occur automatically. Changes in the electricity mix represent the main drivers in declined water demands, with economic growth being the force that promote those changes. In an increasing thirsty world, policy should be aimed not at hindering changes, but at enhancing them.

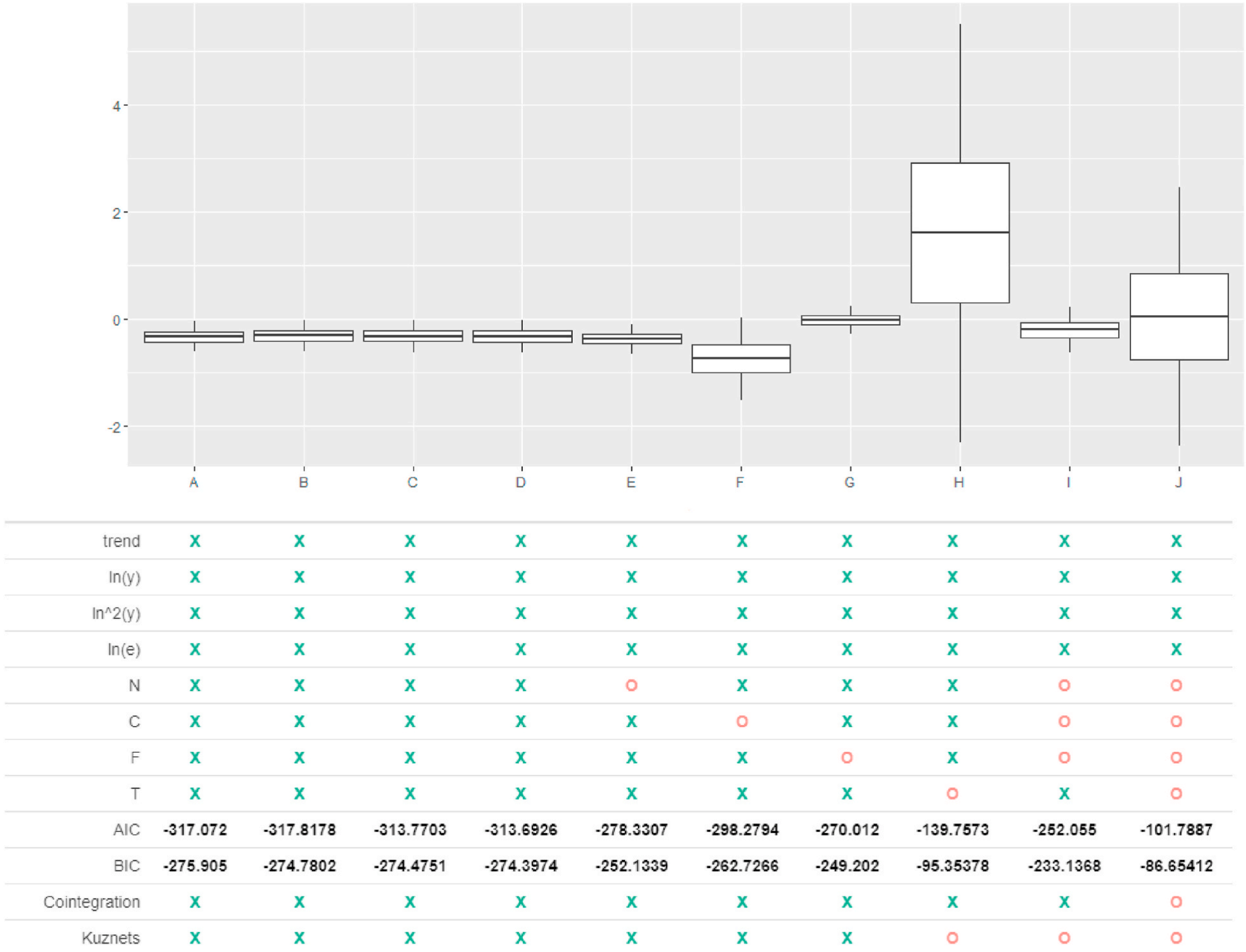
Finally, some limitations and caveats must be introduced. In line with [44]; since we focused on the thermoelectricity sector and only considered conventional thermal and nuclear power plants, our results are sector specific and should be analysed with caution. To account for the whole heterogeneity of our study case we included relevant factors, such as the structure of the thermoelectricity sector and technology. However, other variables related to the level and quality of environmental protection have been omitted due to the lack of data. Including other sectors, generation technologies (i.e., hydropower, concentrated solar power, or photovoltaic solar energy), and variables could have additional implications for this study. These issues represent avenues for future research.

