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Energy intensity convergence and its long-run minimum*

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Abstract

Projections of energy intensity are important for the assessment of future energy demand, future emission pathways, and the costs of climate policies. We estimate and simulate energy intensity based on a conditional convergence approach, and show how based on the results the long-run minimum of energy intensity attainable can be estimated. We consider education, urbanization, and institutional factors and find them to positively impact energy intensity improvements. We link the estimated econometric models to an iterative projection model, resulting in a finite long-term lower limit of energy intensity of GDP to be around $0.35MJ/\$$ at the global level in most SSPs. Yet, by 2100, we estimated that energy intensity below one is hard to achieve based on historical patterns. By 2100, the projected energy intensities are in the range of $1MJ/\$$ at the global level. These results show that scenarios such as the ones used in the SR15 can be rationalized based on empirically founded projections, and that in particular the very low energy demand scenarios can be considered feasible on empirical grounds. The speed at which such ow values are achievable is however the big question and achieving them will require substantially going beyond historical technical change patterns.

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JEL Classification: O44, P18, Q47, C23
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1 Introduction

Growth in energy demand is one of the key challenges for the energy sector (Bauer et al., 2017), and improving energy efficiency is critical for reducing greenhouse gas emissions while addressing the goals of sustainable development related to poverty (Fuso Nerini et al., 2018). Historically, technological improvements and structural changes in the mix of economic activities have helped the world to achieve major reductions in the energy used to produce economic output as shown in Stern (2012) and Voigt et al. (2014). While annual historical improvement rates have been around 1.3% and 0.99% for non-OECD and OECD countries, respectively[1], maintaining the global temperature increase below 2°C and its associated mitigation goals require a significant acceleration in the reduction of energy intensity.

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[1] The value come from the AR5 database of IPCC which forecasts a range of energy intensity values for 2100 between 0.9 MJ/$ and 4.5 MJ/$

The IPCC 5th Assessment Report database projects future average annual improvement rates of energy intensity (EI) between 2010 and 2100 of up to 2.23% per year. The development of energy intensity depends on structural drivers - the composition of economic activities within a specific country along with technological factors - diffusion of innovative technologies, as well as behavioral and institutional factors. Indeed actual implementation of environmental policies and their influence on behaviors and environmental outcomes depend on the broader institutional setting (Stavins, 2004). Good governance and transparency are decisive factors, as bureaucrats are the actors ultimately implementing environmental interventions (Lockwood, 2013), and indeed the influence of institutional quality is apparent even in relation to aggregate outcomes, such as energy intensity, as shown in Fredriksson et al. (2004).

How energy intensity will evolve in the future is deeply uncertain, and model-based scenario analysis has become a key analytical approach to explore uncertainties related to energy demand, as well as the consequences for the economy and the energy system in the context of decarbonization and sustainable development. The Shared Socio-economic Pathways (SSPs) provide a new framework for this type of investigation by proposing five different global futures articulated into quantitative pathways for population change, urbanization, education, economic growth, and qualitative narratives regarding a broad range of elements including inequality, technological advancements and institutional quality (O'Neill et al., 2014). Several publications have already shown how to translate SSP narratives into assumptions that can be used in Integrated Assessment Models (IAMs). Riahi et al. (2017) focus on the baseline SSP drivers (i.e., population, GDP, urbanization and education). However, the translation of the qualitative elements regarding economy and lifestyle, policies and institutions into model assumptions is still limited to a few SSP elements, mostly related to the energy sector such as final energy demand, efficiency of energy conversion technology, and fossil fuel supply (Bauer et al., 2017).

