Australian National University | Crawford School of Public Policy

CAMA

Centre for Applied Macroeconomic Analysis

Time-Varying Human Capital and Energy Consumption for a Panel of OECD Countries in the Long-Run

---

CAMA Working Paper 1/2026
January 2026

Kris Ivanovski
La Trobe University

Russell Smyth
Monash University
Centre for Applied Macroeconomic Analysis, ANU

Xibin Zhang
Monash University

Abstract

We examine how human capital influences energy consumption in a panel of OECD nations in the long run. We make important contributions to understanding how education affects energy consumption. First, much of the existing research on how human capital affects energy consumption, employs time series or panel data which typically span a few decades. We utilise a newly assembled long-run panel spanning 150 years, disaggregated by primary, secondary, and tertiary levels, for a core set of OECD countries. This long panel enables us to capture how the human capital–energy relationship evolved through the industrial revolution, multiple energy transitions, and major global shocks. Second, most prior studies rely on parametric models that assume constant relationships over time. Such approaches yield average effects but fail to capture how the education–energy nexus shifts in response to changes in policies, technologies, and macroeconomic conditions. To overcome this limitation, we employ both a parametric and a semi-parametric estimator, which generates time-varying elasticities. Our parametric results highlight the heterogeneous effects of education, with primary and secondary schooling associated with higher energy consumption and tertiary education linked to lower energy consumption. Semi-parametric findings show that primary and secondary education contributed strongly to energy-intensive growth in the early stages of development, but their influence diminished as economies shifted toward services and improved efficiency, while tertiary education became increasingly connected with lower energy use in later decades.

Keywords

human capital, energy consumption, instrument variables, time-varying panel data models

JEL Classification

I25, Q41, Q43, C26, C33

Address for correspondence:

(E) cama.admin@anu.edu.au

ISSN 2206-0332

Time-varying human capital and energy consumption for a panel of OECD countries in the long-run

Kris Ivanovski[1], Russell Smyth[2], Xibin Zhang[3]

[1]La Trobe Business School La Trobe University | Bundoora, Victoria, 3086, Australia
[2]Department of Economics, Monash University, VIC 3800, Australia and Centre for Applied Macroeconomic Analysis, Australian National University
[3]Department of Econometrics and Business Statistics, Monash University, VIC 3800, Australia

[1]Email: k.ivanovski@latrobe.edu.au
[2]Email: russell.smyth@monash.edu
[3]Email: xibin.zhang@monash.edu

Abstract

We examine how human capital influences energy consumption in a panel of OECD nations in the long run. We make important contributions to understanding how education affects energy consumption. First, much of the existing research on how human capital affects energy consumption, employs time series or panel data which typically span a few decades. We utilise a newly assembled long-run panel spanning 150 years, disaggregated by primary, secondary, and tertiary levels, for a core set of OECD countries. This long panel enables us to capture how the human capital–energy relationship evolved through the industrial revolution, multiple energy transitions, and major global shocks. Second, most prior studies rely on parametric models that assume constant relationships over time. Such approaches yield average effects but fail to capture how the education–energy nexus shifts in response to changes in policies, technologies, and macroeconomic conditions. To overcome this limitation, we employ both a parametric and a semi-parametric estimator, which generates time-varying elasticities. Our parametric results highlight the heterogeneous effects of education, with primary and secondary schooling associated with higher energy consumption and tertiary education linked to lower energy consumption. Semi-parametric findings show that primary and secondary education contributed strongly to energy-intensive growth in the early stages of development, but their influence diminished as economies shifted toward services and improved efficiency, while tertiary education became increasingly connected with lower energy use in later decades.

Key words: Human capital; Energy consumption; Instrument variables; Time-varying panel data models
JEL classification: I25; Q41; Q43; C26; C33

1. Introduction

Investing in human capital brings many benefits (Weisbrod, 1966), such as higher labour productivity (Black & Lynch, 1996), higher economic growth (Mincer, 1984), better health outcomes (Davies et al., 2018), and lower crime rates (Bell et al., 2022), among others. The role of human capital in influencing energy consumption, however, particularly in the long run, remains less understood. This highlights an important gap in the literature, as education is often justified on the basis of the broader social benefits associated with human capital development (Ciccone & Peri, 2006), and that an additional benefit frequently associated with human capital investment is its link to reduced energy use, which in turn supports improved environmental outcomes. (Yao et al., 2021). This is especially salient as the world's major economies grapple with how to reduce carbon dioxide (CO_2) emissions to realise net-zero greenhouse gas emissions by 2050.

Recent empirical work exploring the link between human capital and energy use has generally shown that higher levels of human capital tend to be associated with reduced energy consumption(Akram et al., 2020; Li et al., 2024; Salim et al., 2017), but this likely only tells part of the story. Both the shift toward cleaner energy systems, which is crucial for tackling climate change, and the build-up of human capital unfold as long-term processes (Churchill et al., 2023; Fouquet & Pearson, 2012; Madsen & Murtin, 2017). The relationship between human capital and energy consumption is non-linear, changing from positive to negative at different points in history (Churchill et al., 2023). As such, fully understanding the complex interplay between investing in human capital and energy consumption and what this implies for long-run economic growth and environmental outcomes, necessarily requires taking a long-term perspective (see e.g., Kander & Lindmark, 2004; Malanima, 2024).

We examine the relationship between human capital and energy consumption for a panel of 10 OECD economies - Canada, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, the United Kingdom, and the United States - over the period 1870–2020. In doing so, this paper makes several contributions to the literature on human capital and energy demand.

First, much of the existing research on how human capital relates to energy use, including studies focused on OECD economies, employ either cross-sectional data (Li et al., 2024) or time series or panel data for short periods, which typically span a few decades (Akram et al., 2019, 2020; Cihan & Değirmenci, 2025; Hoa & Hoang, 2024; Salim et al., 2017; Wang et al., 2023). By contrast, this study utilises a newly assembled long-run panel spanning 150 years for a core set of OECD countries. This long panel enables us to examine how the human capital–energy relationship evolved during the Industrial Revolution, multiple energy transitions, and significant global shocks. By focusing on a set of advanced economies with relatively consistent institutional development, we reduce the unobserved heterogeneity that typically affects broader cross-country panels with shorter horizons (Churchill et al., 2023; Le et al., 2024; Madsen et al., 2018). To the best of our knowledge, this is the first dataset in the literature to systematically combine historical series on energy consumption with educational attainment, disaggregated by primary, secondary, and tertiary levels, over such an extended horizon for a subset of core OECD nations.

The only other study that considers the human capital-energy consumption relationship over a long time horizon is Churchill et al. (2023), who examine the relationship between human capital and energy consumption in the United Kingdom over six centuries. We extend the findings in Churchill et al (2023) in two important ways. One way is that we complement the results in Churchill et al (2023) by providing evidence on how human capital influences energy consumption in the long run for a broader set of high-income countries, while leveraging the benefits of panel data for mitigating confounding factors and unobserved heterogeneity. The other way is that we provide the first semi-parametric estimates for the relationship between human capital and energy consumption in the long run.

Second, this study contributes to the debate on the drivers of energy transitions. Conventional accounts emphasise capital accumulation, institutions, and technology as significant long-run determinants of energy use (Fouquet, 2008; Fouquet & Pearson, 2012; Le et al., 2025). In contrast, the influence of human capital on energy demand during past transitions has received comparatively little scholarly attention. Evidence from the United Kingdom, for example, however, suggests that education played an important role in economic development even during the First Industrial Revolution, contrary to the traditional view that it was largely irrelevant (Madsen & Murtin, 2017). Our multi-country analysis builds on this insight, providing evidence on how different tiers of education contributed in distinct ways to the evolution of energy use across a panel of OECD economies over 150 years.

Third, unlike studies that treat education as a single aggregate measure, we separate human capital into overall years of schooling and the distinct levels of primary, secondary, and tertiary education. This distinction is important because the impact of education on energy use is not uniform. Historically, primary and secondary schooling expanded the industrial workforce and bolstered energy-intensive production. This pattern has been documented across developing and recently industrialised economies (e.g., Yao et al., 2019). By contrast, tertiary education often promotes efficiency and cleaner energy through technological adoption and heightened environmental awareness. Evidence shows tertiary attainment reduces fossil fuel use and CO_2 emissions, especially in wealthier economies (Lee et al., 2024; Yao et al., 2020). Likewise, human capital enhances total-factor energy efficiency, with tertiary education playing a particularly important role (Ma, 2022). These findings align with long-run evidence from the United Kingdom showing that rising human capital ultimately reduces energy consumption (Churchill et al., 2023).

Fourth, we address methodological limitations in the existing literature. Most prior studies rely on parametric models that assume constant relationships over time. Such approaches yield average effects but fail to capture how the education–energy nexus shifts in response to changes in policies, technologies, and macroeconomic conditions. To overcome this limitation, we employ both a parametric estimator and a semi-parametric approach, based on Gao et al. (2021) (hereafter GPS), which generates time-varying elasticities. The GPS model is advantageous as it allows us to jointly address endogeneity, heterogeneity, non-stationarity, and cross-sectional dependence. At the same time, the original GPS framework was developed for applications with only two explanatory variables, extending it to accommodate multiple regressors is non-trivial (e.g., Le et al., 2024). In this study, we broaden the scope of the model to include several covariates and apply it to a very long historical panel dataset. This dual strategy not only overcomes the restrictive assumptions of parametric methods but also provides dynamic insights into how the effect of human capital on energy demand has evolved in the long run.

Fifth, our long-run dataset enables us to study nonlinearities that shorter samples may overlook. Each energy transition (i.e., from traditional fuels to coal, from coal to oil, and more recently from fossil fuels to renewables) entailed shifts in both energy consumption and the role of education. Major historical events, such as World Wars, the Great Depression, and the oil crises of the 1970s, also shaped these transitions. Education systems themselves underwent significant transformations, marked by the introduction of compulsory schooling laws, the expansion of mass secondary education, and the rise of tertiary institutions. By analysing these developments within a unified empirical framework, this paper highlights the complex and evolving role of human capital.

Finally, our contribution connects with and extends the conclusions of Yao et al. (2020), which seek to understand how human capital has influenced CO_2 emissions over the past 150 years. These authors investigate the impact of human capital on CO_2 emissions across 20 OECD countries from 1870 to 2014, finding that human capital has contributed to lower CO_2 emissions since the mid-twentieth century. Our findings build on that study by indicating that energy use is a probable pathway through which changes in human capital over time affected CO_2 emissions in the OECD during the period examined.

Our results show that the relationship between human capital and energy consumption in OECD economies is both heterogeneous across education levels and evolves markedly over time. The baseline parametric estimates suggest that broad schooling and primary education have historically contributed to higher energy use, while tertiary education has reduced it; however, these averages obscure the underlying dynamics. The semi-parametric analysis highlights that primary and secondary schooling were central to driving energy-intensive growth in the late nineteenth and early twentieth centuries, when rising literacy supported industrialisation and urbanisation. Their influence weakened in the post-war period as economies shifted toward services and there were marked improvements in energy efficiency (see e.g., Geller et al., 2006). By contrast, tertiary education became increasingly important in later decades, fostering technological innovation, energy efficiency, and environmental awareness. These patterns were shaped by global shocks, such as the oil crises of the 1970s, and long-run transitions, including the rise of knowledge-based economies. These findings demonstrate that the human capital-energy nexus is indeed time-dependent, with advanced education playing a pivotal role in decoupling growth from energy consumption in shaping long-run energy demand.

The rest of the paper is organised as follows. Section 2 outlines the conceptual relationship between human capital and energy consumption. Section 3 presents the model, describes the construction of the historical panel dataset, and reports the preliminary analysis. Section 4 introduces the parametric heterogeneous model and discusses the corresponding results. Section 5 sets out the semi-parametric framework and examines the time-varying estimates. Section 6 concludes with a summary of the key findings and their implications.

2. The theoretical link between human capital and energy consumption

At the macro level, human capital can influence energy use through three primary channels: the income effect, the technology effect, and the degree to which energy and human capital interact as complements or substitutes in production. This section outlines the key conceptual arguments underlying these mechanisms.[1]

2.1. Income impact

[1] The conceptual arguments presented here draw on Churchill et al. (2023), Salim et al. (2017), Yao et al. (2020).

The income effect suggests that human capital raises energy demand by driving economic development. Endogenous growth theory supports the view that human capital fosters long-run growth(Romer, 1990). Historical growth frameworks, including those of Galor and Moav (2002) and Galor and Weil (2000), place human capital at the centre of the shift from Malthusian stagnation to sustained modern growth. Empirical research provides substantial evidence that human capital has been an important driver of economic growth (Mincer, 1984). Madsen and Murtin (2017) find that education was a significant driver of economic growth in the United Kingdom, using time series data from 1270 to 2010. Madsen (2014) finds that human capital contributes positively to productivity, while Madsen (2010) finds that human capital contributes positively to economic growth for panels of OECD countries since 1870. The second element of this mechanism is that stronger economic growth tends to generate greater demand for energy. While the empirical literature has not reached consensus on whether growth drives energy use, energy consumption stimulates growth, or whether the relationship is bi-directional, a number of studies support the view that rising economic activity increases energy demand (see e.g. the review provided in Stern (2019)), consistent with the income effect.

2.2. Technology impact

The effect of technology indicates that human capital reduces energy consumption by encouraging investment in research and development (R&D). As with the income effect, the initial stage involves human capital driving higher economic growth. The subsequent stage, however, is that the gains from growth are channelled into R&D, fostering technological innovation that enhances energy efficiency and ultimately decreases energy use. There is considerable firm-level evidence coherent with the technology effect. Studies suggest that at the micro level better educated managers and firms with better educated workforces are more likely to invest in R&D and that this improves energy efficiency and lowers energy consumption (Arbex & Perobelli, 2010). The macro evidence is more mixed. Both Churchill et al. (2021) and Le et al. (2025) investigate the time-varying role of R&D in shaping energy use across a panel of OECD nations. They find that the relationship is non-linear and that, although there are short periods during which the relationship is negative, for most of the time, the relationship is positive, consistent with rebound and scale effects.

2.3. Complementarity vs. substitutability of energy and human capital

A third pathway by which human capital can shape energy use concerns whether energy and human capital operate as substitutes or complements in production. If they are substitutes (complements), higher levels of human capital reduces (increases) energy consumption, assuming output remains constant. Although the evidence is not conclusive, the connection appears to be time-varying, tending to show complementarity during industrialisation and shifting toward substitution as economies develop and the services sector becomes more prominent. (Arbex & Perobelli, 2010).

2.4. Time-varying relationship between human capital and energy consumption

These conceptual arguments suggest that the relationship between human capital and energy consumption is time-varying, particularly over a 150-year period. We expect that, during the industrialisation phase, the income effect will be dominant and that energy inputs and human capital are complementary, suggesting that higher human capital will lead to higher energy consumption. However, in later stages of economic development, countries will start to invest in R&D, improve energy efficiency, and transition to service economies, consistent with a technology effect, in which human capital will substitute for inputs. The combined effect of these two developments will be that higher human capital will lower energy consumption. Both the technological effect and the transition to a service economy will be reinforced by higher rates of secondary and tertiary enrolments in OECD countries, creating a better educated workforce to facilitate these transitions.