Author contributions

Corresponding author: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. Author 2: Formal analysis, Methodology, Validation, Writing – review & editing.

Funding

This publication has been supported by the grant *HAR2017-860086-R* funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”. Puente-Ajovín must acknowledge the Regional Government of Aragon through the research project



	A	B	C	D	E	F	G	H	I	J
trend	X	X	X	X	X	X	X	X	X	X
ln(y)	X	X	X	X	X	X	X	X	X	X
ln^2(y)	X	X	X	X	X	X	X	X	X	X
ln(e)	X	X	X	X	X	X	X	X	X	X
N	X	X	X	X	○	X	X	X	○	○
C	X	X	X	X	X	○	X	X	○	○
F	X	X	X	X	X	X	○	X	○	○
T	X	X	X	X	X	X	X	○	X	○
AIC	-317.072	-317.8178	-313.7703	-313.6926	-278.3307	-298.2794	-270.012	-139.7573	-252.055	-101.7887
BIC	-275.905	-274.7802	-274.4751	-274.3974	-252.1339	-262.7266	-249.202	-95.35378	-233.1368	-86.65412
Cointegration	X	X	X	X	X	X	X	X	X	○
Kuznets	X	X	X	X	X	X	X	○	○	○

Fig. 6. Specification chart.

reference S39_20R. This research is also funded by the Ministerio de Ciencia e Innovación (references PID2020-114354RA-I00 and PID2020-112773GB-I00). Sesma-Martín also benefits from the post-doctoral research fellowship reference 1295/2019, assigned to the History and Economics Group at Universidad Publica de Navarra (UPNA).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Nuria Osés-Eraso and Mar Rubio-Varas from the Public University of Navarra for their helpful comments and suggestions. We also acknowledge the observations of both the editor and the two anonymous reviewers of this journal. Their comments led to significant improvements to this paper. The remaining errors are solely ours.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wre.2022.100202.