In order to evaluate the future projections of energy intensity trends for different regions of the world we need to comprehend what were the principal determinants of past energy intensity improvements. In this paper we develop a framework which aims to facilitate the modeling of qualitative SSP elements related to the quality of institutions and their impact on energy intensity. Understanding how institutions interact with environmental policies as well as other socioeconomic drivers of energy intensity is an important element for cost-effective transition towards low carbon and sustainable societies (Dasgupta and Cian, 2018), as institutions can affect mitigation costs as well as their distribution (Iyer et al., 2015). Earlier model-based work, such as those presented in AR5 (Clarke et al., 2014), has already shifted from first-best transition pathways (fully oriented towards cost-optimality under perfect conditions) to second-best transition pathways (exploring sociopolitical and other limitations (Kriegler et al., 2013b,a, 2014; Staub-Kaminski et al., 2014; Riahi et al., 2017).

We focus on energy intensity because, as shown in Marangoni et al. (2017), this is the most important determinant of uncertain future energy demand and hence greenhouse-gas emissions . To assess the impact of major determinants of energy intensity changes we use a conditional convergence approach for energy intensity, such as in Csereklyei and Stern (2015) and Csereklyei et al. (2016). We use both a cross-sectional and a panel regression model highlighting the importance of the difference of both widely used models and compare their results. Moreover, this allows us to estimate the effects of covariates including urbanization rates along with variables measuring the role of institutions, and education for explaining historical energy intensity trends.

There is empirical evidence suggesting that urbanization, physical and human capital, as well as institutions, affect aggregate energy intensity patterns and energy convergence (Sadorsky (2013), Stern (2012), Fredriksson et al. (2004)). The empirical evidence on the impact of urbanization on energy use and energy intensity is mixed (Sadorsky, 2013; Elliott et al., 2017) and depends on income level (negative for low-income, positive for high-income). On the one hand, urbanization increases economic activity as well as the consumption of energy-intensive goods (e.g. air conditioning). On the other hand, urbanization has also a scale and structural effect that can create opportunities for lower energy intensity (e.g. production reallocation from industrial to tertiary sector, more efficient buildings, lower use of private transportation in per capita terms). Some studies find that population density is correlated with a lower demand for personal vehicles (Liddle, 2004). More capital and human capital-intensive economies should be less energy intensive as these inputs substitute for energy (Stern, 2012). Investments and capital turnover has been shown to be correlated with income convergence (Papyrakis and Gerlagh, 2007). Moreover, a faster capital turnover facilitates the transition towards more efficient equipment and appliances, leading to a decline in aggregate energy intensity. Human capital and schooling have been shown to be correlated with the rate of adoption of technologies as well as with faster convergence in income (Benhabib and Spiegel, 2005; Comin and Hobijn, 2004). Institutional factors such as corruption, transparency of governments, the quality of bureaucratic quality and speed, influence the ability to implement environmental policies, the type of policy chosen, policy stringency, as well as the effectiveness of the policy implemented, with implications for more aggregate indicators such as green investments (Masini and Menichetti, 2013), R&D (Dasgupta et al., 2016), and energy intensity (Fredriksson et al., 2004). Specifically, good governance encourages the adoption of environmental policies and generally leads to better environmental outcomes, while corruption can be a channel for environmental degradation, as it could lead to a sub-optimal use of resources and inefficiencies (Dasgupta and Cian, 2018). Fredriksson and Svensson (2003) and Fredriksson et al. (2004) find that more corrupted countries have less stringent environmental policies. Masini and Menichetti (2013) and Iyer et al. (2015) focused on the role of institutional quality on investment on renewable energy and low carbon technologies. Both studies led the results that the presence of inferior and inefficient institutions was associated with lower rates of investments on low carbon technologies and renewable energy. Dasgupta et al. (2016) find evidence suggesting that quality of institution matters, and bad governance or corruption can hinder green investments in R&D and innovation.

