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Summary

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Keywords: Water, Energy, Food Nexus, Multivariate Convergence, Sustainable Development Goals, Worldwide Countries Data Set

JEL Classification: C33, Q43, O11, O13, R11

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On the water-energy-food nexus: Is there multivariate convergence?

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ABSTRACT

This paper provides new evidence on the convergence process of energy, water and food per capita consumption levels for 108 countries from 1971 to 2018, using a common data set, with VAR and panel data approach. We establish a new notion of multivariate sigma and beta-convergence. The results reveal that there is evidence of sigma- absolute beta- and conditional beta-convergence process for the countries. Moreover, the multivariate approach reveals that there are spillover effects with complex positive impact of each variable on the others in the analyzed countries. The speed of convergence is simulated to assess when the desired levels according to the prescription of the SDG of per water, energy and food capita consumption is reached by each country. Results have important policy implications for interventions on macro variables. Investment has a positive accelerating effect on water convergence. In addition, investment, openness to foreign trade and inflow of foreign direct investment have a positive accelerating effect on food convergence as well as on energy convergence.

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1. Introduction

Water, energy and food are essential for life and for human well-being, poverty reduction and sustainable development. Projections suggest that the demand for freshwater, energy and food will be on the rise due to, among other factors, demographic changes, economic development, changing diets, rapid urbanization, and international trade. This puts in jeopardy the availability of these resources for different uses. In addition, climate change exacerbates water demands, putting additional pressures on water availability and quality. This in turn affects agricultural productivity through irrigation, threatens biodiversity, and causes extreme events such as floods and droughts, with have severe socioeconomic and environmental consequences.

Water, energy and food are inextricably linked. Agriculture is the largest consumer of the world's freshwater resources and more than one-quarter of the energy used globally is expended on food production and supply. When fossil fuels are replaced by hydropower or biofuels water is a crucial input of energy production. Moreover, changes in energy usage and types of energy production affect water usage and impact agricultural production. These interlinkages form what is referred to as water-food-energy (WEF) nexus: see Table 1. The United Nations Food and Agriculture Organization (FAO, 2014) considers it "a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals. It is about balancing different resource user goals and interests – while maintaining the integrity of ecosystems".

Table 1: List of WEF nexus linkages

	Water	Energy	Food
Water		Desalinization requires energy	Water for sanitation competes with water and food
		Withdrawal of groundwater requires energy	
		Energy is needed for waste water treatment	

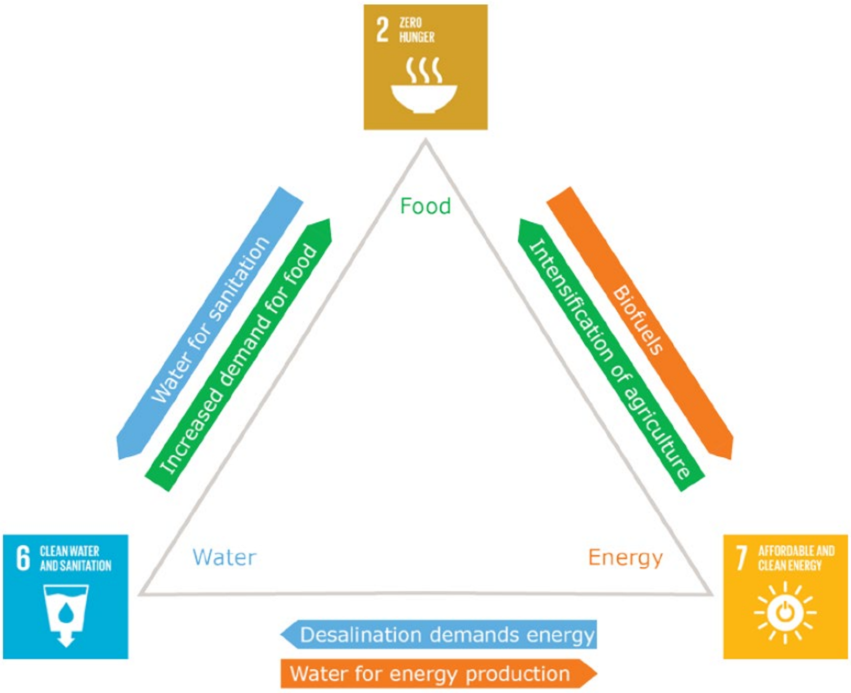
Energy	Water reservoirs for energy production		Bioenergy crops compete for land with food crops
	Fracking (and other types of energy) requires water		
	Bio energy crops need water		
Food	Crops need water	Fertilizer and pesticides use energy	
	Food production may lead to water pollution	Farm mechanization uses energy	
	Water is used in processing	Energy is used in food chain and transport	

Source: reproduced from Reinhard et al. (2017).

The WEF nexus is especially relevant from the viewpoint of policy. In fact, nexus is an approach which considers the interactions between water, food and energy, while taking into account the synergies and trade-offs that arise from the management of these three resources and potential areas of conflict. A large literature has developed with special respect to the policy implications of the nexus (Bazilian et al., 2011; Biggs et al., 2015; Kaddoura and El Khatib, 2017; Weitz et al., 2014; Dai et al., 2018). There is growing recognition that a movement is needed away from a sector-by-sector approach to policy, science and practice in favor of an integrated decision making practice that can be used by policy makers to optimize these synergies and manage trade-offs.

The WEF nexus is related to and very relevant for the U.N. Sustainability Development Goals (SDGs). In particular, "Goal 2: Zero hunger", "Goal 6: Water and sanitation", and "Goal 7: Affordable and clean energy" (see Figure 1). As a matter of fact, most SDGs have elements that link to food, water and energy in one way or another. The SDGs are designed to be cross-cutting and to be implemented together, which is also reflected in a WEF nexus approach. A nexus approach offers a sustainable way of addressing the effects of climate change and increase resilience. Indeed, the WEF accounts for the main drivers of climate change (water, energy and food security) as well as the main affected sectors (water and the environment). Thus, also “Goal 13: Climate action” is relevant for the nexus.

Figure 1: WEF nexus and SDGs



Source: reproduced from Reinhard et al. (2017).

As is well-know, the SDGs set targets to be reached by 2030. Goal 2 envisages to end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round (target 2.1). In addition, the Goal purports to ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality (target 2.4). Goal 6 wants to achieve by 2030 universal and equitable access to safe and affordable drinking water for all (target 6.1). In addition, the Goal aims to substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity (target 6.4).

Finally, Goal 7 wants to ensure universal access to affordable, reliable and modern energy services by 2030 (target 7.1), increasing substantially the share of renewable energy in the global energy mix (target 7.2) and doubling the global rate of improvement in energy efficiency (target 7.3).

The relationship between WEF nexus and Sustainable Development Goals has been investigated in the literature (Weitz et al., 2014; Rasul, 2016; Saladini et al., 2018). While it is important to set targets for water, energy, and food sustainability indicators, another relevant aspect to consider is the trajectory countries are following toward those goals and the speed at which they are attaining them.

In a broad perspective of intercountry comparison, it is of interest is to see whether countries in their transition toward sustainable water, energy, and food consumption levels have been exhibiting convergence of this dynamic process. To this end we adopt the theoretical and methodological framework of convergence.

The theory of economic convergence has been widely studied and applied in the literature after the pioneering work of Barro (1991) (see also Barro and Sala-i-Martin, 1992; Islam, 1995; Sala-i-Martin, 1996). The founding idea was to check if those countries which were lagging in per capita GDP levels would enjoy a higher growth rate of per capita GDP, so as to catch up with the more advanced economies. In this sense, the notion of convergence is a useful paradigm to assess whether growth dynamics brings a reduction of inequalities through time among countries or regions. Convergence in economics has played a central role in the empirical growth literature and refers to the hypothesis that all economies would eventually converge in terms of per-capita output. It is important per se as it reveals whether cross-country differences in performance are reducing or widening and to what extent the gap between “leading” and “backward” countries is closing.