References

[1] T. Distefano, S. Kelly, Are we in deep water? Water scarcity and its limits to economic growth, Ecol. Econ. 142 (2017) 130–147, https://doi.org/10.1016/j.ecolecon.2017.06.019.
[2] P. Malanima, The limiting factor: energy, growth, and divergence, 1820–1913, Econ. Hist. Rev. 73 (2) (2020) 486–512, https://doi.org/10.1111/ehr.12913.
[3] J.C. Terrapon-Pfaff, W. Ortiz, P. Viebahn, E. Kynast, M. Flörke, Water demand scenarios for electricity generation at the global and regional levels, Water 12 (9) (2020) 2482.
[4] P.H. Gleick, Water and energy, Annu. Rev. Energy Environ. 19 (1) (1994) 267–299.
[5] C.A. Scott, S.A. Pierce, M.J. Pasqualetti, A.L. Jones, B.E. Montz, J.H. Hoover, Policy and institutional dimensions of the water–energy nexus, Energy Pol. 39 (10) (2011) 6622–6630, https://doi.org/10.1016/j.enpol.2011.08.013.
[6] A. Siddiqi, L.D. Anadon, The water–energy nexus in Middle East and North Africa, Energy Pol. 39 (8) (2011) 4529–4540, https://doi.org/10.1016/j.enpol.2011.04.023.
[7] A.M. Hamiche, A.B. Stambouli, S. Flazi, A review of the water-energy nexus, Renew. Sustain. Energy Rev. 65 (2016) 319–331, https://doi.org/10.1016/j.rser.2016.07.020.
[8] J. Dai, S. Wu, G. Han, J. Weinberg, X. Xie, X. Wu, Q. Yang, Water-energy nexus: a review of methods and tools for macro-assessment, Appl. Energy 210 (2018) 393–408, https://doi.org/10.1016/j.apenergy.2017.08.243.
[9] OECD/IEA, Water-Energy Nexus; World Energy Outlook 2016 Excerpt, International Energy Agency, Paris, France, 2016. Available at: https://iea.blob.core.windows.net/assets/e4a7e1a5-b6ed-4f36-911f-b0111e49aab9/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf. (Accessed 27 February 2022).
[10] IEA (International Energy Agency), Water for Energy: Is Energy Becoming A Thirstier Resource?, 2012. Paris, France.
[11] IEA (International Energy Agency), World energy outlook 2013, Paris, France, https://www.iea.org/publications/freepublications/publication/WEO2013.pdf, 2013.
[12] M.A.D. Larsen, M. Drews, Water use in electricity generation for water-energy nexus analyses: the European case, Sci. Total Environ. 651 (2019) 2044–2058, https://doi.org/10.1016/j.scitotenv.2018.10.045.
[13] Y. Wada, L.P. Van Beek, N. Wanders, M.F. Bierkens, Human water consumption intensifies hydrological drought worldwide, Environ. Res. Lett. 8 (3) (2013), 034036, https://doi.org/10.1088/1748-9326/8/3/034036.
[14] J. Eliasson, The rising pressure of global water shortages, Nat. News 517 (7532) (2015) 6, https://doi.org/10.1038/517006a.
[15] E.A. Byers, G. Coxon, J. Freer, J.W. Hall, Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain, Nat. Commun. 11 (1) (2020) 1–12, https://doi.org/10.1038/s41467-020-16012-2.
[16] G.M. Grossman, A.B. Krueger, Environmental Impacts of a North American Free Trade Agreement, National Bureau of Economic Research Working Paper 3914, NBER, Cambridge MA, 1991, https://doi.org/10.3386/w3914.
[17] W. Beckerman, Economic growth and the environment: whose growth? Whose environment? World Dev. 20 (4) (1992) 481–496, https://doi.org/10.1016/0305-750X(92)90038-W.
[18] N. Shafik, S. Bandyopadhyay, Economic Growth and Environmental Quality: Time-Series and Cross-Country Evidence, vol. 904, World Bank Publications, 1992.
[19] T. Panayotou, *Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development* (No. 992927783402676), International Labour Organization, 1993.
[20] M.A. Cole, A.J. Rayner, J.M. Bates, The Environmental Kuznets Curve: an Empirical Analysis, Environment and development economics, 1997, pp. 401–416, https://doi.org/10.1017/S1355770X97000211.
[21] J. Andreoni, A. Levinson, The simple analytics of the environmental Kuznets curve, J. Publ. Econ. 80 (2) (2001) 269–286, https://doi.org/10.1016/S0047-2727(00)00110-9.
[22] S. Dasgupta, B. Laplante, H. Wang, D. Wheeler, Confronting the environmental Kuznets curve, J. Econ. Perspect. 16 (1) (2002) 147–168, https://doi.org/10.1257/0895330027157.
[23] S. Dinda, Environmental Kuznets curve hypothesis: a survey, Ecol. Econ. 49 (4) (2004) 431–455, https://doi.org/10.1016/j.ecolecon.2004.02.011.