The main idea behind our approach is to use the evidence from historical data to model the development of energy intensity in Integrated Assessment Models as an endogenous function of urbanization, physical and human capital, and institutions. To do that, we first investigate the empirical relationship between these variables and energy intensity using historical data on energy intensity, years of schooling, urbanization, and institutional quality. The estimates obtained with historical data indicating the impact of each institutional factor on energy intensity changes, are then used to project future energy intensity combining the empirical results with quantitative projections (urbanization, education, GDP, population, institutions) across different SSP scenarios. This representation of energy intensity based on historical dynamics can provide an alternative projection based on historical rather than modeled data. Our approach also contributes to the discussion about substitutability of energy or resource use with capital and labor, notably, about whether or not the long-run energy required to produce one unit of GDP is asymptotically zero, as in Stiglitz (1974) in the context of natural resources, or strictly positive. In this way it contributes to the stylized facts about macroeconomic energy intensity (Smulders and de Nooij, 2003; Gales et al., 2007; Kander et al., 2014; Csereklyei et al., 2016).

The remainder of the paper is organized as follows. Section two describes the method by introducing the theoretical framework of two different models of conditional convergence of energy intensity. Section three discusses the empirical counterparts of the models to estimate them and the data-set used. Section four analyzes the empirical results and based on the estimated coefficients simulation results over the 21st century. Section five concludes.

2 Analytical model

Our analytical approach relies on a cross-sectional and a panel regression approach to model conditional convergence of energy intensity (EI). The cross-sectional approach, originally introduced within the context of economic growth by Kerr et al. (1960) and famous since the 1960s among macro economists has since then extended to the notion of conditional (Barro, 1991) and club convergence (Baumol, 1986; Phillips and Sul, 2007). It has already been used to simulate energy intensity, but most studies build on the assumption of absolute convergence, which suggests that energy intensity across countries would converge towards a uniform steady state, as countries' dynamics in terms of energy intensity is related to the initial level of energy intensity (Greening et al. (1998), Mulder and De Groot (2012), and Meng et al. (2013) for OECD countries and Markandya et al. (2006), Mohammadi and Ram (2012), and Jakob et al. (2012) for developing countries). Compared to historical improvement rates, annual energy intensity improvements projected by models and organizations such as the International Energy Agency (IEA) have been found to be substantial and often subject to large errors, with a tendency to overestimate EI improvements (Stern, 2017). Understanding the factors that accelerate or hinder convergence is also important to understand the complementary measures that need to be implemented in order to achieve energy efficiency improvements , e.g., required to achieve stringent climate policy targets. Indeed, there is evidence of convergence depending on other factors, that is of conditional convergence (Le Pen and Sévi, 2010). The conditional convergence hypothesis postulates convergence in energy intensity within group of countries with similar characteristics and implies that countries with the same initial energy intensity but with a different structure, socio-economic conditions, policy environment, and institutions would experience different improvement rates. Hence, differences in fundamental characteristics such as education, abundance of natural resources, urbanization rates, institutions can affect the convergence process, and lead to different long-run equilibria in energy intensity (Jorgenson (2006),Fredriksson and Wollscheid (2007) and Castiglione et al. (2012)).

Our principal approach to modeling convergence is to update energy intensity at each point in time, using a model for conditional convergence. That is, we specify that the growth rate of energy intensity, in continuous time notation given by $\frac{\dot{EI_i}}{EI_i}$, where we use the notation $\dot{EI_i} = \frac{dEI}{dt}$, depends on the initial level of (the logarithm) of the value of EI, and some other covariates. First assume to have time interval $(0-T)$ over which to compute the change in energy intensity. Considering that for growth rates of EI_i over the period $0-T$, $\Delta lnEI_{i,T} \simeq \frac{\dot{EI_i}}{EI_i}$, we can write a simple process of conditional convergence as follows:

$$\frac{\dot{EI_i}}{EI_i} = \{\alpha + f(y_i)\} + \beta \ln EI_i \tag{1}$$

where $f(y_i)$ represents the factors affecting the long-run limit of convergence, e.g. those factors upon which convergence is conditional on country-specific additional control variables y_i. Equation (1) is a non-linear non-homogeneous, separable, ordinary differential equation (ODE), which can be solved analytically. The solution of this ODE equation yields a Gompertz curve[2]:

$$EI_{it} = e^{\left(\ln EI_{i0} + \frac{\{\alpha+f(y_i)\}}{\beta}\right)e^{\beta t} - \frac{\{\alpha+f(y_i)\}}{\beta}} \tag{2}$$