In a methodological perspective, several tests have been developed to check for convergence and investigate the convergence hypothesis[1] across different countries and regions (Durlauf et al., 2009). The literature has suggested different notions of convergence. Convergence can be understood both in terms of levels and growth rates, which translates into a distinction between so-called σ-convergence and β-convergence.

[1] Several unit root tests are available and alternative ways of testing for stochastic convergence have been proposed, including Bernard and Durlauf (1995, 1996) and Phillips and Sul (2007).

The former refers to a decreasing variance of cross-country differences in output levels, while the latter refers to a tendency of countries with relatively high (low) initial output levels to grow relatively fast, based on the presumption that growth rates tend to decline as countries approach their steady state.[2] A refinement of the σ-convergence measure proposed by Boyle and McCarthy (1997) has been dubbed γ-convergence. Finally, starting with the work of Carlino and Mills (1993), a different notion of convergence has been proposed, dubbed stochastic convergence, which exploits the time series properties of data gains importance. Convergence requires that shocks to output relative to the mean are temporary, implying that the (logged) output series is stationary. On the contrary, the existence of a unit root in the series implies that shocks are not temporary but permanent, so that output is not converging over time.

The question of convergence has been transposed to energy and environmental economics. As to WEF nexus components, convergence of energy intensity and energy use has attracted quite some attention.[3] Papers on convergence of water consumption or food convergence have been much less frequent in the literature.

The empirical work on convergence has always looked at it as a univariate process. However, the nature of the WEF nexus views water, energy, and food as an inherently integrated problem both from the point of view of the analysis and from the policy perspective. In this paper we assess whether there is convergence of water, food, and energy consumption as a unified approach by developing and applying a multivariate convergence analysis. To our knowledge, the one presented here is the first study on multivariate convergence.

This study contributes to the literature in three ways. First, we analyze the differences in energy, food water per capita consumption patterns for 108 countries of the world by looking at σ-convergence, absolute β-convergence and γ-convergence. Second, we introduce a new approach based on multivariate σ-convergence and multivariate β-

[2] Of course, σ-convergence and β-convergence are closely related (Young et al., 2008): a decreasing dispersion of cross-country output differences implies that countries with a relatively poor initial output performance tend to grow relatively fast. However, Quah (1993) has noted that a statistically significant inverse relationship between the initial level and the growth rate of output performance can be consistent with constant or even increasing cross-country output differences, implying that β-convergence is a necessary but not a sufficient condition for σ-convergence.

[3] In addition to energy intensity convergence of energy price co-movements has also been investigated (Serletis and Herbert, 1999; Bastianin et al., 2019) as well convergence in carbon dioxide emissions or emission intensities (Aldy, 2006; Romero-Avila, 2008; Pettersson et al., 2013).

convergence, which is used to consider the existence of spillovers across the three nexus variables. Third, we provide further evidence on the determinants of energy, food water per capita consumption across 108 countries of the world by looking at conditional beta-convergence. The analysis addresses the roles of the openness to foreign trade, inflows of foreign direct investment, gross fixed capital formation and other policy variables.

The results of our study have relevant policy implications toward the implementation of SGDs and the impact of climate change on WEF nexus variables.

The rest of the paper is organized as follows. Section 2 presents a brief review of the literature on convergence. Section 3 discusses the methodology to study convergence and introduces a new multivariate convergence model. Section 4 presents the data and Section 5 the empirical results. Section 6 contains some concluding remarks.

2. A review of the convergence literature for energy, water, and food

Starting with energy, most of the papers have looked at convergence of energy intensities, with only some considering energy consumption. There are two broad lines of analysis: the first is looking only at groups of developed countries and the second is also including emerging countries.

In the first group, Sun (2002) uses mean deviation to measure the level of difference in energy intensities of OECD countries from 1971 to 1998, which are found to have decreased during the observed period. Markandia et al. (2006) investigate energy intensity in 12 transition countries of Eastern Europe and that in the EU15 countries. The raw data show some evidence of convergence, and a carefully estimated econometric model of lagged adjustment confirms this. Liddle (2012) focuses on OECD countries and applies a number of techniques to determine whether energy intensities are converging. The paper finds that OECD energy intensity typically is declining, and a number of parametric and nonparametric methods indicate a strong degree of convergence. However, convergence is conditioned on country specific factors since differences in individual energy/GDP ratios persist. Mulder and de Groot (2012) use a dataset on energy intensity for 18 OECD countries and 50 sectors over the period 1970–2005. Their convergence analysis reveals that only after 1995 cross-country variation in aggregate energy intensity levels clearly tends to decrease, driven by a strong and robust trend break in Manufacturing and enhanced convergence in Services. Kiran (2013) investigates the energy intensity convergence for 21 OECD countries over the period 1980-2010. Using fractional cointegration, the analysis reveals the presence of energy intensity convergence for 9 countries, namely Canada, Chile, Denmark, Finland, Germany, Iceland, Ireland, the Netherlands and Turkey. Mohammadi and Ram (2017) explore convergence in per-capita energy consumption across the US states over the 44-year period 1970–2013. First, the widely-used Barro-type regressions did not indicate beta-convergence during the entire period or any of several subperiods. Second, lack of sigma-convergence was also noted in terms of standard deviation of logarithms and coefficient of variation which did not show a decline between 1970 and 2013, but show slight upward trends. Third, intra-distribution mobility ("gamma convergence") in terms of an index of rank concordance suggested a slow decline in the index. On the whole, the overall impression was that of the lack of convergence across states in per-capita energy consumption. Karimu et al. (2017) test for energy intensity convergence across 14 Swedish industrial sectors. The authors found evidence of energy intensity convergence among the industrial sectors. Bulut and Durusu-Ciftci (2018) examine the energy intensity convergence in 27 OECD countries during the period 1980–2014.

In the second group, Miketa and Mulder (2005) analyzes energy productivity convergence across 56 developed and developing countries, in 10 manufacturing sectors, for the period 1971–1995. The author finds that, except for the non-ferrous metals sector, cross-country differences in absolute energy-productivity levels tend to decline, particularly in the less energy-intensive industries. Ezcurra (2007) applies a non-parametric approach to examine the dynamics of the cross-sectional distribution of energy intensities in 98 countries over the period 1971–2001. The results reveal the presence of a convergence process in energy efficiency levels across the sample countries during the study period, as a result of the evolution experienced by those countries located at both ends of the distribution in 1971. Le Pen and Sévi (2010) evaluate the convergence of energy intensities for a group of 97 countries in the period 1971–2003. A pairwise approach to testing for convergence is adopted. Locally, for Middle East, OECD and Europe sub-groups, non-convergence is less strongly rejected. In Liddle (2010) the world convergence in energy intensity is revisited using two new large data sets: a 111-country sample spanning 1971–2006 and a 134-country sample spanning 1990–2006. Both data sets confirm continued convergence. Investigation of geographical differences reveals that the OECD and Eurasian countries have shown considerable, continued convergence, while the Sub-Saharan African countries have converged amongst themselves, but at a slower rate than the OECD and Eurasian countries; by contrast, Latin American and Caribbean and Middle East and North African countries have exhibited no convergence to divergence in energy intensity. Jakob et al. (2012) use a difference-in-differences estimator on panel data for 30 developing and 21 industrialized countries over the period 1971–2005 to show that, for the average developing country in the sample, economic catch-up in energy use has been accompanied by above-average growth of the use of most primary energy carriers, the consumption of final energy in most sectors and total CO2 emissions. Mohammadi and Ram (2012) look at patterns of convergence in per-capita consumption of energy and electricity for a large cross-country data set covering the period 1971–2007. Unconditional β-convergence, σ-convergence, and a simple model of conditional β-convergence are considered. Among several results, the authors find that global convergence in energy consumption is generally weak, whereas convergence in electricity usage is strong in most cases. Adhikari, D. and Chen, Y.Y. (2014) examine the convergence of energy productivity at the sectoral level across 35 Asian countries from 1991 to 2011 by using the spatial panel data approach. The results reveal that mixed evidence of beta-convergence: it exists in the construction, manufacturing, mining; manufacturing and utilities, transport; storage and communications, and wholesale; retail trade; restaurants and hotels sectors, whereas there is no evidence of energy productivity convergence in the agriculture; hunting; forestry and fishing sector over the study period. Le et al. (2017) empirically examine the cross-country convergence of per-capita energy and electricity usage in APEC countries. The results indicate that per capita energy usage and electricity consumption are converging for all APEC countries, in line with improving living standards in APEC.