3. Model, data, and preliminary analysis

3.1. Model set-up

To investigate the impact of human capital on energy consumption, the empirical specification closely follows that employed in previous studies (Churchill et al., 2023; Yao et al., 2019, 2020) and is based on variable availability, given the long timespan covered:

$$\ln ECPC_{it} = \alpha + \gamma HC_{it}^{j} + \delta \ln X_{it} + \varepsilon_{it}, \quad (1)$$

where the subscripts i and t represent the country and year, respectively, and the errors are independent and identically distributed. The dependent variable, ECPC, is energy consumption per capita. The main explanatory variable of interest, HC^{j}, is human capital based on average schooling years where j denotes either primary, secondary, tertiary or total human capital. Equation (1) incorporates a range of control variables intended to reduce the risk of omitted variable bias. These controls consist of real GDP per capita (GDP), trade openness (TRADE), expressed as a share of GDP (imports plus exports), government final consumption expenditure, expressed as a share of GDP (GOV), and the inflation rate (INF), expressed as a percentage. Including these control variables in examining energy consumption is essential due to their macroeconomic significance. Trade openness can increase energy consumption as countries engage in energy-intensive industrial activities and global economic integration

(Sadorsky, 2011). Government expenditure, particularly on public services and infrastructure, influences energy demand, as public sector activities are often energy-intensive (Yuxiang & Chen, 2010). Inflation can affect energy prices and alter consumer demand, potentially leading to a decrease in energy consumption when prices rise.

A concern in estimating Equation (1) is that human capital is potentially endogenous. Madsen and Murtin (2017) claim that, in the United Kingdom, human capital was shaped primarily by supply-side influences back to the thirteenth century and, as such, is largely exogenous, but are unable to rule out the possibility that investment in education was influenced by economic growth. This concern applies *a fortiori* to a broader set of high-income countries as in our sample. Hence, one source of endogeneity is potential reverse causation. Energy consumption may influence education outcomes through industrialisation and resource allocation. Omitted variables bias is another source of endogeneity. Omitted factors such as institutional quality or technological progress could drive both education attainment and energy demand, leading to biased estimates. Error with measuring human capital is a third source of endogeneity.

To address endogeneity, we employ an instrumental variable (IV) approach. A challenge with employing a panel over such a long time period is that there are very few valid instruments available. As Madsen (2014, p.685) puts it, "it is extraordinarily difficult to find good instruments for education, particularly since [150] years of data for [10] countries are required". We employ two instruments for human capital, for which data are available over two centuries and which have been used in the extant literature. The first is the lagged value of human capital (HC_{it-1}^{j}) and the second is a compulsory schooling dummy ($Comp.Sch$).

To be valid instruments, each needs to satisfy the relevance and exogeneity conditions. We begin with lagged education attainment. Lagged education attainment is a relevant predictor because it captures the persistence of human capital, which evolves slowly and is correlated with current education attainment (Barro & Lee, 2013).[2] The exogeneity condition is met primarily by controlling for macroeconomic factors in order to reduce the likelihood of correlation with contemporaneous shocks in energy demand. We control for real GDP, real GDP per capita, and government consumption expenditure as a share of GDP to reduce the likelihood of correlation with contemporaneous shocks in energy demand.

[2] For evidence on the high level of persistence in human capital accumulation in the OECD from fractional integration methods over the period 1870 to 2019 see Solarin et al. (2024).

We next turn to the requirements for compulsory schooling laws to be a valid IV, beginning with relevance. In some cases, such as parts of the Hapsburg Empire, enrolment was strictly enforced (Cvrcek & Zajicek, 2013); however, in the nineteenth century this was not always the case in all countries (Masden, 2014). If not strictly enforced, compulsory schooling laws may have had little effect on increasing attendance, violating the relevance condition. Yet, as Madsen (2014, p. 686) states "the change in the compulsory years of schooling is likely to reflect a political will to support education financially and politically". The introduction of compulsory schooling laws encouraged attendance through introducing potential punishments for nonattendance (Cvrcek & Zajicek, 2013; Rauscher 2015). In the United States, if parents did not send their children to school in the 1800s, they could be fined $20 (Rauscher, 2016). In parts of the Habsburg Empire, parents were similarly threatened with monetary fines if their children did not attend school (Cvrcek & Zajicek, 2013). Historical evidence suggests that even if the laws were not strictly enforced, many parents still took the threat of fines seriously. In the nineteenth century, in many poor households child labour was a source of income (Parsons & Goldin, 1989). Rauscher (2014) documents that following the introduction of compulsory schooling laws in some states in the United States in the 1850s that parents complained to the Department of Education that given that they now had to send their children to school or be fined that they would "lose the profit of their labor".

Some earlier empirical research suggests that nineteenth-century compulsory schooling laws did not increase attendance (Edwards, 1978; Landes & Solomon, 1972) or were purely symbolic (Tyack, 1976). However, more recent studies have noted data and methodological limitations with this research and revisited the question using better datasets and more recent developments in econometrics, reaching different conclusions. Using county-level difference-in-differences, Puerta (2010) found that the introduction of compulsory schooling laws in the United States increased school attendance by about 7 per cent over the period 1850 to 1920. Using quantile IV estimation, Clay et al. (2021) show that compulsory attendance laws increased school attendance non-linearly in the United States for native-born white males born between 1885 and 1912. The effects of compulsory school laws on attendance can be expected to be stronger for minority and immigrant children. Rauscher (2014, p. 502) points out that nineteenth century compulsory schooling laws "were geared primarily at lower class children; [hence] estimating only average treatment effects makes null effects more likely". Exploiting heterogeneity in social class, Rauscher (2014) finds that in the United States, compulsory schooling laws had stronger effects on elementary school attendance among lower class and immigrant children between 1852 and 1918.

We next turn to the exogeneity requirement. The compulsory schooling dummy exploits institutional changes in education policy that represent arguably exogenous shifts in education supply. Madsen (2014 p. 686) argues that employing compulsory schooling as an IV has the advantage that "it influences the length of schooling and to a large extent is independent of economic incentives dictated by present value considerations". A possible limitation is that the introduction of compulsory schooling may be correlated with economic progress and, by extension, energy consumption, thereby violating the exclusion restriction. The extent to which demand for education responded to economic development in the nineteenth century is debatable. Cvrcek & Zajicek (2013, p. 216) find that in the Hapsburg Empire, "individual demand for education …. does not seem to have responded very strongly to economic development" and that instead schools "were built ahead of demand". In other regions, though, there is at least casual evidence to suggest that compulsory schooling laws were a response to economic progress (Goldin & Katz, 2008). By controlling for real GDP, real GDP per capita and government consumption expenditure as a share of GDP, we control for economic progress (Madsen, 2014) and seek to mitigate this concern. An advantage of employing compulsory schooling laws as an IV for human capital is that their timing is shaped by political or social considerations, making them plausibly unrelated to short-run fluctuations in energy use.

Compulsory schooling laws have been widely used as instruments in the returns-to-education literature (e.g., Angrist & Krueger, 1991; Harmon et al., 2003). It has been used as an IV in human capital studies employing long time series. Madsen (2014) employs compulsory schooling laws as an IV for human capital in his study of human capital and productivity in a panel of OECD countries since 1870. Churchill et al. (2023) also employ compulsory schooling laws as an instrumental variable for human capital accumulation in their analysis of its impact on energy use in the United Kingdom dating back to the sixteenth century. Other studies examined the reduced form estimates of compulsory schooling laws on various outcomes over long periods. For example, Puerta (2010) investigates the effect of the introduction of compulsory schooling laws on fertility in the United States from 1850 to 1920. Rauscher (2015) examines the effects of the introduction of compulsory schooling laws in the United States on assortative mating over the period 1852 to 1918. Rauscher (2016) examines the impact of the introduction of compulsory schooling laws in the United States on intergenerational occupational mobility using linked census data from 1850 to 1930.

3.2. The historical OECD panel

One of the main innovations in this paper is the use of a historical panel of countries that tracks energy consumption and human capital over the last 150 years, from 1870 to 2020. The sample countries consist of a subset of core OECD nations; namely, Canada, France, Germany, Italy, Netherlands, Portugal, Spain, Sweden, the United Kingdom and the United States Historical data for energy consumption per capita (ECPC) for the period 1870 to 2008 for each of the countries except the United States is obtained from the Joint Centre for History and Economics[3] and is assembled by Kander et al. (2014). ECPC is then updated to 2020 using the Statistical Review of World Energy database (SRWE) from the Energy Institute.[4] Data on energy consumption in the United States from 1870 to 1964 is obtained from the United States Energy Information Administration (EIA) database and updated to 2020 using the SRWE.[5] While ECPC is measured in gigajoules (GJ) in the original source for nine of the ten countries, for the United States it is reported in quadrillion BTUs. We thus converted this into units of G.J.

Fig. 1 illustrates the time series plots for ECPC for each country over a 150-year period, reflecting key historical events and economic transitions. For instance, during the post-World War II period, energy consumption in the United States, Canada, Germany, and Japan surged due to industrial expansion and economic recovery (Smil, 2018). However, the 1970s oil crisis led to notable dips in energy use worldwide, particularly in nations heavily reliant on oil imports, such as Italy and the United Kingdom, which subsequently implemented energy-saving measures. Countries like Sweden and France adapted by increasing reliance on renewable energy and nuclear power, stabilising consumption (IEA, 2020). The 2008 Global Financial Crisis led to another downturn in energy consumption, particularly in the United States, Spain, and Italy, where financial instability and housing market collapses significantly impacted energy demand (Hamilton, 2009). Over time, Germany, the United Kingdom and Japan experienced sustained declines in energy use, driven by de-industrialisation, economic stagnation, and gains in energy efficiency (BP Statistical Review, 2022). Resource-rich nations, such as Canada and the Netherlands, maintained relatively high levels of energy consumption due to their natural resource sectors.

[insert Fig. 1 here]

Human capital (HC), proxied by educational attainment, is obtained from Yao et al. (2020) from 1870 to 2014. HC is constructed using average schooling years via the perpetual inventory

---

[3] Available at https://histecon.fas.harvard.edu/energyhistory/index.html.

[4] Available at https://www.energyinst.org/statistical-review. We also made sure that the data update aligned with the Joint Centre for History data so as there were no abrupt changes and thus updated from 1965 using SRWE. The final constructed panel dataset is available upon request.

[5] Available at https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb1601 and https://www.eia.gov/totalenergy/data/annual/index.php Table 1.3. Note, data for the U.S. between 1870 and 1949 was only available at a five-year interval. Thus, we undertook linear interpolation between these years.

method, based on gross enrolment rates data compiled by Madsen (2014). In addition to total human capital (HC^{TOT}), we also utilise educational attainment at the primary (HC^{PRI}), secondary (HC^{SEC}), and tertiary (HC^{TER}) levels. Given that educational attainment is a slow-moving variable, we interpolated all measures of human capital from 2015 to 2020. Fig. 2 presents the average years of schooling for HC^{TOT}, HC^{PRI}, and HC^{SEC}. Before the mid-1920s, the expansion in overall schooling years was predominantly driven by the widespread adoption of primary education. However, as primary education became nearly universal, the focus shifted towards increasing rates of secondary and tertiary education beginning in the middle of the twentieth century. By the late 1970s, higher education enrollments had risen significantly (Makhlouf & Lalley, 2023), while primary education had somewhat levelled off by the end of the sample.

[insert Fig. 2 here]

The control variables, GDP, TRADE, and GOV are sourced from the Jordà-Schularick-Taylor Macrohistory Database (Jordà et al., 2017), while INF is obtained from Global Financial Data. The data on compulsory schooling, which we use as an IV, were taken from Madsen (2014). Furthermore, all variables are expressed in natural logarithms (except for inflation, which remains in percentage form).

While the use of historical data provides valuable insights over many decades, data quality issues may arise. Inconsistencies in energy reporting can become problematic if countries transition from low levels of industrialisation to advanced energy infrastructures, as observed in the post-1950 period. While it is essential to be aware of data limitations when analysing data over extended periods, this concern is mitigated by the fact that our sample countries represent a core group of highly developed nations with advanced energy reporting, accounting, and management systems established during the first wave of globalisation in the 1870s. As such, data quality problems are likely to be less severe than when less developed countries are included in the panel dataset (Awaworyi Churchill et al., 2023).

As discussed above, there can be errors in measuring human capital over extended periods. Madsen (2014), however, subjects the human capital data to a number of reliability tests, concluding that "educational attainment [back to 1870] is likely to have been measured quite accurately" (Madsen, 2014, p. 682). The use of panel data further mitigates measurement error. The fact that panel data allows comparisons of energy consumption and human capital over time (i.e., test-retest reliability) provides added robustness compared with cross-sectional data (Andreß, 2017). Finally, we address measurement error by treating human capital as endogenous and by instrumenting for educational attainment.

3.3. Preliminary analysis

Table A1 in Appendix A presents the summary statistics for the variables. Energy consumption per capita (ECPC) averages 117.7 gigajoules, with wide dispersion across countries, reflecting heterogeneous energy intensity and development levels. Educational attainment is dominated by primary schooling (mean of 6.3 years), while secondary and tertiary attainment remain limited, with means of 1.3 and 0.4 years, respectively. Regarding the macroeconomic indicators, Real GDP per capita (RGDP) averages 39.4 (2005=100), ranging from 5.9 to 122.7, while trade openness (TRADE) spans from 4 to 140 percent of GDP, indicating diverse levels of global integration. Government expenditure (GOV) averages 17.5 percent of GDP, though the maximum exceeds 100 percent in some cases. Inflation (INF) exhibits volatility, underscoring macroeconomic instability in parts of the sample.

Table A2 in Appendix A shows the results of the slope homogeneity test. Following Blomquist and Westerlund (2013), the null hypothesis is that the slope coefficients are homogeneous across countries, while the alternative hypothesis assumes heterogeneity. Both the standard slope homogeneity test statistic (Δ) and its bias-adjusted version (Δ Adjusted) are highly significant at the 1 percent level, providing strong evidence consistent with the alternative hypothesis. These results confirm the presence of country-specific heterogeneity in the data, implying that pooled estimators that impose slope homogeneity may be inappropriate.

Table A3 in Appendix A presents the results of the cross-sectional dependence (CD) test and the panel CADF unit root test. Panel A shows that the null hypothesis of cross-sectional independence is strongly rejected for all variables, with CD statistics highly significant at the 1 percent level. The large absolute correlation coefficients, many of which are above 0.8, confirm the presence of strong cross-sectional dependence across countries. Panel B reports the CADF unit root test results. At levels, only INF and, to a lesser extent, ECPC and GDP, appear stationary. The majority of variables, including HC^{TOT}, HC^{PRI}, HC^{SEC}, HC^{TER}, TRADE, and GOV, are non-stationary in levels. However, all variables become stationary after first differencing, indicating that they are integrated of order one, I(1). Importantly, none of the variables is integrated of order two, I(2), which enables the use of cointegration techniques in the subsequent analysis.