[24] S. Kuznets, Economic growth and income inequality, Am. Econ. Rev. 45 (1) (1955) 1–28. Retrieved July 20, 2021, from, http://www.jstor.org/stable/1811581.
[25] D.I. Stern, The rise and fall of the environmental Kuznets curve, World Dev. 32 (8) (2004) 1419–1439, https://doi.org/10.1016/j.worlddev.2004.03.004.
[26] T.M. Selden, D. Song, Environmental quality and development: is there a Kuznets curve for air pollution emissions? J. Environ. Econ. Manag. 27 (2) (1994) 147–162, https://doi.org/10.1006/jeem.1994.1031.
[27] N.L. Stokey, Are there limits to growth? Int. Econ. Rev. (1998) 1–31.
[28] M.M. Aldaya, D. Sesma-Martín, M. Rubio-Varas, Tracking water for human activities: from the ivory tower to the ground, Water Resour. Econ. 36 (2021) 100190.
[29] S. Cano-Rodríguez, M. Rubio-Varas, D. Sesma-Martín, At the crossroad between green and thirsty: carbon emissions and water consumption of Spanish thermoelectricity generation, 1969–2019, Ecol. Econ. 195 (2022) 107363.
[30] H. Hettige, M. Mani, D. Wheeler, Industrial pollution in economic development: the environmental Kuznets curve revisited, J. Dev. Econ. 62 (2) (2000) 445–476, https://doi.org/10.1016/S0304-3878(00)00092-4.
[31] D.I. Stern, M.S. Common, Is there an environmental Kuznets curve for sulfur? J. Environ. Econ. Manag. 41 (2) (2001) 162–178, https://doi.org/10.1006/jeem.2000.1132.
[32] D.I. Stern, M.S. Common, E.B. Barbier, Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development, World Dev. 24 (7) (1996) 1151–1160, https://doi.org/10.1016/0305-750X(96)00032-0.
[33] M.I.U. Husnain, A. Haider, M.A. Khan, Does the environmental Kuznets curve reliably explain a developmental issue? Environ. Sci. Pollut. Control Ser. 28 (9) (2021) 11469–11485, https://doi.org/10.1007/s11356-020-11402-x.
[34] M. Nasir, F.U. Rehman, Environmental Kuznets curve for carbon emissions in Pakistan: an empirical investigation, Energy Pol. 39 (3) (2011) 1857–1864, https://doi.org/10.1016/j.enpol.2011.01.025.
[35] E. Georgiev, E. Mihaylov, Economic growth and the environment: reassessing the environmental Kuznets Curve for air pollution emissions in OECD countries, Lett. Spatial Resour. Sci. 8 (1) (2015) 29–47, https://doi.org/10.1007/s12076-014-0114-2.
[36] G. Bölük, M. Mert, The renewable energy, growth and environmental Kuznets curve in Turkey: an ARDL approach, Renew. Sustain. Energy Rev. 52 (2015) 587–595, https://doi.org/10.1016/j.rser.2015.07.138.
[37] Y. Wang, R. Han, J. Kubota, Is there an environmental Kuznets curve for SO2 emissions? A semi-parametric panel data analysis for China, Renew. Sustain. Energy Rev. 54 (2016) 1182–1188, https://doi.org/10.1016/j.rser.2015.10.143.
[38] W. Ali, A. Abdullah, M. Azam, Re-visiting the environmental Kuznets curve hypothesis for Malaysia: fresh evidence from ARDL bounds testing approach, Renew. Sustain. Energy Rev. 77 (2017) 990–1000, https://doi.org/10.1016/j.rser.2016.11.236.
[39] X. Ge, Y. Li, A.E. Luloff, K. Dong, J. Xiao, Effect of agricultural economic growth on sandy desertification in Horqin Sandy Land, Ecol. Econ. 119 (2015) 53–63, https://doi.org/10.1016/j.ecolecon.2015.08.006.
[40] Stavros Tsiantikoudis, Eleni Zafeiriou, Grigorios Kyriakopoulos, Garyfallos Arabatzis, Revising the environmental Kuznets curve for deforestation: an empirical study for Bulgaria, Sustainability 11 (16) (2019) 4364, https://doi.org/10.3390/su11164364.
[41] M.A. Cole, Economic growth and water use, Appl. Econ. Lett. 11 (1) (2004) 1–4, https://doi.org/10.1080/1350485042000187435.
[42] I.A. Shiklomanov, Appraisal and assessment of world water resources, Water Int. 25 (1) (2000) 11–32, https://doi.org/10.1080/02508060008686794.
[43] R. Duarte, V. Pinilla, A. Serrano, Is there an environmental Kuznets curve for water use? A panel smooth transition regression approach, Econ. Modell. 31 (2013) 518–527, https://doi.org/10.1016/j.econmod.2012.12.010.
[44] D. Katz, Water use and economic growth: reconsidering the Environmental Kuznets Curve relationship, J. Clean. Prod. 88 (2015) 205–213, https://doi.org/10.1016/j.jclepro.2014.08.017.