Turning to water, Portnov and Meir (2007) find that per capita urban water consumption in Israel's domestic sector tend to converge over time. On the contrary, in the non-residential sector (municipal consumption) water consumption tends to diverge, with heavily water-consuming places raising their per capita water consumption rates more rapidly. According to the explanation proposed, the observed convergence trend in the domestic sector is likely to stem from two major factors—the saturation of water consumption in affluent places, and the rising standards of living in poor localities, enabling them to consume more water for household use. Lu and Xu (2019) measure and analyze the total factor productivity and its decomposition of provincial water resources in China from 2008 to 2015. The adjusted total factor productivity was tested for σ convergence and β convergence. The test results showed that there was no σ-convergence nor conditional β-convergence in the total factor productivity, but there was significant absolute β-convergence, indicating that the gap in total factor productivity gap of water resources between all provinces in China is narrowing and eventually converging to the same steady state equilibrium level. Acuña et al. (2020) analyze the existence of convergence in residential water consumption across geographical regions using econometric methods taken from the economic growth literature and a panel of water consumption of 348 Chilean localities from 2010 to 2015. Convergence was found, and the main causes were factors related to economic and climate variables.

Finally, convergence for food has been studied by Herrmann and Röder (1995) who look at convergence or divergence applied to the demand for food nutrients in OECD countries in 1978 and 1988. The analysis distinguishes between absolute and relative convergence and reveals that absolute and relative differences in food consumption across countries do not always follow the same trend. The empirical results clearly show that the terms capturing convergence are the most important variables, indicating the importance of preferences rather than income prices or availability in an international comparison of food demand. Regmi and Unnevehr (2006) study convergence of food expenditures among 18 high income countries from 1990 to 2004. Convergence is apparent in total expenditures, cereals and meats, but not in other categories. Regmi et al. (2008) use food expenditures and food sales data over 1990-2004 to examine whether food consumption and delivery trends are converging across 47 high- and middle-income countries. Middle-income countries, such as China and Mexico, appear to be following trends in high-income countries, measured across several dimensions of food system growth and change. Convergence is apparent in most important food expenditure categories and in indicators of food system modernization such as supermarket and fast-food sales.

3. Methodology

To empirically investigate WEF convergence we use two well-known empirical concepts: σ-convergence and β-convergence. We investigate both the familiar univariate notion of convergence and, owing to the interrelated nature of the WEF nexus, a multivariate extension of both notions. To the best of our knowledge, this has not been done before.

3.1 Univariate σ-convergence

Let $Y_t = (W_t, E_t, F_t)$ be a three-element vector of our key variables. We begin to assess whether or not there has been convergence over time by using the notion of σ-convergence. The most frequently used summary measure of σ-convergence is the standard deviation (SD) or the coefficient of variation (CV) of the variable of interest. Letting i = 1,…,N denote countries and t = 1,…,T the time periods, we compute:

(1) $$SD_t = \frac{1}{N-1}\sum_{i=1}^{N}(Y_{it} - \bar{Y}_t)^2$$

where $\bar{Y}_t = \frac{1}{N}\sum_{i=1}^{N} Y_{it}$ is the cross sectional average. The standard deviation in (1) is often replaced by the coefficient of variation whereby the standard deviation is divided by the mean:

(2) $$CV_t = SD_t/\bar{Y}_t$$

The coefficient of variation is a normalized measure of dispersion of a probability distribution. It is often reported as a percentage by multiplying the above calculation by 100 which is sometimes referred to as the relative standard deviation. The coefficient of variation is often preferred to the standard deviation which has no interpretable meaning on its own unless the mean value is also reported. For a given standard deviation value, the coefficient of variation indicates a high or low degree of variability only in relation to the mean value.

The two indicators are computed for all time periods of the sample: a decrease over time of the values of CV_t indicates convergence. To see whether a convergence pattern is statistically significant we may perform a simple OLS regression of CV_t on a time trend t and evaluate the statistical significance of the slope parameter b in the following equation:

(3) $$CV_t = a + bt + \epsilon_t$$

where b is expected to be negative. Finally, denoting by Z_t a vector of controls that may be specific to W, F or E, we may study what could be referred to as "conditional of σ-convergence" by means of the regression:

(4) $$CV_t = a + bt + cZ_t + \epsilon_t$$

The vector Z_t may contain specific determinants for each *W, E, F* variable and/or for each country/region, such as local labor market structure (unemployment rate), electricity price differentials, innovation activity (number of patents), public investment, policy variables, the index of freedom and so on.

To examine the intra-distribution mobility of countries, that is to understand whether the individual countries with the highest *W, E, F* variable and the countries with the lowest *W, E, F* variable remain the same, the measure of γ-convergence first proposed by Boyle and McCarthy (1997) can be used. It is a rank concordance index ranging from zero to unity: the closer the value is to zero the greater the extent of mobility within the distribution. γ-convergence is computed as:

(5) $$\gamma_t = Var(R_{tj} + R_{0j})/Var(2 * R_{0j})$$

where Var stands for variance and R_{0j} and R_{tj} are the actual rank of country *i*'s *W, E, F* variable in the initial year 0 and year t, respectively. Expression (5) has the advantage of being easy to compute and of being a single number traced over time in two dimensions. However, it gives an idea of convergence also when the ranking changes only at the bottom of the distribution. So, there is an apparent improvement even if the last moves up one position and the next-to-last moves down to the last place, i.e. both remain anyway at the bottom of the distribution.

3.2 Univariate β-convergence

In order to detect possible catching-up processes, the analysis is extended to the notion of β-convergence. Formally, β-convergence is necessary but not sufficient for σ-convergence (Young et al., 2008). Intuitively, this is either because economies can converge toward one another, but random shocks push them apart or because, in the case of conditional β-convergence, economies can converge towards different steady-states. This and a number of limitations of the β-convergence approach (see for instance Quah, 1993) have led some economists to suggest that the concept of σ-convergence is more revealing of the reality as it directly describes the distribution of variables of interest across economies without relying on the estimation of a particular model.

According to the β-convergence hypothesis, the growth rate of a variable is a function of its initial level. A negative coefficient implies that the lower the initial level, the higher the growth rate, thus supporting the conclusion that there is a catching-up process. Formally we compute for each i-th country:

(6) $$\ln(Y_{it}/Y_{it-\tau}) = \alpha_i + \beta_i \ln(Y_{it-\tau}) + u_{it}$$

For β-convergence the sign and significance of β_i matters: there is evidence of convergence if the coefficient is negative and statistically significant. There is instead evidence of divergence if the coefficient is positive and significant, while no pattern can be inferred if the coefficient is not statistically significantly different. The speed of convergence can be evaluated by computing:

(7) $$\lambda_i = -[\ln(1 + \beta_i)]/T$$

and the half-life is:

(8) $$H_i = \ln(2)/\lambda_i$$

Note that (6) can be also estimated for all countries using panel data methods. In this case we will introduce country and time fixed effects to properly account for unobserved heterogeneity.