The parameters α and β can be estimated through a convergence regression using cross-sectional data. Moreover, equation (2) can be used to project energy intensity improvements into the future in each period.[3] Importantly, for $\beta < 0$, there is a positive long-run limit to the level of convergence defined

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[2] Note that if in the regression one were to use the level of $EI_i(t)$ instead of its logarithm, one obtains a logistic equation for EI_t (with an intrinsic growth rate of the population of $\{\alpha + f(y_i)\}$ and carrying capacity of $-\beta * \{\alpha + f(y_i)\}$), for which the long-run limit becomes $lim_{t\to\infty} EI_i(t) = -\{\alpha + f(y_i)\}/\beta > 0$.

[3] Note that we consider for this example that the exogenous variables y_i are constant over time as in the regression. When actually forecasting EI numerically below, and with exogenous additional time-varying variables in y_i, this will also

as follows[4]:

$$lim_{t \to \infty} EI_{it} = e^{-\frac{\{\alpha + f(y_i)\}}{\beta}} > 0 \tag{3}$$

This value can be considered the minimum energy intensity that can be achieved in the long-run. By solving this differential equation, we implicitly assume that the trajectory of EI is based on an iteratively updated rule based on equation (1). Note that this way we find a finite fixed point or limit of EI, which is a new contribution in the literature on (economic) convergence about it's long-run implications.[5]

Alternatively, and also widely applied in the empirical panel literature, is modeling the annual growth rate in energy intensity as varying over time. In this framework, the factors affecting the long-run limit, $g(y_{it}) = \phi Z_{i,t-1} + \alpha_i$, vary over time, and a linear time trend can be included to account for other time-varying factors not captured by $g(y_{it})$ that affect all cross-sectional units, yielding a modified Gompertz curve that includes a time trend:

$$\frac{\dot{EI}_{it}}{EI_{it}} = \{\alpha_i + g(y_{it})\} + \beta \ln EI_{it} + \gamma t \tag{4}$$

Equation (4) has the following solutions, which we will use for the projection of energy intensity below:

$$EI_{it} = e^{\left(\ln EI_{i0} + \frac{\{\alpha_i + g(y_{it})\}}{\beta} + \frac{\gamma}{\beta^2}\right) e^{\beta t} - \frac{\{\alpha_i + g(y_{it})\}}{\beta} - \frac{\gamma}{\beta^2} - \frac{\gamma}{\beta} t} \tag{5}$$

for which we find the following long-term asymptote at zero:

$$lim_{t \to \infty} EI_i(t) = 0 \tag{6}$$

for $\beta < 0$ and $\gamma < 0$. For $\gamma = 0$, it corresponds to the original Gompertz curve. If any of the two main parameters is positive, it diverges. Both equations (1) and (4) can be taken to the data to estimate the parameters of interest, α_i, β , and γ using a convergence regression, and subsequently combined with projections for $f(y_i)$ and $g(y_{it})$ to project future energy intensity. That is, we can combine convergence regressions with projections based on functions that resemble Gompertz curve patterns.