Given the presence of cross-sectional dependence and the confirmation that the variables are predominantly I(1), the next step is to examine whether a long-run equilibrium relationship exists among them. Results for the Westerlund (2007) error-correction based panel cointegration test are reported in Table A4 in Appendix A. The null hypothesis is that there is no cointegration across the panel. The group-mean test (Gt) and the panel test (Pt) are statistically significant at the 5 percent level in both the asymptotic and bootstrapped versions. By contrast, the group-mean test, based on levels (Ga), and the panel test based on levels (Pa) are not significant. Since the Gt and Pt statistics are generally regarded as the most reliable in panels of moderate size, the evidence supports rejection of the null hypothesis of no cointegration. This indicates the presence of a long-run equilibrium relationship among the variables.

4. Parametric analysis

4.1. Dynamic heterogeneous IV estimates

Building on the preliminary results, we next estimate Eq. (1) using a dynamic heterogeneous panel framework that allows the short- and long-run responses of energy consumption to vary across countries. This specification includes a lagged dependent variable, thereby capturing persistence in energy use and permitting country-specific adjustment dynamics. To address potential endogeneity in human capital, we instrument education using its lagged values – which reflect its strong temporal persistence – and a compulsory schooling variable, which captures exogenous, policy-driven changes in educational attainment. This instrument set leverages both historical inertia and institutional reforms, strengthening identification of the causal effect of human capital on energy use. By combining a dynamic mean-group structure with an IV strategy, the estimator provides country-level flexibility while yielding unbiased average effects of human capital on energy consumption.

[insert Table 1 here]

Table 1 presents the dynamic heterogeneous IV estimates. The coefficients on HC vary across education levels and their magnitudes are economically meaningful. In the HC^{TOT} and HC^{PRI} models (columns (1) and (2)), human capital is positive (0.074 and 0.220, respectively) and significant at the 5 and 1 percent levels, respectively, suggesting that broad educational attainment, particularly primary schooling, is associated with higher energy consumption per capita. Quantitatively, an additional year of total schooling is associated with a 7 percent increase in ECPC, while an extra year of primary schooling is associated with a 22 percent increase. These effects are consistent with the historical experience of OECD economies, where the expansion of basic schooling during the late nineteenth and early twentieth centuries supported industrialisation and urbanisation. Primary education raised literacy rates and expanded the labour force, enabling more people to participate in energy-intensive production and urban economic activities that relied heavily on coal and later oil. The coefficient on HC^{SEC} is also positive but smaller in magnitude (0.015), suggesting that an additional year of secondary education increases ECPC by about 1.5 percent. Secondary education expanded most rapidly in the mid-twentieth century and complemented industrial development and the growth of the service sector. While this stage of education reinforced energy demand by supporting skilled labour and consumption growth, its incremental effect on energy consumption was more modest, as the foundation of energy-intensive industrialisation had already been laid. In contrast, HC^{TER} is negative (-0.093) and statistically significant at the 1 percent level, indicating that tertiary education reduces energy demand. An additional year of tertiary education reduces ECPC by about 9 percent. From the post-war period onward, OECD economies increasingly transitioned toward knowledge-based growth, technological progress, and tighter environmental regulation. Tertiary education is widely recognised in the literature as a key input into innovation and the diffusion of energy-efficient and cleaner production technologies, while also shaping preferences toward environmental sustainability (Nowotny et al., 2018). Although the present analysis does not directly observe innovation or energy-efficiency improvements, the negative association between higher education and energy consumption documented in this study is consistent with these well-established channels. In this sense, tertiary education may contribute to lower energy use even as income levels rise

When all three education levels are included simultaneously (column 5), the signs remain consistent – HC^{PRI} and HC^{SEC} continue to increase energy use, whereas HC^{TER} continues to reduce it, though the coefficients are somewhat attenuated, reflecting overlap between the schooling stages. The persistence of these relationships in the joint model strengthens the interpretation that education influences energy demand through complementary but distinct channels: foundational and intermediate education levels expand economic activity and energy consumption, while advanced education fosters technological progress and efficiency improvements that curb overall energy use. This pattern underscores the dynamic role of human capital accumulation in the long-run transition from industrial to knowledge-driven energy systems.

These results using a parametric framework complement those of Yao et al. (2019), who analysed the impact of secondary and tertiary education on energy use across a wider group of OECD countries during 1965–2014. They found that tertiary education reduced energy consumption while secondary education had no significant effect. These findings closely align with our results, which show that tertiary attainment lowers energy demand, whereas the impact of secondary education is small and positive. The similarity between our study, which spans a long historical period from 1870 to 2020, and Yao et al. (2019), which covers a more recent period, suggests that the role of advanced education in promoting energy efficiency has been persistent over time. While the expansion of primary and secondary education initially contributed to energy-intensive industrialisation in the early phases of OECD development, the growth of tertiary education in the second half of the twentieth century reinforced a shift toward knowledge-based economies where efficiency and sustainability play a greater role.

The adjustment parameter (ECPC$_{t-1}$) is negative and significant across all specifications, suggesting a mean-reverting process in energy use. GDP is strongly positive in all models, confirming the scale effect of economic growth on energy use across the historical period. TRADE is generally insignificant, except in the tertiary model, where it becomes positive, suggesting that openness reinforces energy demand in more advanced economies with higher integration into global markets. GOV has mixed signs. In the primary model, it is positive, reflecting the role of public investment in infrastructure and services that raised energy demand during industrialisation. In the other specifications, it is negative, indicating that government spending has more often enabled higher efficiency and social services rather than expanding energy-intensive activities. INF is consistently positive but small in magnitude, indicating only a marginal influence on energy use over the long run.

4.2. Addressing reverse causality

A potential concern in long-run panel data is that the relationship between human capital and energy consumption may be bi-directional. While our identification strategy already employs lagged educational attainment and compulsory schooling laws as instruments, reverse causation may still arise if changes in energy demand influence educational investment or the political economy of schooling. To address this issue, we formally examine the causal direction between human capital and energy consumption using heterogeneous weak-exogeneity tests that explicitly accommodate nonstationarity, cross-sectional dependence, and country-specific dynamics.

Given the strong evidence of cointegration (Section 3.3), we estimate country-specific error–correction equations augmented with cross-sectional averages following the DCCE approach (see Chudik and Pesaran, 2015 and Appendix B for details):

$$\Delta \ln ECPC_{it} = \phi_i(\ln ECPC_{it-1} - \gamma_i HC_{it-1} - \delta_i Z_{it-1} + \sum_{k=1}^{p} \beta_{ik} \Delta HC_{it-k} + \lambda_i \bar{X}_t + \varepsilon_{it}, \quad (2)$$

$$\Delta HC_{it} = \psi_i(HC_{it-1} - \eta_i \ln ECPC_{it-1} - \xi_i Z_{it-1}) + \sum_{k=1}^{p} \alpha_{ik} \Delta \ln ECPC_{it-k} + \mu_i \bar{X}_t + v_{it}, \quad (3)$$

where Z_{it} contains the control variables (GDP, TRADE, GOV, INF). Human capital Granger-causes energy consumption if we reject the null $H_0: \beta_{i1} = \beta_{i2} = \cdots = 0$, and analogously for the reverse direction using the coefficients α_{i1}. Country-level statistics are combined using mean-group panel tests, producing $W^{HC \rightarrow ECPC}$ and $W^{ECPC \rightarrow HC}$ statistics.

The results reported in Table 2 present compelling evidence on the direction of causality between human capital and energy consumption. Across all specifications, the panel statistics and the proportion of countries rejecting the null hypothesis consistently point to a dominant causal flow from human capital accumulation to energy use.

Three patterns are particularly noteworthy. First, HC is found to be a strong predictor of ECPC: the null of weak exogeneity is rejected at the 1% level across all educational categories, and between 60–90% of countries show significant causality from education to energy use. Second, there is little evidence supporting the reverse causal relationship. The panel statistics for ECPC Grager-causing HC are uniformly insignificant (p > 0.25), and only one or two countries exhibit such reverse causality, typically in historical episodes such as wartime disruptions or early industrialisation. Third, the null $HC^{TER} \rightarrow ECPC$ is rejected at the 1% level in 9 of 10 countries, whereas $ECPC \rightarrow HC^{TER}$ is never rejected.

[insert Table 2 here]

Collectively, these results indicate that the dominant long-run causal flow runs from educational accumulation to energy demand, not vice versa.

4.3. Robustness check on IV validity

A further concern is that the relationship between human capital and energy consumption may be driven by common secular trends rather than a structural link. To address this issue, we conduct a comprehensive set of robustness checks assessing instrument relevance, exogeneity, and sensitivity to long-run trends.

Standard IV diagnostics. Conventional diagnostics for the level specifications are reported in Table C1 in Appendix C. Lagged educational attainment and compulsory schooling reforms are strong instruments, and Wu–Hausman tests confirm that schooling should be treated as endogenous. At the same time, Sargan over-identification tests reject strict exogeneity in levels. In long-run macro panels, however, such rejections are common when variables share strong upward trends or are exposed to persistent common shocks. These results motivate additional checks rather than constituting definitive evidence of instrument invalidity.

Detrending and updated diagnostics. To isolate short-run variation from long-run co-movement, we construct a detrended measure of human capital by removing country-specific linear time trends. For each country i, human capital is detrended by estimating $HC_{it} = \alpha_i +$

$\kappa_i t + r_{it}$ and setting $\widetilde{HC}_{it} = r_{it}$. We then re-estimate the dynamic IV specification using $\widetilde{HC}_{it}$ as the endogenous regressor, instrumented by its own lag and compulsory-schooling reforms.

The diagnostic results, reported in Table 3, provide strong support for the IV specification. Instrument relevance remains extremely strong, with a joint first-stage F statistic exceeding 105. In contrast to the level specification, the Wu–Hausman test no longer rejects exogeneity, and both the Sargan over-identification test and the residual orthogonality test of Madsen (2014) fail to reject the exclusion restriction. The estimated coefficient on detrended human capital is small and statistically insignificant, indicating that short-run deviations in educational attainment do not independently affect per capita energy consumption once long-run trends are removed.

[insert Table 3 here]

Taken together, these robustness checks indicate that the IV results are not driven by reverse causality, shared secular trends, or instrument invalidity. The positive association between human capital and energy consumption observed in the level specifications reflects long-run co-movement during development, while detrended human capital does not exert a detectable short-run effect. Appendix C provides additional technical details and complementary identification-robust analyses.

5. The semi-parametric method

The parametric results in the previous section illustrate the effect of human capital in shaping energy demand across OECD economies, yet they are derived from a parametric framework that imposes constant coefficients over time. To capture potential shifts in the education–energy relationship, we proceed to the primary empirical analysis by outlining and implementing the semi-parametric model introduced by GPS, which is specifically designed to address endogeneity, heterogeneity, non-stationarity, and cross-sectional dependence in panel settings. This framework enables us to recover time-varying elasticities for the effect of human capital on energy consumption while accommodating these econometric challenges. In what follows, we present the structural specification, the kernel-weighted local estimator, and the generalisation of the model to multiple regressors, drawing on GPS, its recent extension by Le et al. (2024), and Ivanovski et al. (2025). All regularity conditions, identification assumptions, and convergence properties supporting the estimator are detailed in Appendix D.

Structural system and reduced form. Let $y_{it} = \ln(ECPC_{it})$ and $x_{it} = (HC_{it}, X_{it})'$ denote the human capital variable and control variables, respectively. The time-varying coefficient structural model is

$$y_{it} = x_{it}'\beta_0(\tau_t) + \lambda_i'f_t + u_{it}, \;\; \tau_t = t/T \tag{4}$$

where $\beta_0(\tau_t)$ is smooth in $\tau \in [0,1], \lambda_i$ captures heterogeneous factor loadings, and f_t are unobserved common factors.

Since some components of x_{it} (especially human capital) may be endogenous, we follow GPS and introduce instruments z_{it} consisting of lagged human capital (HC_{it-1}) and the compulsory schooling ($Comp.Sch$) dummy. Endogeneity is handled through the auxiliary equations

$$x_{1,it} = x_{2,it}'\delta_0(\tau_t) + \theta_{1,i}'f_t + \varepsilon_{1,it}, \tag{5}$$

$$x_{2,it} = \Gamma_0(\tau_t)z_{it} + \theta_{2,i}'f_t + \varepsilon_{2,it}, \tag{6}$$

Where $(x_{1,it}, x_{2,it})$ partition the endogenous variables and remaining regressors. Stacking (5)–(6) yields the reduced form

$$x_{it} = \mathrm{B}_0(\tau_t)z_{it} + \Theta_i f_t + \varepsilon_{it}, \tag{7}$$

which generalises naturally to high-dimensional x_{it} as shown in Le et al. (2024).

Kernel-weighted Local Estimation. To estimate $\beta_0(\tau)$ at each $\tau = \tau_t$, we use the local-constant kernel estimator. Define the weights

$$K_h(\tau_s - \tau_t) = \frac{1}{h}K\left(\frac{\tau_s - \tau_t}{h}\right),$$

where $K(\cdot)$ is a symmetric second-order kernel (we employ the Epanechnikov kernel) and $h = h_T$ is a bandwidth satisfying $h \to 0$ and $Th \to \infty$.

Let $\hat{f}_t$ be the estimated common factors obtained via locally weighted principal components as in GPS. The local estimator solves

$$\left(\beta(\tau_t), \{\hat{\lambda}_i(\tau_t)\}\right) = \arg\min_{\beta,\{\lambda_i\}} \sum_{i=1}^{N}\sum_{s=1}^{T} K_h(\tau_s - \tau_t)(y_{is} - x_{is}'\beta - \lambda_i'\hat{f}_s)^2 \tag{8}$$

Instrumental-variable adjustment enters by replacing x_{it} with its locally weighted fitted value:

$$\hat{x}_{it}^{IV}(\tau_t) = \widehat{\mathrm{B}}(\tau_t)z_{it}. \tag{9}$$

Substituting (9) into (8) yields the IV-GPS estimator:

$$\hat{\beta}^{IV}(\tau_t) = \left(\sum_{i,s} K_h(\tau_s - \tau_t)\,\hat{x}_{is}^{IV}\hat{x}_{is}^{IV\,\prime}\right)^{-1}\left(\sum_{i,s} K_h(\tau_s - \tau_t)\hat{x}_{is}^{IV}y_{is}\right). \tag{10}$$

This estimator produces a smooth coefficient curve $\tau \to \hat{\beta}^{IV}(\tau_t)$ for each human capital measure and each control variable. Confidence bands are constructed via a block bootstrap as in GPS.

Extension to multiple regressors. The original GPS system accommodates two regressors. We adopt the generalisation in Le et al. (2024), which extends (5)–(6) and (7) to the full vector:

$$x_{it} = (HC_{it}, GDP_{it}, TRADE_{it}, GOV_{it}, INF_{it})'.$$

Estimation then proceeds by replacing the scalar/two-dimensional expressions above with their multivariate analogues in (7)–(10). All regularity, identification, and convergence conditions required for consistency and asymptotic normality of $\hat{\beta}^{IV}(\tau)$ are stated in Appendix D.