Conditional β-convergence obtains when (6) is extended to include a vector of controls to account for the contribution of these variables to the convergence process. To this end we have:

(9) $$\ln(Y_{it}/Y_{it-\tau}) = \alpha_i + \beta_i \ln(Y_{it-\tau}) + \varphi_i Z_{it} + u_{it}$$

Inference on the β_i coefficient reveals the potential existence of an unconditional β-convergence process. Note that the controls are variables linked to economic structure or to policy actions, in which case we can construct counterfactual simulations, to study the effectiveness of actions aimed at enhancing the convergence process.

3.3 Multivariate σ-convergence

We propose a new concept of σ-convergence, which we label multivariate σ-convergence, which extends the concept to the *W, E, F* dimension. We consider the evolution through time of the dimension of the cross-sectional covariance matrix.

Let Σ_t be the (3x3) covariance matrix in each period t of our key variables Y_{ikt}, where k = (W, E, F). The typical element σ_{klt} of the covariance matrix is computed as:

(10) $$\sigma_{klt} = \frac{1}{N-1} \sum_{i=1}^{N} (Y_{ikt} - \bar{Y}_{ikt})(Y_{jlt} - \bar{Y}_{jlt})$$

where $\bar{Y}_{ikt} = \frac{1}{N}\sum_{i=1}^{N} Y_{ikt}$ is the cross sectional average in period t of each variable Y_k. The matrix Σ_t changes over time and we propose the notion of multivariate σ-convergence as the study of the determinant of the matrix $\Phi_t = det[\Sigma_t]$. The decrease of the sequence Φ_t indicates convergence. To see whether a convergence pattern is statistically significant we may perform a simple OLS regression:

(11) $$\Phi_t = a + bt + \epsilon_t$$

where b is expected to be negative. Finally, denoting by Z_t a vector of controls that may be specific to (W, F, E), we may study what can be referred to as "conditional multivariate σ-convergence" by means of the regression:

(12) $$\Phi_t = a + bt + cZ_t + \epsilon_t$$

3.4 Multivariate $\boldsymbol{\beta}$-convergence

The present analysis aims to uncover the potential existence of convergence for our measures of water, energy and, food. As it is well documented, these three variables are highly interconnected: hence the term nexus. We propose a new concept of β-convergence, which we label multivariate β-convergence, with the aim to effectively capture the notion of nexus among the variables, by estimating a multivariate version of the usual unconditional or conditional β-convergence equation. This results in the following simultaneous equations system:

(13) $$\ln(Y_t/Y_{t-\tau}) = A + B\ln(Y_{t-\tau}) + \Phi Z_t + U_t$$

where $Y_t = (W_t, E_t, F_t)$ and B is a (3 x 3) coefficient matrix whose off-diagonal elements account for the possibility that the initial value of one component of the nexus affects the growth rate of another component and Φ is a matrix of coefficients of the exogenous covariates Z_t. Under the restriction $\Phi = 0$, (13) represents our multivariate unconditional β-convergence model. In detail, each equation of (13) corresponding to water, energy and food, respectively, is as follows:

$$(14)\quad \ln(W_{it}/W_{it-\tau}) = A_{Wi} + B_{WWi}\ln(W_{it-\tau}) + B_{WEi}\ln(E_{it-\tau}) + B_{WFi}\ln(F_{it-\tau}) + \Phi_{Wi}Z_{Wit} + U_{Wit}$$

$$(15)\quad \ln(E_{it}/E_{it-\tau}) = A_{Ei} + B_{EEi}\ln(E_{it-\tau}) + B_{EWi}\ln(W_{it-\tau}) + B_{EFi}\ln(F_{it-\tau}) + \Phi_{Ei}Z_{Eit} + U_{Eit}$$

$$(16)\quad \ln(F_{it}/F_{it-\tau}) = A_{Fi} + B_{FFi}\ln(F_{it-\tau}) + B_{FEi}\ln(E_{it-\tau}) + B_{FWi}\ln(W_{it-\tau}) + \Phi_{Wi}Z_{Fit} + U_{Wit}$$

The system (13) or (14)-(16) is efficiently estimated by means of an appropriate system method.

4. Data

To empirically investigate (*W,E, F*) convergence according to the above indexes we use annual data for a panel of 108 countries covering the period 1971 to 2018 representing 90% of the World population. The list of countries is provided in the appendix A.1.

The data are drawn from different sources, as detailed in Appendix A.2. Our measure of Water (W) is the renewable internal freshwater resources per capita (cubic meters per capita). The data are available at quinquennium frequency; annual data have been obtained by interpolation. The source of the data is U.N. Food and Agriculture Organization (FAO), AQUASTAT database.[4]

For energy (E) we use the measure of energy use per capita (keo: kilograms of oil equivalent per capita), available at annual frequency. The source of the data is the International Energy Agency (IEA) Energy Statistics Database.

[4] The data were accessed through the World Bank indicators. Website accessed on [19/02/2020 9:11]: https://data.worldbank.org/indicator/ER.H2O.INTR.PC.

For food (F) we use the measure of the daily caloric supply (kcal/person/day). The data are annual and come from FAO.[5]

The other variables used in conditional convergence analysis are from the World Bank World Development Indicators. These were population, value added, energy use, export performance, access to FDI, investment and other policy variables.

Table 2 presents the main descriptive statistics of the (*W, E, F*) variables used in the empirical estimation. For them we both report the log and the growth rate, together with the exogenous variables – exports, foreign direct investment (*FDI*) inflow, gross fixed capital formation (*GCFC*) – all expressed in terms of *GDP, a*nd the world GDP per capita (GDPW) and population living in large cities as percentage of urban population (poplarge).

Table 2: Main descriptive statistics

var	Mean	Std. Dev.	Minimum	Maximum	1st Qrt.	Median	3rd Qrt.
log(W)	8.732	1.753	0.349	13.298	7.709	8.753	9.945
log(E)	0.194	1.053	-2.444	2.715	-0.712	0.013	1.106
log(F)	7.893	0.201	7.271	8.250	7.724	7.922	8.060
Δlog(W)	-0.080	0.161	-2.501	2.071	-0.126	-0.075	-0.030
Δlog(E)	0.046	0.181	-1.932	1.587	-0.034	0.044	0.124
Δlog(F)	0.019	0.069	-0.649	0.542	-0.010	0.019	0.049
Export/GDP	34.243	23.351	0.005	221.197	19.187	28.768	44.382
FDI/GDP	3.47038	14.330	-58.3229	451.6393	0.35097	1.34773	3.310
GFCF/GDP	22.134	7.907	0	89.386	18.596	22.157	25.793
GDPW	26643.9	21260.7	2409.4	71067.6	8723.8	21534.3	43907.9
poplarge	17.08	0.762	16.09	18.20	16.28	17.01	17.81

5. Empirical results

We start by presenting the results for the traditional univariate convergence measures for the three variables of the nexus, food, energy and water. We then move to the multivariate case.

[5] The source for 1961 2013 is: http://www.fao.org/faostat/en/#search/Food%20supply%20kcal%2Fcapita%2Fday. For 2014-2018: http://www.fao.org/faostat/en/#search/Food%20supply%20kcal%2Fcapita%2Fday.

5.1 Univariate convergence

First, we address the analysis of the traditional convergence. We present the results of σ-convergence as defined in (1) in Figures 2-4.