3 Empirical model and data

Building on the conditional convergence framework outlined in the previous section, we develop two empirical models that we take to the data. We estimate a difference equation version of equation (1) using a cross-sectional convergence regression for energy intensity in country i between time 0 and T. Considering, that for small annualized growth rates, we can approximate $\frac{\dot{EI_i}}{EI_i}$ by the annualized growth rate $T^{-1} \Delta lnEI_{i,T}$ where $\Delta lnEI_{i,T} = lnEI_{i,T} - lnEI_{i,0}$, we can write a simple process of conditional convergence empirically as follows:

$$T^{-1} \Delta lnEI_{i,T} = \alpha + \beta lnEI_{i,0} + \phi Z_{i,0} + \epsilon_i \tag{7}$$

Here, $EI_{i,0}$ is the level of energy intensity at the beginning of the time period considered in country i. The average annual change in energy intensity (EI) between time 0 and T , $T^{-1} \Delta lnEI_{i,T}$, is defined over the period from 1996 until 2016. This equation is the empirical counterpart of (4), where $f(y_i) = \phi Z_i$, are a set of control variables that affect the long-run level of energy intensity. The coefficient β coefficient

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lead to some changes in EI, but it does not change the convergence process qualitatively.

[4] We can rewrite the equation as a weighted average of today's value and the long-term limit as$EI_i(t) = (EI_0)^{e^{\beta t}} \left(e^{-\{\alpha + f(y_i)\}/\beta}\right)^{(1-e^{\beta t})}$.

[5] Note that instead the projection procedure is not performed iteratively, eventually two different starting values will eventually cross and diverge.

is expected to be negative, in line with the hypothesis of conditional convergence. The set of coefficients ϕ will determine whether the hypothesis of conditional convergence is supported by the data.

Secondly, we estimate (4) using a fixed effects panel data model including the convergence term. The dependent variable here is the the annual growth rate of energy intensity, $\Delta lnEI_{i,t} = lnEI_{i,t} - lnEI_{i,t-1}$:

$$\Delta lnEI_{i,t} = \beta lnEI_{i,t-1} + \phi Z_{i,t-1} + \gamma t + \alpha_i + \epsilon_{it} \tag{8}$$

Here, the conditioning function is specified as $\phi Z_{i,t-1} + \alpha_i$, which comprises region and time specific control variables as well as country-specific fixed effect α_i. This specification also includes a common time trend accounting for common, time factors affecting all cross sectional units, such as energy prices or technical change. The Z variables include years of schooling, urbanization rate and a measure of institutional quality.[6] While the existing literature suggests that the coefficients of human capital can be expected to have a negative sign, as these are factors that accelerate the improvements in energy intensity, the literature is less clear about the sign of urbanization and institutions. Whether urbanization has a positive or negative impact on the growth rate of energy intensity depends on how the process is managed, as well as on other socioeconomic factors such as income. Institutional quality, measured as good governance and efficient control of corruption, can also have an impact on energy efficiency improvements.

In order to estimate equations (7) and (8), we construct a country panel data set for the period 1996 - 2016. Energy intensity (EI) is defined as the ratio between total primary energy supply (TPES), and GDP. Total Primary Energy Supply is obtained from the World Energy Balances from the International Energy Agency (IEA)[7] and Gross Domestic Product (GDP) from the World Development Indicators (WDI) measured in USD[PPP] of 2005.[8]

Years of schooling (WDI) is the average years of schooling in the population over 25 years old. Since this variable is available only every five years, we created a new variable schooling as linear interpolation of the original variable as available every five years. Urbanization is the share of population living in urban centers based on WDI data. Institutional quality is measured using the World Governance Indicators (WGI) (Kaufmann et al., 2010), combining several sub-indices as a broad institutional measure as computed in Andrijevic et al. (2020). Table 1 below summarizes the main variables used on the analysis and shows the energy intensity growth rate over different time windows and the initial values.

Table 1: Descriptive statistics

Statistic	N	Mean	Min	Max	St. Dev.
education_years	2,974	7.63	0.91	13.42	3.11
Governance	3,520	0.53	0.09	0.96	0.19
GDP per capita	3,847	11,266.33	170.56	101,844.60	16,026.92
Energy Intensity	2,757	7.35	1.43	40.95	5.25
Urbanisation	3,902	55.22	7.41	100.00	23.37
$T^{-1}\Delta lnEI_{i,T}$	123	−0.36	−1.88	−0.05	0.33

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[6] We also considered the industry share of the economy, which however turned out to be not significant in all specifications.