5.1. The time-varying human capital and energy consumption results

5.1.1. Total education and energy consumption

The semi-parametric estimates for the effect of HC^{TOT} on ECPC are reported in Fig. 3a. The right panel reports the time-varying results where the solid blue line represents the time-varying coefficient while the dashed lines denote the upper and lower bound 95% confidence intervals. The right panel shows the elasticity of HC^{TOT}. The estimated coefficients for HC^{TOT} show a positive, time-varying impact on ECPC, with values ranging from 0.2 to 0.7 over the sample period. The effect was also statistically significant from 1888 to 2020, as evidenced by the error bands not crossing the zero line. While the time-varying estimates exhibit trending behaviour, the magnitudes of these coefficients also vary over time. For instance, a moderate rise occurred from 1870 to 1934, with coefficients ranging from 0.2 to 0.45. Immediately following this period, an increase occurred, with coefficients ranging from 0.4 to 0.7 between 1935 and 1955, followed by a subsequent decline from 1956 to 1975. Another rise in the time-varying coefficients was observed from 1976, with a peak in 1990, and this gradually declined until the end of the sample period.

[insert Fig. 3a here]

The fluctuations in the magnitude of the coefficients for the impact of HC^{TOT} on ECPC can be attributed to country- and global-level factors across the decades, beginning with the Industrial Revolution and the late nineteenth-century electrification. Energy consumption during this period was dominated by coal, steam power, and the early stages of electrification in countries such as the United States and the United Kingdom. While educational attainment remained relatively limited by modern standards, the gradual rise in HC^{TOT} coincided with broader processes of industrialisation, capital deepening, and technological diffusion. Rather than acting as a direct driver of energy demand, expanding education during this era likely complemented these structural changes by supporting the adoption and operation of energy-intensive production technologies (Smil, 2018). In this context, rising energy consumption primarily reflects industrial activity, with education evolving alongside these transformations. Estimates of HC^{TOT} during the early twentieth century (1900-1930s) indicate a period of stability, possibly reflecting technological advancements made during and after World War I. Energy consumption began to increase as the electricity and automotive industries expanded, particularly in the United States and Western Europe (Broadberry & O'Rourke, 2010). The stable positive relationship between HC^{TOT} and ECPC could reflect the growing need for a more educated workforce to manage increasingly complex technologies and industries. For example, countries in Western Europe, such as France and Germany, implemented educational reforms in this period, expanding access to education. These educational reforms contributed to a more skilled labor force capable of driving energy-intensive industrial growth, particularly in the manufacturing sector (Cohen, 1998).

The large surge in HC^{TOT} during the 1950s coincided with post-World War II reconstruction in Europe, driven by initiatives such as the Marshall Plan and a broader economic boom (Broadberry & O'Rourke, 2010). Education systems expanded rapidly, particularly in Western European countries such as Germany, Italy, and France, with the aim of replenishing the human capital lost during the war (Schofer & Meyer, 2005). This likely magnified the impact of educational attainment on energy use, as these nations underwent modernisation and industrialisation during the “Golden Age”. The era was also marked by technological innovations, with household appliances becoming widespread, automobile ownership rising, and oil and natural gas infrastructure expanding, amid an increasingly educated population.

The energy crises of the 1970s led to sharp volatility, as energy prices surged suddenly due to supply disruptions (Yergin, 2012). While human capital was still driving energy-intensive industrial growth leading up to these crises, the subsequent drop in the trend likely reflects the early decoupling of human capital from energy use as countries shifted focus toward energy efficiency and alternative sources (Stern, 2011). By the 1980s, the rise of environmental consciousness further shaped the trajectory. Western European nations, alongside Canada and the United States, have begun investing heavily in renewable energy and energy-efficient technologies, and have adopted cleaner energy policies, resulting in a decline in the trend (Belaïd et al., 2023). Educational attainment contributed to the promotion of these energy-efficient practices. Better educated electorate placed pressure on governments to address climate change and politicians responded accordingly (Nowotny et al, 2018)

From the 2000s onward, educational attainment began to fuel growth in the information technology and knowledge-based sectors, which are less energy-intensive than manufacturing industries. This may explain the lower, more stable relationship between HC^{TOT} and energy consumption in this period. The decline in HC^{TOT} toward the end of the sample (post-2000s) likely reflects the continued emphasis on energy efficiency, the rise of renewable energy, and the reduced need for energy consumption in an increasingly digital and service-based economy.

The points at which the confidence intervals suddenly widen or narrow in Fig. 3a may indicate a sudden severance (or reconnection) of the relationship between HC^{TOT} and ECPC. In Fig. 3a, the confidence intervals around the time-varying relationship between HC^{TOT} and ECPC were relatively tight at the beginning of the twentieth century, but widened considerably in the period following each of the World Wars and again at the end of the twentieth century, indicating that the estimates in these periods are more uncertain.

Global shocks generate uncertainty and associated imprecision in estimates (Bloom, 2009; Jurado et al., 2015). In particular, global shocks can lead to sudden changes in output and, consequently, in energy consumption (Ahir et al. 2022). It is likely that the imprecision in the estimates following World War II is related to the massive investment in education that led to the expansion of secondary and higher education, the introduction of new curricula focused on civic education and STEM, and policies like the Butler Act in the UK and the GI Bill in the US that increased access to education for millions. The imprecision in estimates at the end of the twentieth century is related to the global shock associated with the ICT revolution (Jorgenson & Vu, 2016) and the shift to the knowledge-based sector. Both World Wars (see, e.g., Goldin, 1994; Topel, 1999) and the ICT revolution (see, e.g., Lane & Saint-Martin, 2021; Reshef & Toubal, 2024) created considerable uncertainty about labour market restructuring, with spillover effects on investment in human capital and energy consumption.

Fig. 3b displays the time-varying estimates for the control variables and reveals distinct trends in the estimated coefficients. The time-varying impact of GDP on ECPC is positive and statistically significant across the entire sample period. From the late nineteenth to the early twentieth centuries, the positive relationship between GDP and energy use steadily grew, reflecting the rise of industrial production and urbanisation across Europe and North America. However, the early 1920s marked a decline in this relationship, coinciding with the onset of the Great Depression, which triggered a severe contraction in economic activity and, by extension, energy demand (Temin, 1991). GDP during World War II (and in the immediate years following) exhibits a sharp rise, reflecting wartime efforts and increased energy consumption. The oil crises of the 1970s introduced notable volatility as the sharp rise in energy prices disrupted global markets and constrained energy consumption (Yergin, 2012). In the decades that followed, the relationship between GDP and energy consumption began to stabilize, reflecting a shift toward service-oriented economies and advances in energy efficiency.

The influence of TRADE on ECPC shows two distinct periods of trending behaviour. From 1870 until the onset of World War II, TRADE was positive and mostly statistically significant. This period roughly corresponds to the first wave of globalisation, during which technological advancements in transportation and communication facilitated greater international trade (Findlay & O'Rourke, 2009). This growing interconnectedness has inevitably increased energy demand, particularly in trade-dependent sectors such as shipping and manufacturing. However, a sharp dip is observed from 1940 to 1960, closely linked to the protectionist backlash of the period, which curtailed global trade flows (Feenstra, 1998) and, consequently, energy consumption. The effect of TRADE on ECPC remained negative until 1970, was indistinguishable from zero until the early 1990s, and then began to increase again toward the end of the sample period. Indirectly, the resurgence in the effect of trade on energy use can be attributed to the establishment of global institutions, such as the GATT and later the WTO, which fostered liberalisation and economic growth, particularly through expanded international supply chains and trade networks (Krugman, 1992). Toward the end of the twentieth century, the relatively smaller effect of trade on energy use may reflect improvements in energy efficiency, particularly in transportation, and a transition toward less energy-intensive economic activities in advanced economies (Giraudet & Missemer, 2023).

The time-varying effect of GOV on ECPC illustrates distinct fluctuations over the sample period driven by historical events and shifts in economic policy. From 1870 to 1924, the time-varying coefficients remain stable at roughly 0.22. However, from 1925 until 1950, government spending increased energy use to a peak coefficient estimate of 0.5 in 1947-48, which can be attributed to military and industrial buildup in the period leading up to, during, and in the immediate aftermath of World War II. From 1950 to the early 1990s, the time-varying effect of GOV on ECPC gradually declined, with the rate of decline increasing during the oil crises of the 1970s and briefly becoming negative.[6] Nevertheless, since the mid-1990s, the time-varying effect of GOV on ECPC has increased. This increase reflects the shift toward service

[6] Skyrocketing oil prices during the 1970s forced governments to re-evaluate their energy policies and reduce reliance on fossil fuels. Energy consumption growth slowed, and energy-saving measures became a focus in many advanced economies. Also, fiscal policies became more conservative in the face of rising inflation and stagnant growth, weakening the link between government spending and energy consumption.

economies, the privatisation of energy-intensive industries, and, in recent years, investments in infrastructure and green energy initiatives (IEA, 2020).

The effect of INF on ECPC in the last three decades of the nineteenth century is positive and the time-varying coefficients are relatively stable. However, over the first half of the twentieth century, the effect turns negative, reflecting the economic disruptions of the World Wars and the Great Depression, during which deflationary pressures and reduced industrial output led to a decline in energy consumption (Feinstein et al., 1997). After 1950, the sharp positive shift corresponds to the post-World War II economic boom, characterized by rapid industrial growth and rising consumer demand, which drove both inflation and energy consumption. From 1960 to 2020, the relationship between INF and ECPC fluctuates but remains positive, reflecting inflationary pressures during the oil crises of the 1970s and more stable inflation after the 1980s, due to central banks' inflation-targeting policies. However, energy consumption remained sensitive to price fluctuations and technological changes (Bernanke & Mishkin, 1997).

[insert Fig. 3b here]

5.1.2. Primary education and energy consumption

The time-varying coefficients of HC^{PRI} on ECPC are reported in Fig. 4 and reveal a consistently positive association across the sample period. In the period before 1935, the coefficients were moderately positive, reflecting the growing role of primary education in supporting industrialisation. As literacy rates rose and basic schooling became more widespread, workers became better equipped to engage with energy-dependent industries, boosting energy consumption. During this time, economies underwent rapid industrialisation, and energy-intensive sectors, such as mining, steel production, and transportation, required a more educated workforce. Primary education provided the foundational skills necessary for workers to participate in these growing sectors, contributing to increased energy demand.

A significant rise in HC^{PRI} occurred from 1935 to 1955, with a pronounced peak around 1955. This period encompasses the buildup to World War II, World War II itself and the subsequent post-war economic boom, during which many advanced economies experienced rapid industrial expansion and reconstruction phases (Eichengreen, 1996). Human capital, in the form of education, became increasingly important in supporting these energy-intensive processes. The expansion of public education systems during this period also played a pivotal role in sustaining industrial growth, as a more educated workforce was essential for rebuilding economies ravaged by the war (Lindert, 2004). Additionally, post-war reconstruction policies, such as the Marshall Plan, were instrumental in revitalising manufacturing, urbanisation, and infrastructure development (Scott, 1992), all of which required substantial energy inputs.

However, after 1955, there is a decline in the HC^{PRI} coefficients, which lasts approximately two decades until 1977. This period coincides with key events such as the global energy crisis of the 1970s. The sharp rise in energy prices, combined with efforts to improve energy efficiency and reduce reliance on energy-intensive industries, likely moderated the impact of human capital on energy consumption during this period. As many advanced economies began transitioning from manufacturing-based to service-oriented economies, which are typically less energy-intensive, the role of primary education in driving energy consumption declined. This decline suggests that improvements in education facilitated structural economic changes, reducing the direct link between education and energy demand.

A second increase in the time-varying HC^{PRI} coefficients occurs from 1980 to 1995, linked to the growing importance of education as countries adapted to new energy-dependent technologies in transportation, communications, and computing. However, from 1995 until 2020, the time-varying coefficients declined, indicating, once again, a reduced link between HC^{PRI} and ECPC. This period coincides with increasing global effort directed toward sustainability and the widespread adoption of energy-saving technologies, particularly in advanced economies. Although human capital continued to play a role in energy consumption, the shift towards energy-efficient practices, renewable energy sources, and decarbonization efforts weakened the direct relationship between primary education and energy use (Fouquet, 2011). This decline also reflects the changing role of education in modern economies, as higher education and specialised skills have become more critical in driving innovation and technological progress, while primary education plays a diminishing role in this context.

In Fig. 4, the confidence intervals around the time-varying relationship between HC^{PRI} and ECPC generally exhibit patterns similar to those in Figure 3a – i.e., they were relatively tight at the beginning of the twentieth century but widened considerably following World War I and again after World War II. However, in contrast to the time-varying relationship between HC^{TOT} and ECPC, the confidence intervals tighten in 1980, but have been wider since 1980. A possible explanation is that near-universal primary education and the shift to energy-efficient practices, renewable energy sources, and decarbonization efforts have weakened the relationship between HC^{PRI} and ECPC and made the estimates more imprecise. This is consistent with the downward trend in HC^{PRI} since the 1990s and shift in focus to higher education.

[insert Fig. 4 here]

5.1.3. Secondary education and energy consumption

The time-varying coefficients of HC^{SEC} on ECPC are reported in Fig. 5. The confidence intervals around HC^{SEC} and ECPC are wide until the beginning of the twentieth century, but have been relatively tight over the remaining period. For roughly the first 50 years studied (1870–1918), secondary education exhibited a negative relationship with energy consumption per capita. This era corresponds to the latter stages of the Industrial Revolution, particularly in the countries in our sample. During this period, much of industrial production remained labour-intensive, relying on primary education and manual labor, and not yet requiring the higher-level cognitive skills associated with secondary education. Education played a limited role in driving energy consumption during this period, while other factors, such as mechanisation and the diffusion of steam power, were more dominant.

From 1919 to the early 1960s, the relationship between HC^{SEC} and ECPC shifted positively, reaching its peak during the post-World War II industrial boom. This shift reflects the growing importance of secondary education as countries transitioned toward more capital-intensive industries that require skilled labour. The expansion of secondary schooling in the twentieth century provided the technical expertise necessary for mechanised production and electrification, both of which drove substantial increases in energy consumption (Goldin & Katz, 2018). The peak in the early 1960s coincided with a period of rapid urbanisation and mass production, particularly in Western economies, where energy-intensive industries were prominent. The rising number of educated workers with secondary-level skills, such as engineering and technical expertise, may have contributed to the energy demand associated with these processes. However, after the 1960s, the relationship between HC^{SEC} and ECPC began to weaken, although it remained positive until 1977. This decline can be attributed to several factors, including the shift toward less energy-intensive sectors, particularly after the oil crises of the 1970s. As economies diversified and technological innovations reduced energy consumption, the link between education and energy demand weakened.

A final rise in the time-varying coefficients of HC^{SEC} is observed from the 1980s to the early 1990s, reflecting the impact of the information technology revolution and the globalisation of economies. Secondary education played a pivotal role in equipping the workforce with the skills necessary for emerging industries, such as telecommunications and computing, which, although not as energy intensive as traditional manufacturing, still contributed to higher energy consumption. After the early 1990s, the time-varying coefficients of HC^{SEC} declined, coinciding with a period characterised by substantial improvements in energy efficiency and technological progress that contributed to a decoupling of energy consumption from economic growth. During this phase, tertiary education and specialised skills appear to be more strongly associated with energy demand than secondary education, consistent with evidence that advanced human capital becomes increasingly relevant in knowledge-based economies (Yao et al., 2019).