Figure 2: Univariate σ-convergence – Water

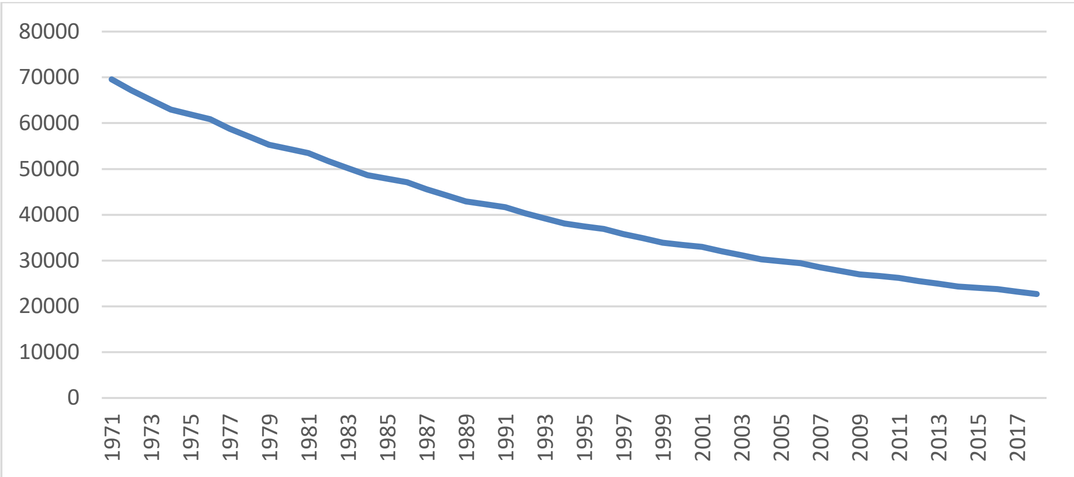


Figure 3: Univariate σ-convergence - Energy

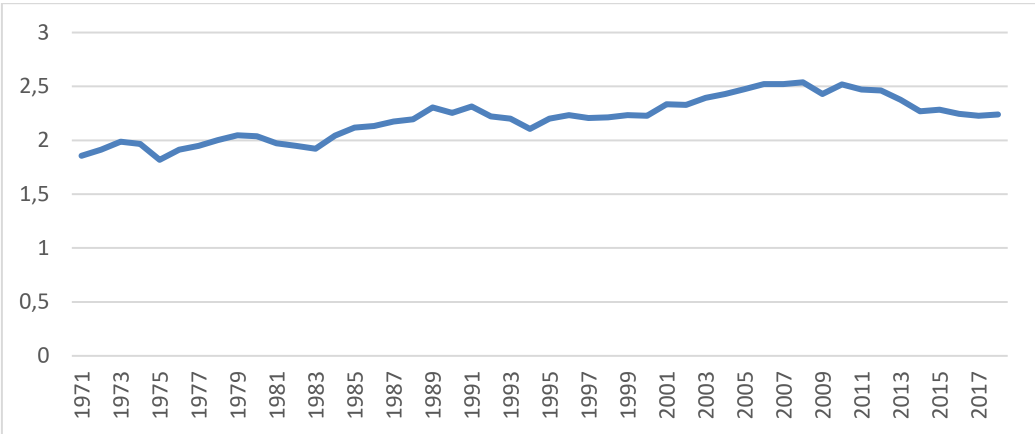
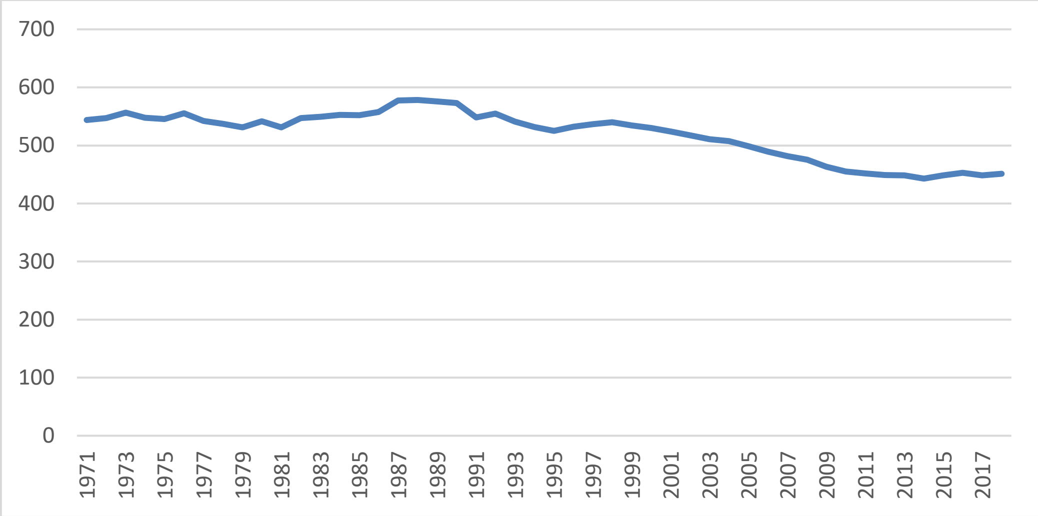
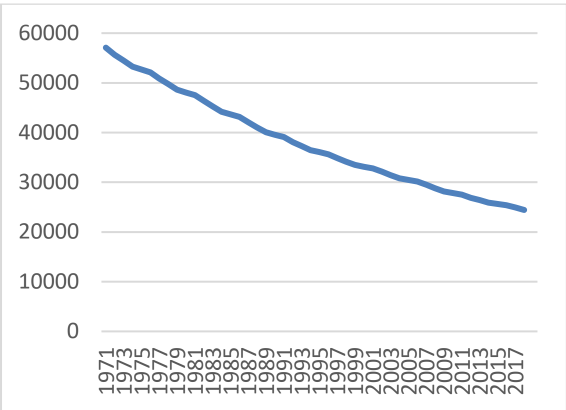


Figure 4: Univariate σ-convergence – Food



Convergence is apparent and pronounced for water, less so for food after especially the mid-80s. No convergence is detected for energy until the breakout of the financial and economic crisis in 2008-09. We may ask if these tendencies are confirmed when we disaggregate the world countries in OECD and non-OECD countries. This is done in Figures 5-7.

Figure 5: Univariate σ-convergence – Water – OECD and non-OECD countries



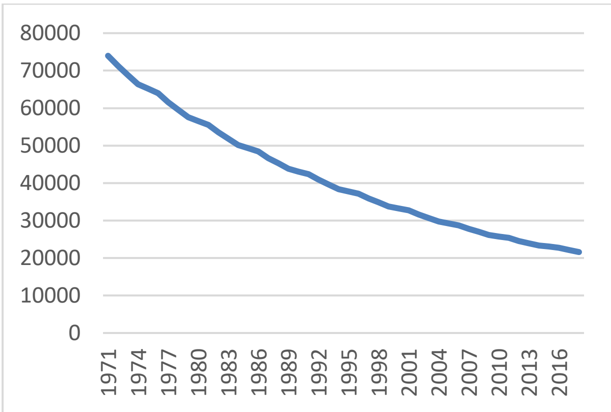
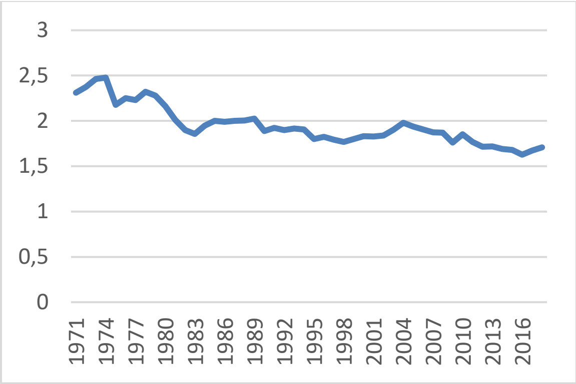