[45] U.K. Pata, M. Aydin, Testing the EKC hypothesis for the top six hydropower energy-consuming countries: evidence from Fourier Bootstrap ARDL procedure, J. Clean. Prod. 264 (2020) 121699.

[46] J. Roca, E. Padilla, M. Farre, V. Galetto, Economic growth and atmospheric pollution in Spain: discussing the environmental Kuznets curve hypothesis, Ecol. Econ. 39 (2001) 85–99, https://doi.org/10.1016/S0921-8009(01)00195-1.

[47] J. Roca, M. Serrano, Income growth and atmospheric pollution in Spain: an input–output approach, Ecol. Econ. 63 (1) (2007) 230–242, https://doi.org/10.1016/j.ecolecon.2006.11.012.

[48] V. Esteve, C. Tamarit, Is there an environmental Kuznets curve for Spain? Fresh evidence from old data, Econ. Modell. 29 (6) (2012) 2696–2703, https://doi.org/10.1016/j.econmod.2012.08.016.

[49] J. Balaguer, M. Cantavella, Estimating the environmental Kuznets curve for Spain by considering fuel oil prices (1874–2011), Ecol. Indicat. 60 (2016) 853–859, https://doi.org/10.1016/j.ecolind.2015.08.006.

[50] UNESA (various years). Memoria Estadística Eléctrica 1971-2015. Madrid. UNESA.

[51] REE (Red Eléctrica España) (various years). Informe del Sistema Eléctrico. Available at https://www.ree.es/es (Accessed 26 February 2022).

[52] J. Macknick, R. Newmark, G. Heath, K.C. Hallett, Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature, Environ. Res. Lett. 7 (4) (2012), 045802, https://doi.org/10.1088/1748-9326/7/4/045802.

[53] V. Fthenakis, H.C. Kim, Life-cycle uses of water in US electricity generation, Renew. Sustain. Energy Rev. 14 (7) (2010) 2039–2048.

[54] J.F. Kenny, N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, M.A. Maupin, *Estimated Use of Water in the United States in 2005* (No. 1344), US Geological Survey, 2009.

[55] T.A. DeNooyer, J.M. Peschel, Z. Zhang, A.S. Stillwell, Integrating water resources and power generation: the energy–water nexus in Illinois, Appl. Energy 162 (2016) 363–371, https://doi.org/10.1016/j.apenergy.2015.10.071.

[56] A.S. Stillwell, C.W. King, M.E. Webber, I.J. Duncan, A. Hardberger, The energy-water nexus in Texas, Ecol. Soc. 16 (1) (2011). Retrieved July 20, 2021, from, http://www.jstor.org/stable/26268863.

[57] D. Sesma-Martín, M.d.M. Rubio-Varas, Freshwater for cooling needs: a long-run approach to the nuclear water footprint in Spain, Ecol. Econ. 140 (2017) 146–156, https://doi.org/10.1016/j.ecolecon.2017.04.032.

[58] R.F. Engle, C.W. Granger, Co-integration and error correction: representation, estimation, and testing, Econometrica: J. Econom. Soc. (1987) 251–276, https://doi.org/10.2307/1913236.

[59] S. Johansen, K. Juselius, Maximum likelihood estimation and inference on cointegration—with appucations to the demand for money, Oxf. Bull. Econ. Stat. 52 (2) (1990) 169–210.

[60] M.H. Pesaran, Y. Shin, R.J. Smith, Bounds testing approaches to the level analysis of level relationships, J. Appl. Econom. 16 (3) (2001) 289–327, https://doi.org/10.1002/jae.616.

[61] P.K. Narayan, The saving and investment nexus for China: evidence from cointegration tests, Appl. Econ. 37 (17) (2005) 1979–1990.

[62] R.L. Brown, J. Durbin, J.M. Evans, Techniques for testing the constancy of regression relationships over time, J. Roy. Stat. Soc. B 37 (2) (1975) 149–163, https://doi.org/10.1111/j.2517-6161.1975.tb01532.x. Available at:.