[insert Fig. 5 here]

5.1.4. Tertiary education and energy consumption

The time-varying coefficient of HC^{TER} on ECPC is illustrated in Fig. 6 and reveals several important shifts over time. Between 1870 and 1934, the coefficient was negative, indicating that higher levels of tertiary education were associated with lower energy consumption. This may be linked to the fact that, during the late nineteenth and early twentieth centuries, industrialisation in developed economies was dominated by manual labor and energy-intensive processes. As tertiary education expanded during this period, it likely drove more efficient labor practices, promoting less energy-intensive industries, particularly in the services sector (Smil, 2018). A significant change occurs between 1935 and 1960, when the relationship between HC^{TER} and ECPC becomes positive. This period encompasses the aftermath of the Great Depression, World War II, and post-war reconstruction efforts in major economies. Industrial growth surged as economies rebuilt and modernised, heavily relying on energy consumption for manufacturing and infrastructure development (Crafts, 2000). The expansion of tertiary education during this period likely contributed to higher energy consumption as economies experienced rapid economic growth and urbanisation (Maddison, 2007).

From 1961 to 1985, the coefficients of HC^{TER} becomes negative again. This period reflects a shift toward more energy-efficient technologies and a global emphasis on reducing energy dependence following the 1970s oil shocks (Yergin, 2012). Structural changes in advanced economies led many to shift from manufacturing to services and technology-based sectors, which are less energy-intensive. Tertiary education likely played a role in this transition by fostering the development of knowledge-based industries.

From 1985 to 2020, the relationship fluctuated, reflecting the varying global economic conditions and technological advancements. While there were periods of growth in energy demand due to globalisation and industrial expansion in some countries, particularly in the 1990s, the recent period from 2010 to 2020 saw the relationship turn negative again. This trend aligns with the growing influence of sustainability, renewable energy, and energy efficiency efforts, particularly in advanced economies.

The estimated coefficient interval for the time-varying effect of HC^{TER} jumps significantly after World War I, reaching a peak around World War II. It then tightens until around 2010 and then gradually widens again. This suggests that HC^{TER} was relatively imprecisely estimated between the World Wars, when higher education enrolments in OECD countries were lower and primary and secondary education were more important drivers of energy consumption; however, following World War II, there was a stronger connection between HC^{TER} and ECPC. Not too much can be read into the widening of the confidence intervals after 2010, as this is likely an end-of-sample effect characteristic of semi-parametric modelling.

[insert Fig. 6 here]

6. Conclusion

This paper examines the relationship between human capital and energy consumption in OECD economies over the period 1870–2020, utilising a newly constructed historical dataset. The analysis combined a baseline parametric model with a semi-parametric time-varying approach to capture both average long-run effects and evolving dynamics across different stages of development. Our core results from the semi-parametric methods reveal a time-varying relationship between human capital and energy consumption in the panel, consistent with earlier evidence based on shorter samples and parametric approaches (Akram et al., 2019; Salim et al., 2017; Yao et al., 2019) and from single country analysis (the United Kingdom) using a time-varying framework (Churchill et al., 2023).

Overall, we find that human capital has largely contributed to higher levels of energy consumption. This might be explained in terms of the income effect being dominant, particularly in the nineteenth and the first half of the twentieth centuries. In the late twentieth century and after 2000, it is possible that the technology effect was cancelled out by rebound and scale effects in high-income countries, offsetting the benefits of investment in R&D to improve energy efficiency. This aligns with the findings on R&D and energy use documented by Churchill et al (2019) and Le et al. (2025).

The relationship between human capital and energy consumption is more nuanced, though, when it comes to distinguishing between levels of education. We find that primary and secondary education were historically linked with higher energy use, reflecting their role in supporting industrialisation and expansion of energy-intensive sectors, consistent with the income effect. However, tertiary education was more often associated with reductions in energy consumption, particularly in later decades, consistent with a technology effect and with human capital substituting for energy inputs in production as service economies emerged. The semi-parametric results reinforce and extend this picture by revealing how the education–energy nexus has shifted over time. Primary education was most influential during the first wave of industrialisation, secondary schooling during the mid-twentieth century expansion of mass production and services, and tertiary education in the post-war period, when knowledge-based growth and energy efficiency became increasingly important. These findings suggest that the contribution of education to energy demand has evolved over time in OECD economies, with the technology effect becoming increasingly important relative to the income effect once human capital is disaggregated into primary, secondary, and tertiary education.

From a policy perspective, the results imply that investments in education can influence the trajectory of energy demand in complex ways. Expansions of basic schooling in earlier eras supported energy-intensive growth, while higher levels of education have increasingly been associated with innovation and, post-2000, potentially with cleaner technologies.

Many countries have set the objective of achieving carbon net-zero emissions by 2050 to address climate change. For these countries, there is a strong focus on transition to clean energy. A concrete policy implication from our results is that investing in higher education can help facilitate the clean energy transition by reducing energy consumption. This result supports extant findings that higher education can facilitate the transition to cleaner energy over shorter time horizons (e.g., Yao et al., 2020). As Meng & Hao (2024, p. 2) note:

> "As individuals attain higher levels of education, they become increasingly aware of sustainability and environmental issues. Armed with knowledge and critical thinking skills, they are more likely to advocate for and support environmental policies aimed at promoting sustainable energy practices. Higher education cultivates a deeper understanding of the intricate connections between human activities, energy consumption, and environmental degradation" (references omitted)."

Increasing enrolments in higher education could be complemented by more targeted policies to increase awareness of sustainability and environmental issues among university graduates. For example, universities could expand interdisciplinary programs in sustainable engineering and urban planning, embed energy literacy into curricula, support student-led audits and pilot projects, prioritise equity in access to green tech education, and lead by example. For instance, many Australian universities, including Monash, La Trobe, RMIT, Swinburne, and the University of Melbourne, have set net-zero or carbon-neutral targets, often with earlier deadlines than the global 2050 goal. For example, Monash aims for net-zero by 2030, RMIT by 2025, and the University of Melbourne is working towards being climate positive by 2030 (Denvir, 2023). Such policies increase awareness of sustainability issues among graduates.

While we employ data for a panel of OECD countries, our findings also have policy implications for developing and emerging countries. The advantage of producing time-varying estimates over a long time is that we can observe how primary education and secondary education contributed to higher energy consumption in earlier time periods in OECD countries. Many developing countries are still predominantly agrarian or industrial economies in which primary and secondary education is likely to fuel energy intensive growth, consistent with what we observe in OECD countries, prior to the rapid expansion of higher education in these countries following World War II. The challenge for developing countries seeking to transition to clean energy and achieve carbon net-zero targets is that increased primary and secondary schooling will drive higher energy consumption. The implication is that developing economies should invest in higher education as soon as possible. This is consistent, for instance, with evidence that higher education is increasingly facilitating the shift toward lower energy consumption and clean energy initiatives in Brazil, China, and India (Khosla et al., 2020).

Future research can extend this work in several directions. While this study provides a historical perspective, data constraints limit the examination of the precise mechanisms through which education affects energy use, such as technology adoption or preferences for sustainability. Further, the sample is restricted to a core group of OECD economies. Extending the dataset to emerging economies or subnational regions would provide valuable insights into whether the historical patterns observed here hold in different contexts. Another avenue for extending this research is to empirically explore the channels through which human capital influences energy consumption. Given the data challenges of doing so over such a long time period as this study, future research could consider a shorter time period, either for a panel or a single country. Finally, methodologically, advances in time-varying and nonparametric techniques offer opportunities to test the robustness of these findings across OECD countries and alternative samples, as well as to explore additional sources of heterogeneity.

References

Ahir, H., Bloom, N., & Furceri, D. (2022). The world uncertainty index. National Bureau of Economic Research Working Paper No. w29763

Akram, V., Jangam, B. P., & Rath, B. N. (2019). Does human capital matter for reduction in energy consumption in India? *International Journal of Energy Sector Management, 13*(2), 359-376.

Akram, V., Jangam, B. P., & Rath, B. N. (2020). Examining the linkage between human capital and energy consumption: cross-country evidence. *OPEC Energy Review, 44*(1), 3-26.

Andreß, H.-J. (2017). The need for and use of panel data. *IZA World of Labor*, pp.1-10

Angrist, J. D., & Krueger, A. B. (1991). Does compulsory school attendance affect schooling and earnings? *The Quarterly Journal of Economics, 106*(4), 979-1014.

Arbex, M., & Perobelli, F. S. (2010). Solow meets Leontief: Economic growth and energy consumption. *Energy Economics, 32*(1), 43-53.

Awaworyi Churchill, S., Ivanovski, K., Mintah, K., & Zhang, Q. (2023). The impact of financial development on house prices. *The World Economy, 46*(10), 3154-3181.

Barro, R. J., & Lee, J. W. (2013). A new data set of educational attainment in the world, 1950–2010. *Journal of Development Economics, 104*, 184-198.

Belaïd, F., Al-Sarihi, A., & Al-Mestneer, R. (2023). Balancing climate mitigation and energy security goals amid converging global energy crises: The role of green investments. *Renewable Energy, 205*, 534-542.

Bell, B., Costa, R., & Machin, S. (2022). Why does education reduce crime? *Journal of Political Economy, 130*(3), 732-765.

Bernanke, B. S., & Mishkin, F. S. (1997). Inflation targeting: a new framework for monetary policy? *Journal of Economic Perspectives, 11*(2), 97-116.

Black, S. E., & Lynch, L. M. (1996). Human-capital investments and productivity. *The American Economic Review, 86*(2), 263-267.

Blomquist, J., & Westerlund, J. (2013). Testing slope homogeneity in large panels with serial correlation. *Economics Letters, 121*(3), 374-378.

Bloom, N. (2009). The impact of uncertainty shocks. *Econometrica*, *77*(3), 623-685.

BP Statistical Review. (2022). *BP Statistical Review of World Energy 2022*. Retrieved from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Broadberry, S., & O'Rourke, K. H. (2010). *The Cambridge economic history of modern Europe: Volume 2, 1870 to the present*: Cambridge University Press.

Chudik, A., & Pesaran, M. H. (2015). Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. *Journal of Econometrics, 188*(2), 393-420.

Churchill, S. A., Inekwe, J., & Ivanovski, K. (2021). R&D expenditure and energy consumption in OECD nations. *Energy Economics, 100*, 105376.

Churchill, S. A., Inekwe, J., Ivanovski, K., & Smyth, R. (2023). Human capital and energy consumption: Six centuries of evidence from the United Kingdom. *Energy Economics, 117*, 106465.

Ciccone, A., & Peri, G. (2006). Identifying human-capital externalities: Theory with applications. *TheReview of Economic Studies, 73*(2), 381-412.

Cihan, K. A., & Değirmenci, N. (2025). The effects of schooling rates and income levels on energy consumption in households: A panel data analysis on OECD countries. *Journal of the Knowledge Economy, 16*(1), 5271-5294.

Clay, K., Lingwall, J., & Stephens Jr, M. (2021). Laws, educational outcomes, and returns to schooling evidence from the first wave of US state compulsory attendance laws. *Labour Economics*, *68*, 101935.

Cohen, D. (1998). *The Wealth of the World and the Poverty of Nations*: MIT Press.

Crafts, M. N. (2000). Globalization and Growth in the Twentieth Century. *IMF Working Papers*(2000/044).

Cvrcek, T., & Zajicek, M. (2013). *School, what is it good for? Useful Human Capital and the History of Public Education in Central Europe* (No. w19690). National Bureau of Economic Research.

Davies, N. M., Dickson, M., Davey Smith, G., Van Den Berg, G. J., & Windmeijer, F. (2018). The causal effects of education on health outcomes in the UK Biobank. *Nature Human Behaviour, 2*(2), 117-125.

Denvir, P. (2023) Net Zero Tracker and THE Impact Rankings of leading Australian universities. https://100percentrenewables.com.au/2023-net-zero-tracker-and-the-impact-rankings-of-leading-australian-universities/

Edwards, L. N. (1978). An empirical analysis of compulsory schooling legislation, 1940-1960. *The Journal of Law and Economics*, *21*(1), 203-222.

Eichengreen, B. (1996). Institutions and economic growth: Europe after World War II. *In Crafts NFR & Toniolo G (Eds) Economic Growth in Europe Since 1945 Cambridge, UK: Cambridge Univ. Press*, 38-72.

Feenstra, R. C. (1998). Integration of trade and disintegration of production in the global economy. *Journal of Economic Perspectives, 12*(4), 31-50.

Feinstein, C. H., Temin, P., & Toniolo, G. (1997). *The European Economy Between the Wars*: OUP Catalogue, Oxford University Press.

Findlay, R., & O'Rourke, K. H. (2009). Power and plenty: trade, war, and the world economy in the second millennium. In *Power and Plenty*: Princeton University Press.

Fouquet, R. (2008). *Heat, power and light: revolutions in energy services*: Edward Elgar Publishing.

Fouquet, R. (2011). Long run trends in energy-related external costs. *Ecological Economics, 70*(12), 2380-2389.

Fouquet, R., & Pearson, P. J. (2012). Past and prospective energy transitions: Insights from history. *Energy Policy*, 50, 1-7.

Galor, O., & Moav, O. (2002). Natural selection and the origin of economic growth. *The Quarterly Journal of Economics, 117*(4), 1133-1191.

Galor, O., & Weil, D. N. (2000). Population, technology, and growth: From Malthusian stagnation to the demographic transition and beyond. *American Economic Review, 90*(4), 806-828.

Gao, J., Peng, B., & Smyth, R. (2021). On income and price elasticities for energy demand: A panel data study. *Energy Economics, 96*, 105168.

Geller, H., Harrington, P., Rosenfeld, A. H., Tanishima, S., & Unander, F. (2006). Polices for increasing energy efficiency: Thirty years of experience in OECD countries. *Energy Policy, 34*(5), 556-573.

Giraudet, L.-G., & Missemer, A. (2023). The history of energy efficiency in economics: Breakpoints and regularities. *Energy Research & Social Science, 97*, 102973.

Goldin, C. (1994) "Labor Markets in the Twentieth Century," NBER Working Paper h0058 (https://doi.org/10.3386/h0058.

Goldin, C. & Katz, L. (2008) The Race Between Education and Technology, Cambridge: Harvard University Press.

Goldin, C., & Katz, L. F. (2018). The race between education and technology. In *Inequality in the 21st Century* (pp. 49-54): Routledge.