Figure 6: Univariate σ-convergence – Energy – OECD and non-OECD countries



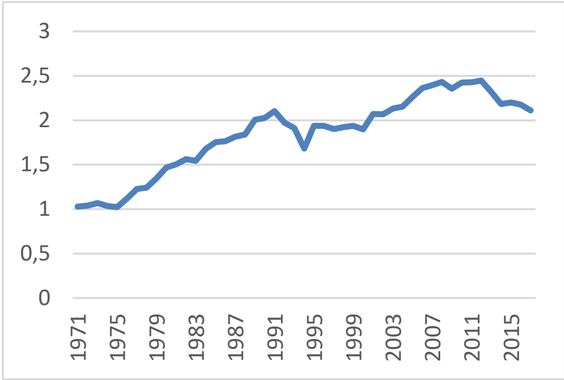
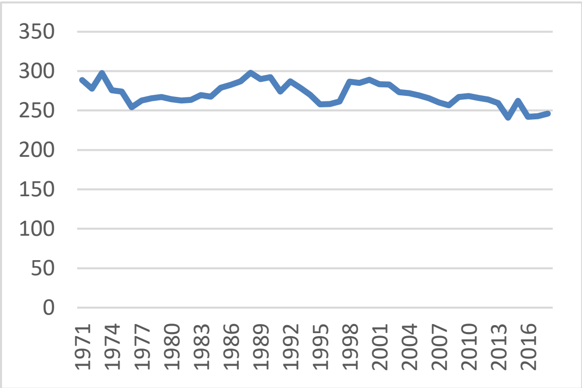
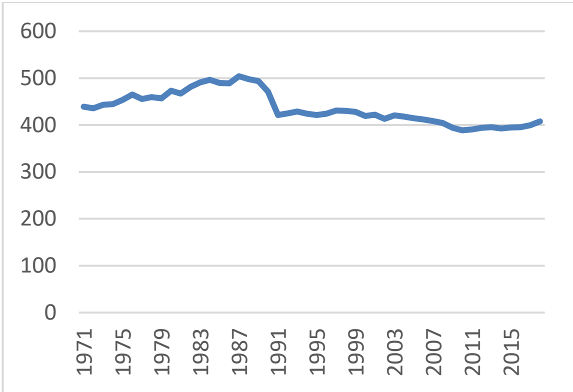


Figure 7: Univariate σ-convergence – Food – OECD and non-OECD countries





Convergence is pronounced in the case of water for both groups of countries. This hods for energy only in the OECD country group during the entire period, whereas this is not the case for the other group, except for the last few years. In the case of food, convergence is mild in both country groups.

Next we compute the γ-convergence index. This index takes into account the intra-distribution mobility of countries and is computed according to (5). The results are shown in Table 3 for selected years.

Table 3: γ-convergence – selected years

	1971	1995	2018
Water	1	0.99	0.97
Energy	1	0.85	0.82
Food	1	0.49	0.47

Note that there is a clear indication of mobility for food (γ-convergence in 2018 = 0.47), somewhat for energy (γ-convergence in 2018 = 0.82), and less for water (γ-convergence in 2018 = 0.97).

Turning to the popular notion of β-convergence, we compute it according to (6) and present the results in Table 4.

Table 4: Unconditional β-convergence

Dep. variable	$\ln(W_t/W_{t-5})$	$\ln(E_t/E_{t-5})$	$\ln(F_t/F_{t-5})$
N. obs.	4456	4455	4456
Durbin-Watson	2.31	1.81	1.75
F (zero slopes)	11.6	16.3	25.9
R-squared	0.22	0.29	0.23
Log likelihood	2350.3	2040.1	6151.9
Expl. variables	Coefficient	Coefficient	Coefficient
C	2.19**	-0.060**	2.43**
$\ln(W)_{t-5}$	-0.177**	-0.261**	-0.32**
Dep. variable	$\ln(W_t/W_{t-10})$	$\ln(E_t/E_{t-10})$	$\ln(F_t/F_{t-10})$
N. obs.	3919	3920	3920
Durbin-Watson	2.30	1.74	1.66
F (zero slopes)	25.2	3311	27.0
R-squared	0.41	0.48	0.42
Log likelihood	1664.6	979.5	4756.3
Expl. variables	Coefficient	Coefficient	Coefficient
C	2.13**	-0.111**	4.83**
$\ln(W)_{t-10}$	-0.308**	-0.499**	-0.633**

Notes: (i) sample period: 1971-2018; (ii) country fixed effects are included but not reported; (iii) ** denotes significance at 1% confidence level.

The top panel show the results for lag t-5 and the bottom panel lag t-10. We note that the coefficient b is negative and significant for all three variables both for t-5 and t-10. This evidence supports the conclusion that there is convergence in water, energy, and food over the period 1971-2018. The estimated speed and half-life for lags 5 and 10 are reported in table 5.

Table 5: Estimated half-life and speed of convergence

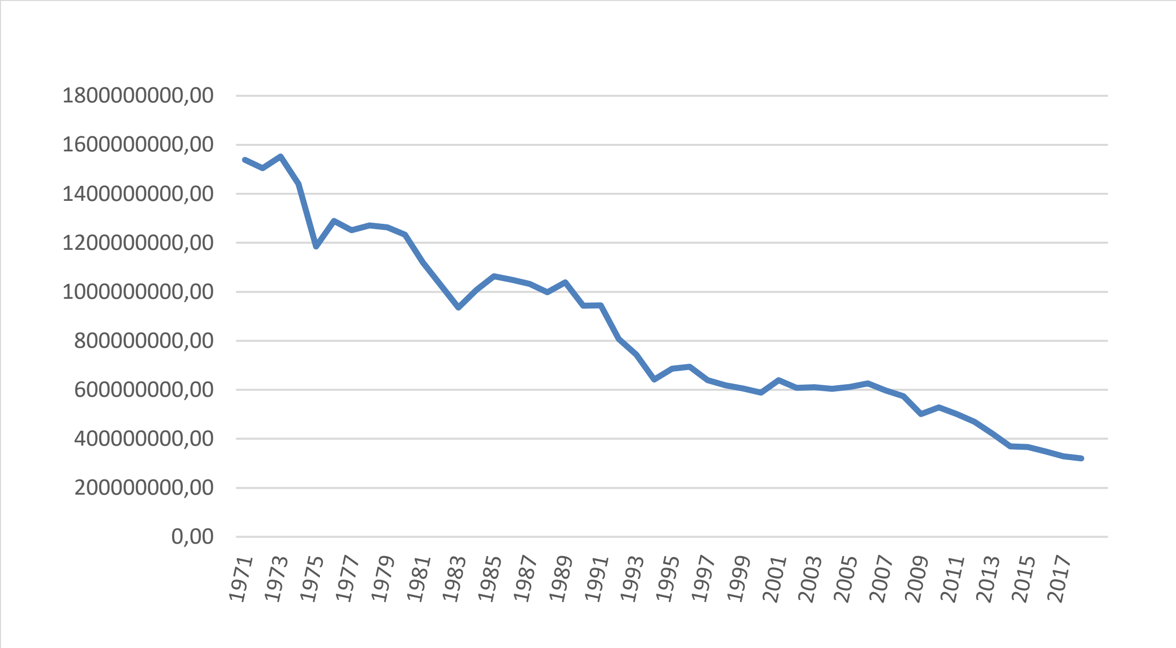
	Lag t-5	Lag t-10
Water		
λ_W	0.032	0.027
H_W	21.2	25.2
Energy		
λ_E	0.046	0.040
H_E	14.9	17.1
Food		
λ_F	0.055	0.048
H_F	12.5	14.4

The values for food are similar to Regmi et al. (2008), who report 16 and 18 years of half-life. The values for water show a somehow faster speed. The values for energy are similar to Qi et al. (2019) and Liu and Chang (2020).

5.2 Multivariate convergence

We begin by computing the multivariate version of σ-convergence according to (10). The results for Φ_t = det[Σ_t] are shown in Figure 8 and show a distinct convergent pattern. To confirm this fact, we regressed the determinant Φ_t on a time trend according to (11) or a time trend and other controls according to (12). The results are presented in Table 6.

Figure 8: Multivariate σ-convergence



Note: on the vertical axis values of $\Phi_t = \det[\,\Sigma_t\,]$.

Table 6: Multivariate σ-convergence

Dep. variable	$\Phi_t = \det[\Sigma_t]$		
N. obs.	48	48	48
F (zero slopes)	693.3	535.1	316.3
R-squared	0.94	0.96	0.97
Expl. variables	Coefficient	Coefficient	
C	0.149**	0.148**	.338*
trend	-24.21**	-35.47**	-41.1**
World GDP		7.80**	6.56**
GFCF/GDP			613.1**
Pop. large cities			-1878.9**

Notes: (i) ** denotes significance at 1% confidence level; (ii) pop. Large cities is the population living in large cities as percentage of urban population

The coefficient of the time trend is negative and significant, showing the existence of multivariate σ-convergence. World GDP as a control variable in (12) was found to be in significant. In addition, we find significant effects also for gross fixed capital formation as percentage of GDP and of the population living in large cities as percentage of urban population.

We now turn to multivariate β-convergence. We begin by estimating the unconditional multivariate β-convergence equation system (13) with lag t-5 and lag t-10 and with the restrictions $\Phi_{wi} = \Phi_{Ei} = \Phi_{Fi} = 0$. The results are reported in Table 7.

Table 7: Multivariate unconditional β-convergence

Dep. variable	$\ln(W_t/W_{t-5})$	$\ln(E_t/E_{t-5})$	$\ln(F_t/F_{t-5})$
N. obs.	4456	4455	4456
Durbin-Watson	2.37	1.83	1.97
F (zero slopes)	11.1	16.7	12.6
R-squared	0.22	0.34	0.24
Log likelihood	2361.1	2071.2	6191.9
Variable	Coefficient	Coefficient	Coefficient
C	1.908**	-1.388**	2.908
$\ln(E)_{t-5}$	-0.028**	-0.302**	-0.013
$\ln(F)_{t-5}$	-0.068**	0.201**	-0.344
$\ln(W)_{t-5}$	-0.198**	-0.028**	-0.036
Dep. variable	$\ln(W_t/W_{t-5})$	$\ln(E_t/E_{t-5})$	$\ln(F_t/F_{t-5})$
N. obs.	3920	3919	3920
Durbin-Watson	2.30	1.81	1.88
F (zero slopes)	33.11	35.2	27.8
R-squared	0.41	0.51	0.45
Log likelihood	1672.1	1060.2	4837.2
Variable	Coefficient	Coefficient	Coefficient
C	2.350**	-1.227**	5.622
$\ln(E)_{t-10}$	-0.043**	-0.583**	-0.016
$\ln(F)_{t-10}$	-4.95E-03**	0.2749**	-0.667
$\ln(W)_{t-10}$	-0.333**	-0.1302**	-0.069

Note: ** denotes significance at 1% confidence level.

We have also computed the speed and half-life for lag = 5 and lag = 10 (Table 8). We note that the speed of convergence is similar for food and energy and lower for water.

Table 8: Estimated half-life and speed of convergence for multivariate model

	Lag t-5	Lag t-10
Water		
λ_W	0.036	0.028

H_W	19.2	24.1
Energy		
λ_E	0.053	0.045
H_E	13.2	15.1
Food		
λ_F	0.059	0.051
H_F	11.7	13.6

To appreciate the significance of the multivariate approach to β-convergence, we performed a likelihood ratio (LR) test by also estimating the system (13) with the restrictions of a diagonal B_i matrix, i.e. imposing $B_{YX} = 0$ for $Y, X = W, E, F$ with $Y \neq X$. This obviously boils down to the traditional univariate β-convergence. The LR tests for each equation are reported on Table 9 for the specifications at lag t-5 and lag t-10.

Table 9: Likelihood ratio tests of multivariate vs traditional β-convergence

Equation	t-5	t-10
Water	21.4	15.2
Energy	62.1	161.5
Food	79.9	159.7

Note: The LR test is distributed chi-square with 2 degrees of freedom. The critical value at 1% confidence level is equal to 9.21.

On the basis of the LR test it clearly emerges that the multivariate β-convergence is a significant generalization of the univariate single equation model, with a 1% confidence level. The 3x3 matrix of coefficients taken from Table 7 is reported in Table 10.

Table 10: Multivariate unconditional β-convergence coefficients

lag t-5			
	Water	Energy	Food
Water	**-0.198**	-0.028	-0.036
Energy	-0.028	**-0.302**	-0.013
Food	-0.068	0.201	**-0.345**
lag t-10			

Water	**-0.333**	-0.130	-0.069
Energy	-0.043	**-0.583**	-0.017
Food	-0004	0.275	**-0.668**

Note: in bold the coefficients on the main diagonal.

We note the coefficients on the main diagonal are all negative, as required for convergence for all three variables, i.e. for each variable a lower past value implies a higher growth rate. It is interesting to note that the off-diagonal coefficients are both positive and negative. In the case of food, we note that water reinforces the convergence while energy works in the opposite direction, that is, a lower past value of energy determines a lower effect on the growth rate of food. In case of water and energy, the other variables' effects are reinforcing the convergence process.

As a last step, we augmented the multivariate equations (14)-(16) relaxing the restrictions $\Phi_{wi} = \Phi_{Ei} = \Phi_{Fi} = 0$, adding as exogenous determinants: the export to GDP ratio as a measure to openness of the economy, the FDI to GDP ratio as a measure to dependence from foreign aid, and the gross fixed capital formation to GDP ratio as a measure of strength of the capability to sustain long-term growth. The results are reported in Table 11 and the 3x3 matrix of coefficients in Table 12.

Table 11: Multivariate conditional β-convergence

Dep. variable	$\ln(W_t/W_{t-5})$	$\ln(E_t/E_{t-5})$	$\ln(F_t/F_{t-5})$
N. obs.	4461	4460	4461
Durbin-Watson	2.38	1.83	1.98
F (zero slopes)	33.1	19.9	13.4
R-squared	0.23	0.34	0.26
Log likelihood	2388.3	2219.4	6248.6
Variable	Coefficient	Coefficient	Coefficient
C	2.07**	-1.51**	2.85**
$\ln(E)_{t-5}$	-0.019*	-0.298**	-0.012**
$\ln(F)_{t-5}$	-0.71**	0.21**	-0.341**
$\ln(W)_{t-5}$	-0.215**	-0.036**	-0.036**
Export/GDP	-0.0012**	0.0006**	0.0002**
FDI/GDP	-0.0002	-0.0004*	0.0002
GFCF/GDP	0.0012**	0.0071**	0.0016**
Dep. variable	$\ln(W_t/W_{t-10})$	$\ln(E_t/E_{t-10})$	$\ln(F_t/F_{t-10})$

N. obs.	3921	3920	3921
Durbin-Watson	2.32	2.32	1.91
F (zero slopes)	33.11	39.0	28.7
R-squared	0.42	0.54	0.46
Log likelihood	1689.8	1190.6	4889.9
Variable	Coefficient	Coefficient	Coefficient
C	2.49**	-1.47**	5.56**
$\ln(E)_{t-10}$	-0.031**	-0.56**	-0.012**
$\ln(F)_{t-10}$	-0.0032	-0.0032**	-0.665**
$\ln(W)_{t-10}$	-0.351**	-0.125**	0.067**
Export/GDP	-0.0013**	0.0002**	-0.0003
FDI/GDP	-0.00018*	0.00023	-0.00027**
GFCF/GDP	0.0015**	0.0005**	0.0023**

Note: (i) ** denotes significance at 1% confidence level; (ii) * denotes significance at 5% confidence level

Table 12: Multivariate conditional β-convergence coefficients

lag t-5			
	Water	Energy	Food
Water	**-0.215**	-.036	-.036
Energy	-0.019	**-.298**	-.012
Food	-0.71	0.21	**-.341**
lag t-10			
Water	**-.351**	-.125	0.067
Energy	-.031	**-.560**	-.012
Food	-0.003	-0.003	**-0.665**

Note: in bold the coefficients on the main diagonal.