Hamilton, J. D. (2009). Causes and Consequences of the Oil Shock of 2007-08 (No. w15002). National Bureau of Economic Research.
Harmon, C., Oosterbeek, H., & Walker, I. (2003). The returns to education: Microeconomics. *Journal of Economic Surveys, 17*(2), 115-156.
Hoa, L. D. T., & Hoang, P. V. H. (2024). The impact of human capital on energy consumption in Vietnam. *International Journal of Energy Economics and Policy, 14*(5), 279-291.
IEA. (2020). *World Energy Outlook 2020*. Paris: IEA.
Ivanovski, K., Awaworyi Churchill, S., & Zhang, X. (2025). Time-varying impacts of energy access on income inequality: a semi-parametric analysis. *Environmental and Ecological Statistics*, 1-23.
Jordà, Ò., Schularick, M., & Taylor, A. M. (2017). Macrofinancial History and the New Business Cycle Facts. In M. Eichenbaum & J. A. Parker (Eds.), *NBER Macroeconomics Annual 2016, Volume 31* (pp. 213-263). Chicago: University of Chicago Press.
Jorgenson, D. W., & Vu, K. M. (2016). The ICT revolution, world economic growth, and policy issues. *Telecommunications Policy*, *40*(5), 383-397.
Jurado, K., Ludvigson, S. C., & Ng, S. (2015). Measuring uncertainty. *American Economic Review*, *105*(3), 1177-1216.
Kander, A., & Lindmark, M. (2004). Energy consumption, pollutant emissions and growth in the long run: Sweden through 200 years. *European Review of Economic History, 8*(3), 297-335.
Kander, A., Malanima, P., & Warde, P. (2014). Power to the People: Energy in Europe over the Last Five Centuries. Princeton University Press.
Khosla, R., Kamat, A. S., & Narayanamurti, V. (2020). Successful clean energy technology transitions in emerging economies: learning from India, China, and Brazil. *Progress in Energy*, *2*(4), 043002.
Krugman, P. (1992). *Geography and trade*: MIT press.
Landes, W. M., & Solmon, L. C. (1972). Compulsory schooling legislation: An economic analysis of law and social change in the nineteenth century. *The journal of economic history*, *32*(1), 54-91.
Lane, M., & Saint-Martin, A. (2021). The Impact of Artificial Intelligence on the Labour Market: What do we know so far? OECD Social, Employment, and Migration Working Papers, NO. 256
Le, H. C., Bhattacharya, M., Smyth, R., & Zhang, X. (2024). Does economic growth cause energy intensity of well-being in the very long run? Semi-parametric evidence for selected OECD countries. *Energy Economics, 139*, 107889.
Le, H. C., Bhattacharya, M., Smyth, R., & Zhang, X. (2025). The impact of R&D on energy consumption: Evidence from non-linear semi-parametric estimations for selected OECD countries. *Energy Economics*, 108708.
Lee, H., Park, C., & Jung, H. (2024). The role of tertiary education on CO2 emissions: evidence from 151 countries. *Environment, Development and Sustainability, 26*(12), 32081-32103.
Li, X., Mao, H., & Fang, L. (2024). The impact of rural human capital on household energy consumption structure: evidence from Shaanxi Province in China. *Sustainable Futures, 8*, 100301.
Lindert, P. H. (2004). *Growing public: Volume 1, the story: Social spending and economic growth since the eighteenth century* (Vol. 1): Cambridge University Press.
Ma, W. (2022). Exploring the role of educational human capital and green finance in total-factor energy efficiency in the context of sustainable development. *Sustainability, 15*(1), 429.

Maddison, A. (2007). *Contours of the World Economy, 1-2030 AD: Essays in Macro-economic History*: Oxford University Press.
Madsen, J. B. (2010). The anatomy of growth in the OECD since 1870. *Journal of Monetary Economics, 57*(6), 753-767.
Madsen, J. B. (2014). Human capital and the world technology frontier. *Review of Economics and Statistics, 96*(4), 676-692.
Madsen, J. B., Islam, M. R., & Doucouliagos, H. (2018). Inequality, financial development and economic growth in the OECD, 1870–2011. *European Economic Review, 101*, 605-624.
Madsen, J. B., & Murtin, F. (2017). British economic growth since 1270: the role of education. *Journal of EconomicGrowth, 22*(3), 229-272.
Makhlouf, Y., & Lalley, C. (2023). Education expansion, income inequality and structural transformation: Evidence from OECD Countries. *Social Indicators Research, 169*(1), 255-281.
Malanima, P. (2024). International inequality in energy use and CO2 emissions (1820–2020). *Structural Change and Economic Dynamics, 70*, 233-244.
Meng, B., & Hao, Z. (2024). Role of green finance and higher education in fostering the sustainability and energy transition practices. *Humanities and Social Sciences Communications*, *11*(1), 1-8.
Mincer, J. (1984). Human capital and economic growth. *Economics of Education Review, 3*(3), 195-205.
Nowotny, J., et al. (2018). Towards global sustainability: Education on environmentally clean energy technologies. *Renewable and Sustainable Energy Reviews, 81*, 2541-2551.
Parsons, D. O., & Goldin, C. (1989). Parental altruism and self-interest: Child labor among late nineteenth-century American families. *Economic Inquiry*, *27*(4), 637-659.
Puerta, J. M. (2009, January). 'The Fewer, the Merrier': Compulsory Schooling Laws, Human Capital, and Fertility in the United States. In *Population Association of America Annual Meeting April* (Vol. 17, p. 2010).
Reshef, A., & Toubal, F. (2024). Automation, techies, and labor market restructuring. In *Handbook on Labour Markets in Transition* . Edward Elgar Publishing, pp. 15-35.
Rauscher, E. (2014). Hidden gains: Effects of early US compulsory schooling laws on attendance and attainment by social background. *Educational Evaluation and Policy Analysis*, *36*(4), 501-518.
Rauscher, E. (2015). Effects of early US compulsory schooling laws on educational assortative mating: The importance of context. *Demography*, *52*(4), 1219-1242.
Rauscher, E. (2016). Does educational equality increase mobility? Exploiting nineteenth-century US compulsory schooling laws. *American Journal of Sociology*, *121*(6), 1697-1761.
Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy, 98*(5, Part 2), S71-S102.
Sadorsky, P. (2011). Trade and energy consumption in the Middle East. *Energy Economics, 33*(5), 739-749.
Salim, R., Yao, Y., & Chen, G. S. (2017). Does human capital matter for energy consumption in China? *Energy Economics, 67*, 49-59.
Schofer, E., & Meyer, J. W. (2005). The worldwide expansion of higher education in the twentieth century. *American Sociological Review, 70*(6), 898-920.
Scott, M. (1992). Dynamic Forces in Capitalist Development: A Long-run Comparative View. *The Economic Journal, 102*(414), 1281-1282.
Smil, V. (2018). *Energy and civilization: a history*: MIT press.

Solarin, S. A., Gil-Alana, L. A., & Hernández-Herrera, M. (2024). Persistence of human capital development in OECD countries over 150 years: Evidence from linear and non-linear fractional integration methods. *Economic Systems, 48*(3), 101215.

Stern, D. I. (2011). The role of energy in economic growth. *Annals of the New York Academy of Sciences, 1219*(1), 26-51.

Stern, D. I. (2019). Energy and economic growth. In *Routledge handbook of Energy economics* (pp. 28-46): Routledge.

Temin, P. (1991). *Lessons from the great depression*: MIT Press.

Topel, R. (1999) Labor markets and economic growth, Handbook of Labor Economics, Elsevier, Volume 3, Part C, pp. 2943-2984.

Wang, M., Zheng, Y., Ma, S., & Lu, J. (2023). Does human capital matter for energy consumption in China? Evidence from 30 Chinese provinces. *Environmental Science and Pollution Research, 30*(40), 93030-93043.

Weisbrod, B. A. (1966). Investing in human capital. *The Journal of Human Resources, 1*(1), 5-21.

Yao, Y., Ivanovski, K., Inekwe, J., & Smyth, R. (2019). Human capital and energy consumption: Evidence from OECD countries. *Energy Economics, 84*, 104534.

Yao, Y., Ivanovski, K., Inekwe, J., & Smyth, R. (2020). Human capital and CO2 emissions in the long run. *Energy Economics*, 104907.

Yao, Y., Zhang, L., Salim, R., & Rafiq, S. (2021). The effect of human capital on CO2 emissions: Macro evidence from China. *The Energy Journal, 42*(6).

Yergin, D. (2012). *The quest: Energy, security, and the remaking of the modern world*: Penguin.

Yuxiang, K., & Chen, Z. (2010). Government expenditure and energy intensity in China. *Energy Policy, 38*(2), 691-694.

Table 1
Dynamic heterogeneous IV estimates

	Human Capital (Total)	Human capital (Primary)	Human capital (Secondary)	Human capital (Tertiary)	Human capital (All education levels)
	(1)	(2)	(3)	(4)	(5)
HC^{TOT}	0.074**				
	(0.034)				
HC^{PRI}		0.220***			0.170
		(0.084)			(0.147)
HC^{SEC}			0.017***		0.054**
			(0.004)		(0.025)
HC^{TER}				-0.094***	-0.124**
				(0.028)	(0.050)
$ECPC_{t-1}$	-0.165***	-0.194***	-0.141***	-0.174***	-0.288***
	(0.016)	(0.038)	(0.018)	(0.053)	(0.072)
GDP	0.186***	0.210***	0.138***	0.228***	0.330***
	(0.026)	(0.030)	(0.025)	(0.056)	(0.086)
TRADE	-0.004	0.011	-0.0002	0.016*	0.049**
	(0.009)	(0.010)	(0.008)	(0.009)	(0.017)
GOV	-0.023***	0.021**	-0.021***	-0.020**	-0.011
	(0.008)	(0.008)	(0.006)	(0.007)	(0.013)
INF	0.001***	0.0009*	0.001***	0.001**	0.001
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(.0006)
Obs.	1,500	1,500	1,500	1,500	1,500
R^2	0.24	0.28	0.22	0.28	0.39
RMSE	0.06	0.05	0.06	0.05	0.05
Wald F-test					$F(3,1418) = 7.03$
[p-value]					[0.0001]

Notes: Column (1) reports the specification for total human capital, while columns (2)-(4) report the disaggregated education measures of primary, secondary, and tertiary human capital, respectively, while column (5) reports all disaggregated education measures jointly. The Wald F-test tests the joint significance of HC^{PRI}, HC^{SEC}, and HC^{TER}. The contemporaneous value of HC is instrumented using its first lag and a compulsory schooling dummy. Estimates are obtained using the dynamic mean-group IV estimator and include a (pooled) constant and trend. Robust standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 2
Weak-exogeneity/Granger-causality test results.

Direction tested	Panel statistic	p-value	%countries rejecting H_0
$HC^{TOT} \rightarrow ECPC$	W = 4.12	< 0.01	80%
$HC^{PRI} \rightarrow ECPC$	W = 3.76	< 0.01	70%
$HC^{SEC} \rightarrow ECPC$	W = 2.98	0.01	60%
$HC^{TER} \rightarrow ECPC$	W = 5.21	< 0.01	90%
$ECPC \rightarrow HC^{TOT}$	W = 1.03	0.31	20%
$ECPC \rightarrow HC^{PRI}$	W = 0.88	0.41	10%
$ECPC \rightarrow HC^{SEC}$	W = 1.11	0.26	20%
$ECPC \rightarrow HC^{TER}$	W = 0.72	0.48	0%

Notes: "→" denotes Grager-causality.

Table 3

Diagnostics for IV model using detrended human capital

Test	Statistic	p-value
Coefficient on $\widetilde{HC}_{it}$	0.0033	0.788
Weak-IV (joint first-stage F)	1.67×10^5	< 0.001
Wu–Hausman endogeneity test	0.588	0.443
Sargan over-identification test (AER)	0.319	0.572
Sargan (nR^2)	0.312	0.576
Madsen (2014) orthogonality (F) test	0.158	0.854

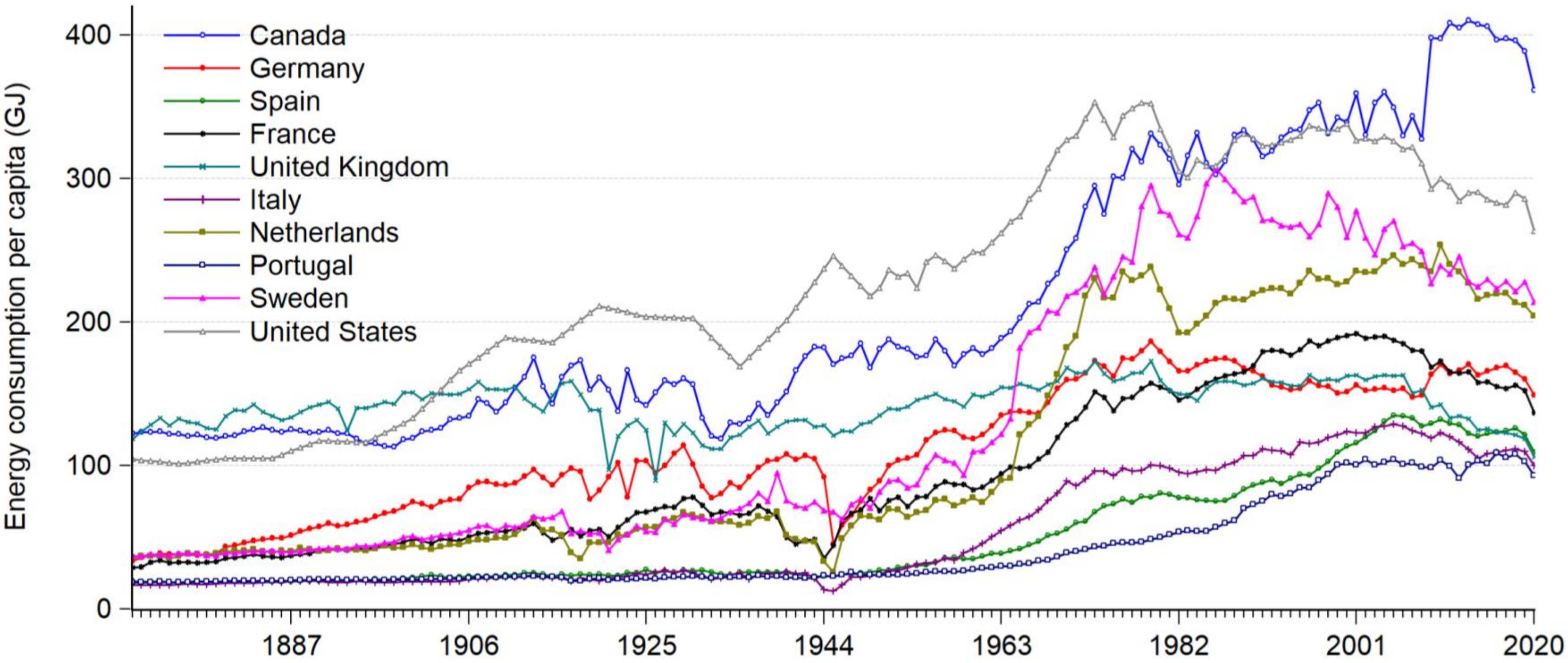

Fig . 1 – Time series plot of ECPC (G.J.) for each country (1870-2020).