The evidence of Table 11 confirms the existence of a significant nexus among water, energy and food that emerges also when analyzing convergence. In addition, this process is significantly influenced by the exogenous determinants. In particular, we find that investment has a positive accelerating effect on water convergence. Investment, openness to foreign trade and inflow of foreign direct investment have a positive accelerating effect on food convergence. Investment and openness to foreign trade and inflow of foreign direct investment have a positive accelerating effect on energy convergence. The coefficients of the conditional multivariate interaction in Table 12 confirm the previous results in general. We observe that in the case of water with lag=10, lower lagged values of food have a lower effect on the growth rate of water. For energy and food, the other variables reinforce the effect on the growth rate, thus reinforcing the convergence process.

Table 13: Estimated half-life and speed of convergence for multivariate model

	Lag t-5	Lag t-10
Water		
λ_W	17.8	23.1
H_W	0.039	0.030
Energy		
λ_E	13.2	15.5
H_E	0.052	0.044
Food		
λ_F	11.8	13.6
H_F	0.058	0.051

The speed and half-life for lag t- 5 and lag t-10 of Table 13 shows that convergence is similar for food and energy and lower for water.

These results have important policy implications, because the fact that convergence can be influenced by specific determinants could suggest that appropriate policy intervention can be designed to spur the speed of convergence. In particular, openness to trade is exerting a beneficial effect on convergence of Food and Water. FDI has a positive additional effect on convergence of Water.

6. Conclusions

In this paper we have investigated the water-energy-food nexus from a new angle, by asking whether there is convergence in per capita water, energy, and food for 108 countries around the world, or 90% of total population. Using the familiar notions of σ-convergence and β-convergence we generally find evidence in favor of such a process.

However, the very concept of water-energy-food nexus is that of an integrated and interrelated process. In order to take this fact into account, we develop and apply a multivariate approach to convergence for both concepts. Importantly, convergence is confirmed and, in addition, it is affected by the starting value of the other components of the nexus, thus confirming a multivariate approach. This is important for suggesting an integrated policy strategy that can address the water-energy-food nexus in a coordinated fashion and not with a piecemeal approach.

We also study the role of additional exogenous factors affecting the multivariate convergence process. In particular, we find that investment has a positive accelerating effect on water convergence. In addition, investment, openness to foreign trade and inflow of foreign direct investment have a positive accelerating effect on food convergence as well as on energy convergence. Our results have important policy implications, because the fact that convergence can be influenced by specific determinants could suggest that appropriate policy intervention can be designed to spur the speed of convergence of the three nexus dimensions.

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Appendix

A.1 Country list

The country list is in Table A1.

Table A.1 – Country list – 108 countries

Country Name	Country Code	Country Name	Country Code		
Albania	ALB	Haiti	HTI	Paraguay	PRY
Algeria	DZA	Honduras	HND	Peru	PER
Angola	AGO	Hungary	HUN	Philippines	PHL
Argentina	ARG	India	IND	Poland	POL
Australia	AUS	Indonesia	IDN	Portugal	PRT
Austria	AUT	Iran	IRN	Romania	ROU
Azerbaijan	AZE	Iraq	IRQ	Russia	RUS
Bangladesh	BGD	Ireland	IRL	Saudi Arabia	SAU
Belgium	BEL	Israel	ISR	Senegal	SEN
Benin	BEN	Italy	ITA	Slovakia	SVK
Bolivia	BOL	Jamaica	JAM	Slovenia	SVN
Botswana	BWA	Japan	JPN	South Africa	ZAF
Brazil	BRA	Jordan	JOR	South Korea	KOR
Bulgaria	BGR	Kazakhstan	KAZ	Spain	ESP
Cambodia	KHM	Kenya	KEN	Sri Lanka	LKA
Cameroon	CMR	Korea Dem	PRK	Sweden	SWE
Canada	CAN	Kuwait	KWT	Switzerland	CHE
Chile	CHL	Lebanon	LBN	Syria	SYR
China	CHN	Luxembourg	LUX	Tanzania	TZA
Colombia	COL	Malaysia	MYS	Thailand	THA
Congo	COG	Malta	MLT	Togo	TGO
Costa Rica	CRI	Mauritius	MUS	Trinidad and T	TTO
Côte d'Ivoire	CIV	Mexico	MEX	Tunisia	TUN
Cuba	CUB	Mongolia	MNG	Turkey	TUR
Cyprus	CYP	Morocco	MAR	Ukraine	UKR
Czechia	CZE	Mozambique	MOZ	UAE	ARE
Denmark	DNK	Myanmar	MMR	United Kingdom	GBR
Dominican Rep.	DOM	Namibia	NAM	United States	USA
Ecuador	ECU	Nepal	NPL	Uruguay	URY
Egypt	EGY	Netherlands	NLD	Venezuela	VEN
Finland	FIN	New Zealand	NZL	Viet nam	VNM
France	FRA	Nicaragua	NIC	Yemen	YEM
Gabon	GAB	Niger	NER	Zambia	ZMB
Germany	DEU	Nigeria	NGA	Zimbabwe	ZWE
Ghana	GHA	Norway	NOR		
Greece	GRC	Pakistan	PAK		
Guatemala	GTM	Panama	PAN		

A.2 Data sources

Food data is the daily caloric supply as computed by FAO, United Nations Food and Agriculture Organization. The unit of measurement is kcal/person/day. The period is 1961 – 2018.

The source for 1961 2013 is:

http://www.fao.org/faostat/en/#search/Food%20supply%20kcal%2Fcapita%2Fday

The source for 2014 2018 is:

http://www.fao.org/faostat/en/#search/Food%20supply%20kcal%2Fcapita%2Fday

According to FAO, the data here give estimates of total and per caput food supplies available for human consumption during the reference period in terms of quantity and, by applying appropriate food composition factors for all primary and processed products, also in terms of caloric value and protein and fat content. Calorie supplies are reported in kilocalories. Per caput supplies are derived dividing the quantities of Food by the total population, using the mid-year estimates of population published by the United Nations Population Division.

Water data is the renewable internal freshwater resources per capita. The unit of measurement is cubic meters/per capita/year. The period is 1962-2017 and the data are available at quinquennium frequency. Annual data are obtained by interpolation. The year 2018 data is obtained with preliminary estimation.

The source is: World Bank indicators, Food and Agriculture Organization, AQUASTAT Main Database. Website accessed on [19/02/2020 9:11]:

https://data.worldbank.org/indicator/ER.H2O.INTR.PC

Energy data is the energy use per capita. The unit of measurement is kg of oil equivalent per capita. The data are annual and the period is 1971-2018. The Energy Statistics Database contains comprehensive energy statistics on the production, trade, conversion and final consumption of primary and secondary; conventional and non-conventional; and new and renewable sources of energy. The Energy Statistics dataset, covering the period from 1990 onwards, is available at U.N. data.

The source for 1971 2013 is: IEA Statistics

https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE

The source for 2014 2018 is:

https://databank.worldbank.org/home.aspx

and

www.iea.org

As to the other variables, annual data for the period 1971 2018 were taken from the World Development Indicators (WDI), the primary World Bank collection of development indicators, compiled from officially recognized international sources. It presents the most current and accurate global development data available, and includes national, regional and global estimates. Update: 1 July 2020.

A small number of occurrences of missing data for some periods have been estimated. Access to: https://databank.worldbank.org/home.aspx

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