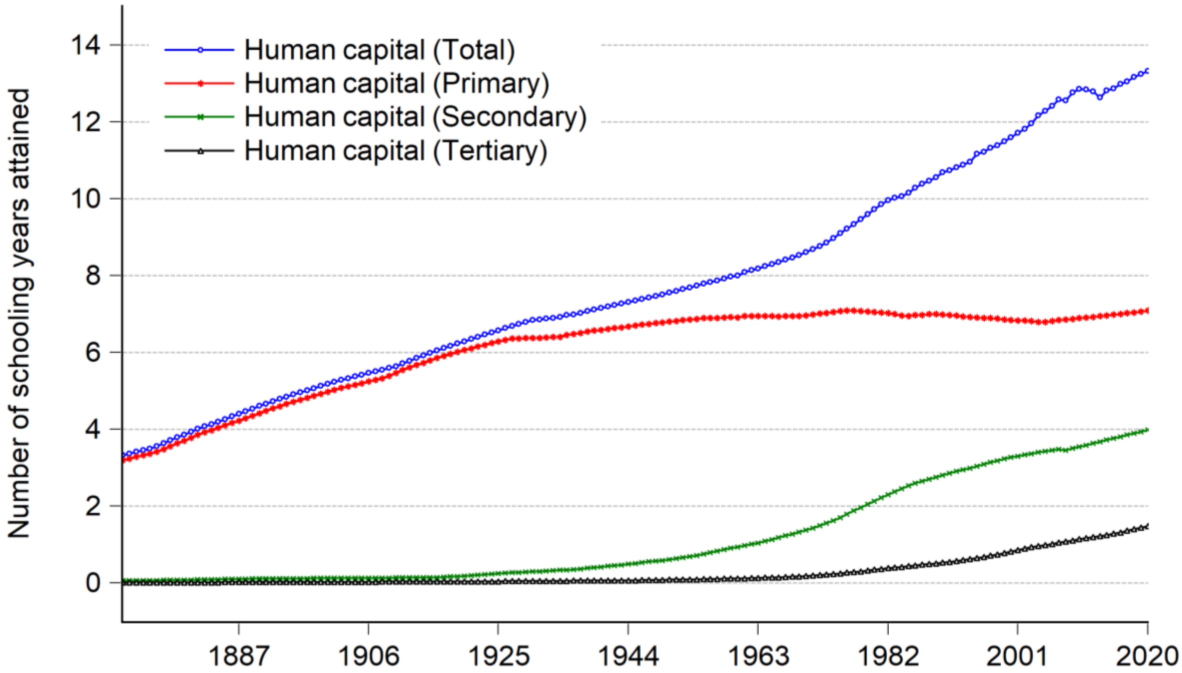

Fig . 2 – Time series plot of human capital (by education level) for the panel (1870-2020).

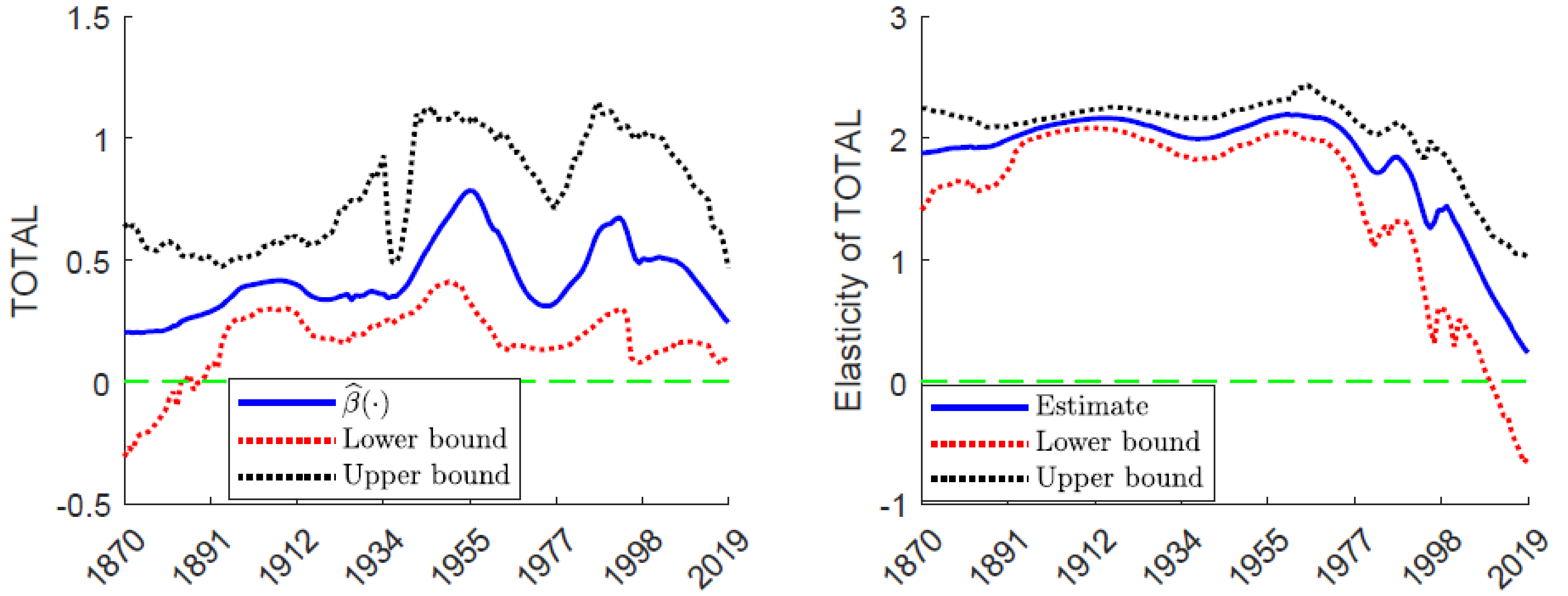

Fig. 3a – Time-varying impact of HC^{TOT} on ECPC.

Notes: left panel represents the time-varying estimates (solid blue line) of $\beta_0(\cdot)$. Right panel represents the time-varying elasticities (solid blue line). The dotted black and red lines denote the 95% confidence intervals.

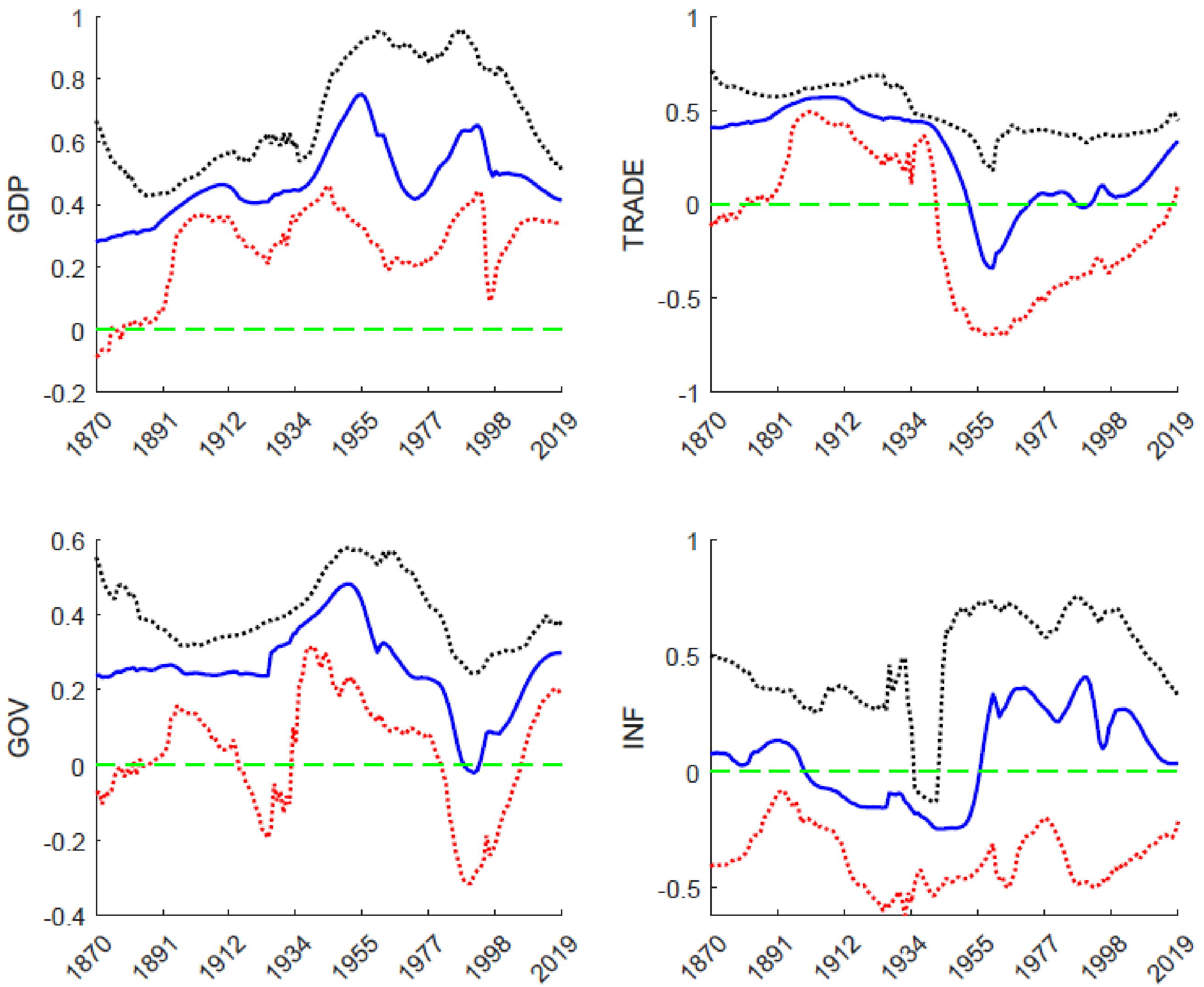

Fig. 3b – Time-varying impact of control variables on ECPC.
Notes: see notes to **Fig. 3a**.

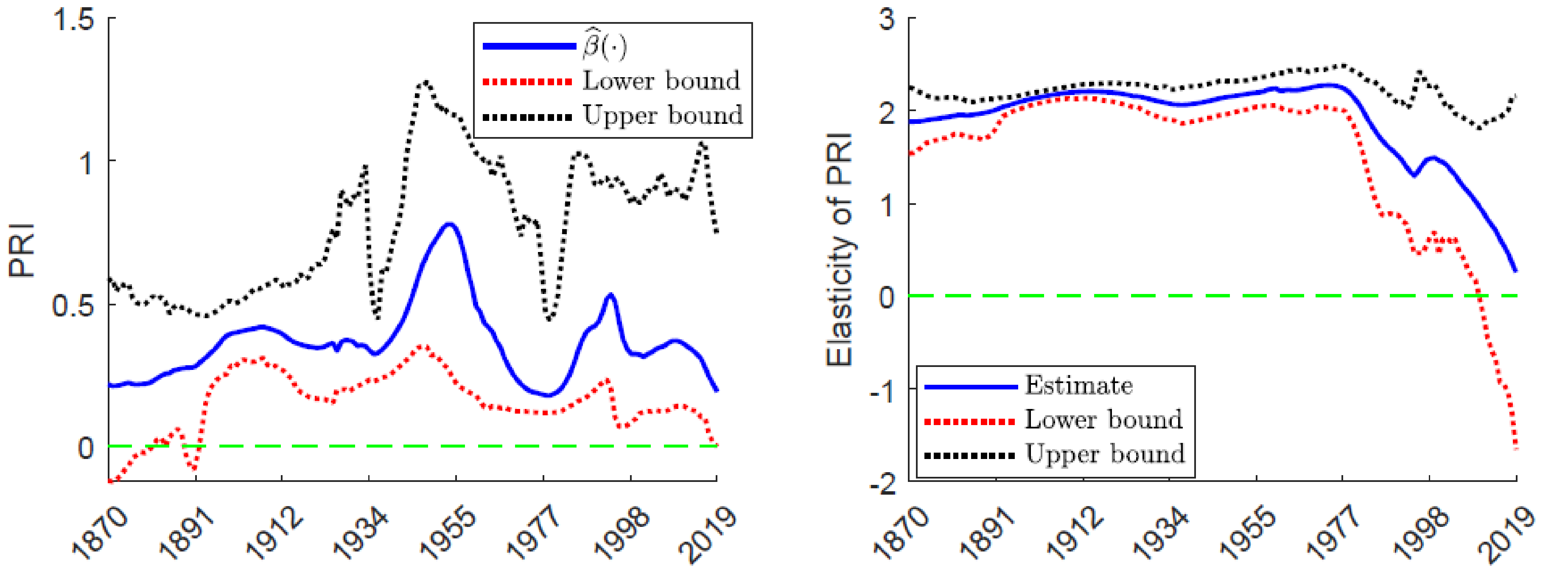

Fig. 4 – Time-varying impact of HC^{PRI} on ECPC.
Notes: see notes to **Fig. 3a**.

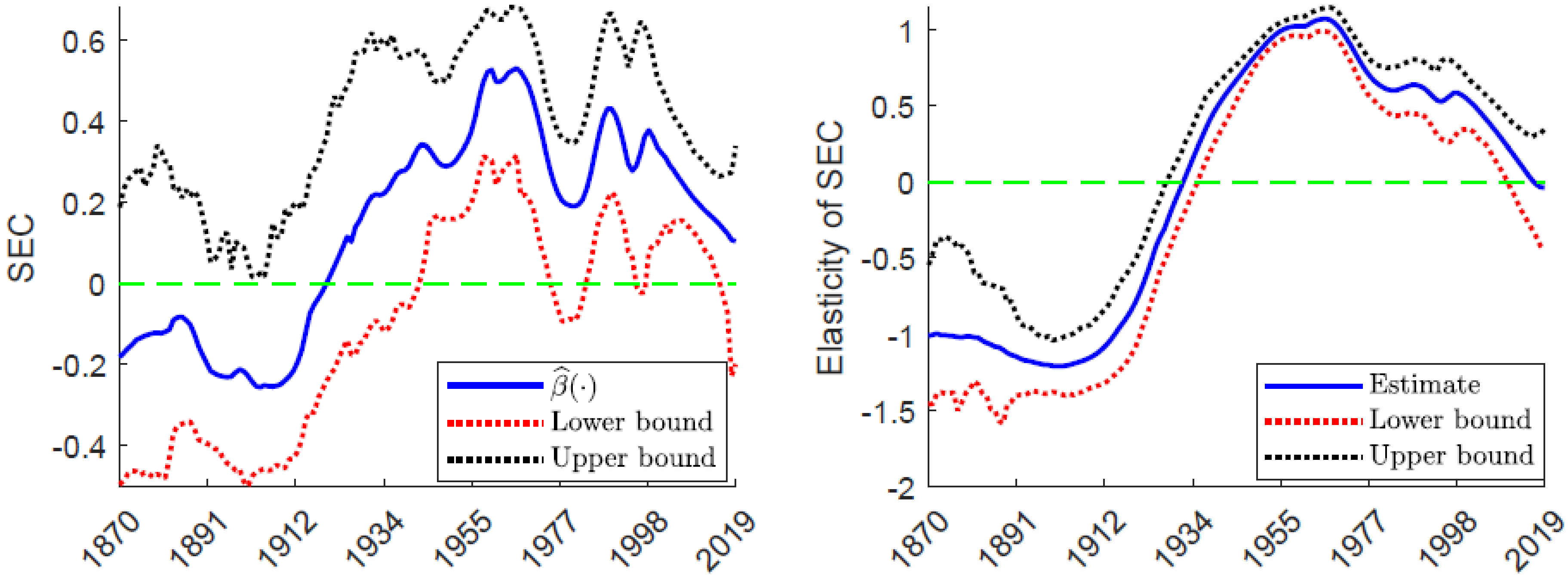

Fig. 5 – Time-varying impact of HC^{SEC} on ECPC.
Notes: see notes to **Fig. 3a**.

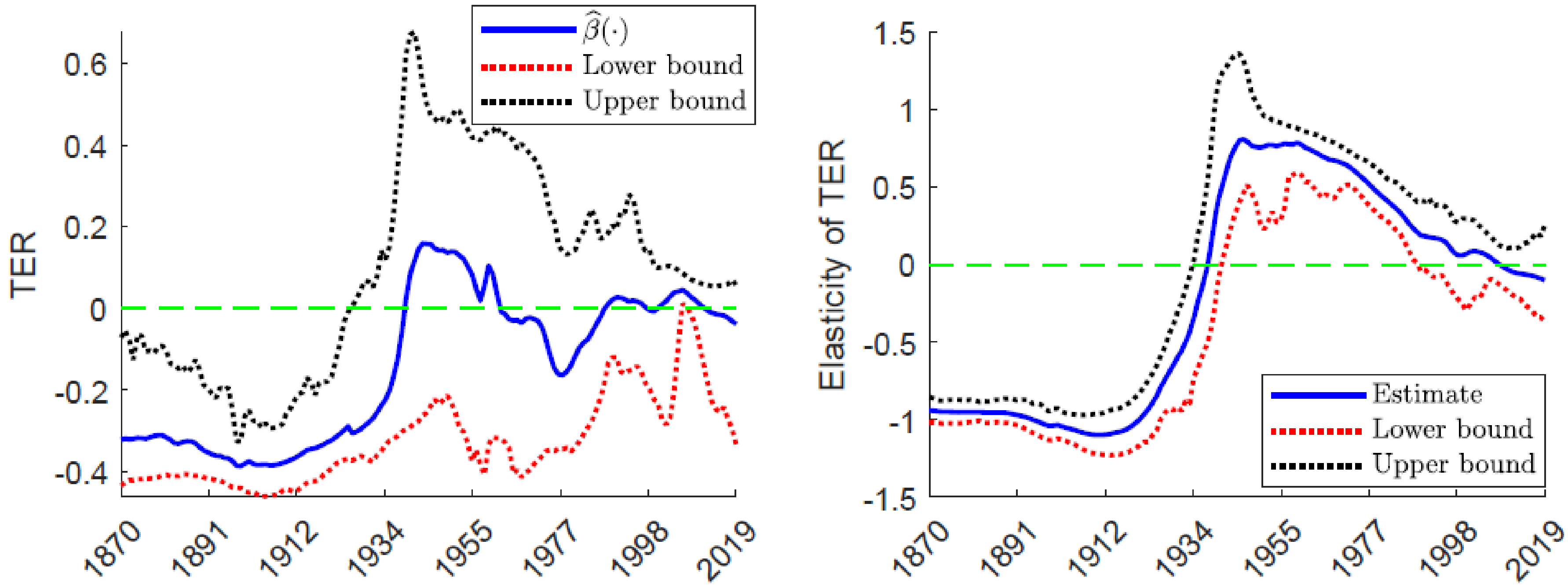

Fig. 6 – Time-varying impact of HC^{TER} on ECPC.
Notes: see notes to **Fig. 3a**.

Appendix A. Summary statistcs and preliminary results

Table A1
Summary statistics.

Variable (description)	Mean	Std. dev.	Min	Max
ECPC (energy consumption per capita, GJ)	117.72	88.19	12.4	410.58
HC^{TOT} (total education attainment)	7.92	3.32	0.62	16.04
HC^{PRI} (primary education attainment)	6.27	1.96	0.59	9.49
HC^{SEC} (secondary education attainment)	1.27	1.39	0.01	5.49
HC^{TER} (tertiary education attainment)	0.36	0.59	0.01	3.83
RGDP (Real GDP per capita, index, 2005=100)	39.39	33.60	5.92	122.71
TRADE (import plus exports % of GDP)	38.47	25.59	4.08	140.18
GOV (government expenditure % of GDP)	17.53	11.00	1.42	105.69
INF (inflation, %)	4.00	15.99	-99.9	491.57

Table A2
Slope homogeneity test.

	HC^{TOT}	HC^{PRI}	HC^{SEC}	HC^{TER}
Slope Homogeneity (Δ)	57.792***	60.797***	55.803***	74.039***
Slope Homogeneity (Δ Adjusted)	59.18***	62.258***	57.144***	75.818***

Notes: Table reports the Blomquist and Westerlund (2013) slope homogeneity test using Eq. (1). *** denotes significance at the 1% level.

Table A3
Panel CD and CADF test results.

	Panel A: CD test			Panel B: CADF test	
	CD stat	p-value	abs(corr)	Level	1st diff
ECPC	67.85	0.000	0.823	-2.349**	-6.163***
HC^{TOT}	79.57	0.000	0.965	-1.851	-4.379***
HC^{PRI}	68.87	0.000	0.835	-1.613	-3.007***
HC^{SEC}	80.44	0.000	0.976	-0.772	-2.871***
HC^{TER}	80.35	0.000	0.975	-1.319	-2.627***
RGDP	80.43	0.000	0.976	-2.318**	-6.190***
TRADE	48.52	0.000	0.607	-1.904	-6.190***
GOV	63.40	0.000	0.769	-2.136	-6.190***
INF	29.01	0.000	0.352	-3.639***	-6.190***

Notes: All variables are expressed in logs (except for INF). The CADF The critical values for the CADF test at the 10%, 5% and 1% are -2.580, -2.650, and -2.780, respectively. ***, **, * indicates statistical significance at 1%, 5% & 10% levels.

Table A4
Westerlund panel cointegration test results.

Model	Test statistics (Z-value)			
	G_τ	G_α	P_τ	P_α
ECPC - HC^{TOT}	-2.104**	0.195	-2.335**	-0.646
ECPC - HC^{PRI}	-4.677***	-1.972**	-4.691***	-2.611**
ECPC - HC^{SEC}	-1.889**	-1.463**	-2.541***	-1.617**
ECPC - HC^{TER}	-2.494**	-0.425	-3.057**	0.241

Notes: the null hypothesis is no cointegration. All models in include the full set of control variables. ***, **, * indicates statistical significance at 1%, 5% & 10% levels.

Appendix B. Causality testing framework and robustness analyses

This appendix provides the formal econometric structure underlying the causal-direction analysis in Section 4.2. We first present the general weak-exogeneity testing framework for heterogeneous, cross-sectionally dependent panels, followed by additional robustness checks to validate the direction of causality between human capital and energy consumption.

B.1 Error–correction representation and weak-exogeneity tests. Given the presence of cointegration among $\ln ECPC_{it}$, $\ln HC_{it}$, and the controls Z_{it} (as shown in Table A4), the long-run equilibrium for country i is written as:

$$\ln ECPC_{it} = \gamma_i \ln HC_{it} + \delta_i Z_{it} + u_{it}, \tag{B.1}$$

Following Chudik and Pesaran (2015), we express the dynamics as a country-specific error–correction model augmented with cross-sectional averages:

$$\Delta \ln ECPC_{it} = \phi_i u_{it-1} + \sum_{k=1}^{p} \beta_{ik} \Delta \ln HC_{it-k} + \lambda_i \bar{X}_t + \varepsilon_{it}, \tag{B.2}$$

$$\Delta \ln HC_{it} = \psi_i \tilde{u}_{it-1} + \sum_{k=1}^{p} \alpha_{ik} \Delta \ln ECPC_{it-k} + \mu_i \bar{X}_t + v_{it}, \tag{B.3}$$

where $\bar{X}_t$ collects cross-sectional averages of the regressors and the dependent variable. The null hypotheses for causal-direction testing are:

$$H_0^{EC\to ECPC}: \beta_{i1} = \beta_{i2} = \cdots = \beta_{ip} = 0, \;\; H_0^{ECPC\to HC}: \alpha_{i1} = \alpha_{i2} = \cdots = \alpha_{ip} = 0.$$

Country-specific Wald statistics are computed as:

$$W_i^{HC\to ECPC} = \hat{\beta}_i' \left(\widehat{Var}(\hat{\beta}_i)\right)^{-1} \hat{\beta}_i' \tag{B.4}$$

$$\Delta \ln HC_{it} = \psi_i \tilde{u}_{it-1} + \sum_{k=1}^{p} \alpha_{ik} \Delta \ln ECPC_{it-k} + \mu_i \bar{X}_t + v_{it}, \tag{B.5}$$

Panel statistics follow the standard mean-group (MG) aggregation:

$$W^{MG} \frac{1}{N} \sum_{i=1}^{N} W_i, \tag{B.6}$$

with p-values derived from simulated critical values that account for cross-sectional dependence and heterogeneous short-run dynamics.

B.2 Testing alternative lag structures. To ensure robustness to the dynamic specification, we estimate the weak-exogeneity tests under lag lengths $p \in \{1,2,3,4\}$, selected using the BIC and by historical reasoning (e.g., schooling and energy systems adjust slowly). The causal direction $HC \to ECPC$ remains significant at the 1% level for all p, while $ECPC \to HC$ remains insignificant (p > 0.25) for all choices.

B.3 Toda–Yamamoto augmented causality in a DCCE environment. To ensure that unit-root and cointegration uncertainty does not distort inference, we follow a panel adaptation of the Toda and Yamamoto (1995) augmented VAR procedure. For each country, we: (i) augment the system with the maximum integration order $d_{max} = 1$; (ii) estimate a levels VAR$d_{p+d_{max}}$ with DCCE augmentation; and (iii) test for zero restrictions only on the first p lag coefficients. The results are consistent with the ECM-based tests such that $HC \rightarrow ECPC$ is significant at 1% level and $ECPC \rightarrow HC$ is insignificant.

B.4 Bootstrap factor-augmented Granger-causality tests. Because common global shocks (e.g., World Wars, oil crises, ICT revolution) may induce spurious causality, we perform bootstrap tests that explicitly incorporate estimated common factors. We extract r factors from $\bar{X}_t$ using Bai and Ng (2002) IC criteria and bootstrap the panel VAR with factor augmentation. Across 1,000 bootstrap replications the results show that the rejection frequency for $HC \rightarrow ECPC$ exceeds 0.85 for all education levels, and the rejection frequency for $ECPC \rightarrow HC$ is below 0.10 in all cases.

B.5 Overidentification-based causality checks using IV residuals. Since our baseline model uses two instruments (lagged human capital and compulsory schooling laws), we can exploit the Hansen J-test and its decomposition to assess whether energy-driven changes in education contaminate the IV structure. Specifically:

$$J = \hat{u}'Z(Z'WZ)^{-1}Z'\hat{u},$$

where $\hat{u}$ is the DCCE-IV residual. We further test whether:

$$\text{Cov}\,(\hat{u}_{it}, \Delta \ln ECPC_{it-k}) = 0, \quad k = 1,2,$$

after partialling out common factors.

Across all specifications, both the Hansen J-test and the covariance restrictions fail to reject the null (p > 0.20), indicating that energy consumption does not explain the variation used by the instruments to identify human capital.

B.6 Summary of robustness results. All robustness tests – alternative lag lengths, augmented VAR causality, factor-augmented bootstrap tests, and overidentification-based causality checks—consistently confirm the asymmetric causal structure:

$$HC \rightarrow ECPC, \qquad ECPC \nrightarrow HC.$$

These findings reinforce the interpretation in Section 4.2 that human capital is a structural driver of long-run energy consumption patterns rather than a response to them.

Appendix C. Instrument validity and supplementary diagnostics

This appendix reports supporting diagnostic evidence for the IV specifications discussed in Section 4.3. All interpretation is provided in the main text, and here we document the underlying tests and robustness procedures.

C.1 Standard IV diagnostics (levels). Table C.1 reports conventional IV diagnostics for the baseline (level-specification) models using lagged human capital and compulsory schooling reforms as excluded instruments. The weak-instrument F-statistics indicate extremely strong instrument relevance across all measures of schooling. Wu–Hausman tests reject exogeneity of human capital, justifying IV estimation. Sargan over-identification tests reject the null in all cases, motivating further analysis of trend dependence and instrument orthogonality in Section 4.3.

Table C1
Standard IV diagnostics (levels)

	HC^{TOT}	HC^{PRI}	HC^{SEC}	HC^{TER}
Weak IV F-statistic	632,389	975,312	119,188	221,908
Wu–Hausman p-value	3.4×10^{-10}	9.4×10^{-14}	9.0×10^{-9}	2.5×10^{-9}
Sargan p-value	1.5×10^{-15}	6.4×10^{-16}	$< 10^{-16}$	1.0×10^{-14}

C.2 Identification-robust estimators. Because standard IV diagnostics rely on restrictive assumptions, we also consider identification-robust alternatives, such as the Lewbel (2012) heteroskedasticity-based IV estimators, the Oster (2019) δ-bounds for sensitivity to selection on unobservables, and the Kinky least squares (KLS) bounds that allow controlled violations of instrument exogeneity. Across these procedures, the estimated effect of human capital on energy consumption remains stable in sign and magnitude relative to the baseline IV results. Full implementation details are available upon request.

C.3 Identification-robust estimators. In long-T macroeconomic panels, the assumptions underlying the Sargan test – homoskedasticity, serial independence, and cross-sectional independence – are unlikely to hold. Strong rejections in level specifications may therefore reflect persistent common shocks or secular trends rather than instrument failure. Consistent with this interpretation, once human capital is detrended, both the Sargan and Madsen (2014) orthogonality tests fail to reject exogeneity. Together with the results in Section 4.3, this supports the validity of the IV strategy employed in the main analysis.

Appendix D. Regularity and convergence conditions

For completeness, we summarise the high-level assumptions ensuring identification, consistency, and asymptotic normality of the IV–GPS estimator. These conditions follow Gao et al. (2021) and Le et al. (2024).

D.1 Smoothness. The coefficient functions $\beta_0(\tau)$, $B_0(\tau)$, and $\Gamma_0(\tau)$ are twice continuously differentiable on [0, 1].

D.2 Factor structure. The data admit the representation

$$(y_{it}, x'_{it}) = \Lambda'_i f_t + v_{it},$$

with $\frac{1}{N}\Lambda'\Lambda \to \Sigma_\Lambda > 0$ and $\frac{1}{N} f'f \to \Sigma_\Lambda > 0$.

D.3 Error moments and weak dependence. The idiosyncratic components v_{it} and ε_{it} have finite moments of order $2 + \delta$ and satisfy weak dependence conditions ensuring LLN and CLT for kernel-weighted sums.

D.4 Bandwidth conditions. The bandwidth satisfies

$$h \to 0, \;\; Th \to 0, \;\; Nh \to 0$$

ensuring valid local estimation and factor extraction.

D.5 Instrument relevance and rank condition. The matrix $\mathbb{E}[z_{it}x'_{it}]$ has full column rank, guaranteeing that the instrumented regressors identify the time-varying structural coefficients.