[7] The energy values are converted from tons of oil equivalent (toe) into Mega Joule (MJ) by using the conversion rate 1 toe= 41,840 MJ.

[8] There are several measurement issues around energy intensity: firstly, one could consider final or primary energy. Secondly, GDP across countries can be compared or by conversion at market exchange rates (MER) and at purchasing power parity (PPP). The two conversions yield different GDP estimations and consequently different energy intensity ratios. In our study we consider GDP converted at PPP. Moreover it is worthwhile to specify that as shown in Levin et al. (2008) using GDP at MER the non-OECD countries exhibit greater amount of energy consumption per unit of economic output with respect to OECD countries, while this difference significantly dwells when using GDP at PPP.

4 Results

4.1 Empirical results

Table 2 shows the result for the conditional convergence regressions using cross sectional data considering the growth rate in energy intensity between 1996 and 2016. Table 3 reports the estimates from the panel data for the same time period. The first specification points at the evidence for absolute convergence using both cross sectional and panel data. When additional covariates are added to test for the hypothesis of conditional convergence, the speed of convergence increases because some of the covariates have an opposite effect. Regarding the impact of urbanization, results from cross-sectional and panel data suggest a positive contribution to the growth rate in energy intensity, suggesting that scale effect and structural changes towards more energy intensive economies tends to prevail over efficiency gains of well-managed urban centers. Yet, the effect of urbanization is not always precisely identified, suggesting that the effect could actually go in both directions. Regarding human capital, both contribute to accelerate the improvement in energy intensity, though the effect is more precisely identified in the cross sectional data. In the panel data model, urbanization has a negative impact on energy intensity improvements, while education has a positive albeit insignificant effect. Finally, improvements in government effectiveness lead to a small and insignificant improvement of intensity improvements. Based on the significance of results, we consider the variables concerning education and urbanization relevant while institutions don't seem to matter in a statistical sense. Hence, we consider the specifications panel regression (3) and cross-sectional specification (3) as our baseline estimates for developing future projections.

Table 2: Energy Intensity trends: Cross section

	(1)	(2)	(3)	(4)
Ln EI	-0.01881***	-0.01931***	-0.01019***	-0.01062***
	(0.00294)	(0.00305)	(0.00254)	(0.00325)
Urbanisation		-0.00006	0.00026***	0.00027***
		(0.00007)	(0.00008)	(0.00009)
School Years			-0.00350***	-0.00320***
			(0.00060)	(0.00067)
Governance				-0.00850
				(0.00972)
Constant	0.01931***	0.02351***	0.01436**	0.01671*
	(0.00551)	(0.00785)	(0.00628)	(0.00863)
Observations	120	120	110	108
Adjusted R^2	0.335	0.333	0.396	0.392

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

4.2 Projections and modeling energy intensity

Building on the empirical results on the convergence relationship described in the previous section, we combine the estimates with scenarios for the SSP elements to project future energy intensity based on the analytical expressions of the solutions of the implied differential equations derived above. We combine the central point estimates of the coefficients associated with the three SSP elements of interest from 2 and with quantitative projections of urbanization, education and institutions, to simulate EI improvements using equation 8. We compare the results from the conditional convergence approach to that from the absolute convergence approach, using the estimates from both the cross sectional and panel model.

Table 3: Energy Intensity trends: Panel model

	(1)	(2)	(3)	(4)
L.ln EI	-0.0947***	-0.0979***	-0.1124***	-0.1507***
	(0.0156)	(0.0154)	(0.0157)	(0.0194)
Time	-0.0017***	-0.0021***	-0.0021***	-0.0025***
	(0.0003)	(0.0003)	(0.0004)	(0.0006)
L.Urbanisation		0.0010	0.0014**	0.0010
		(0.0006)	(0.0006)	(0.0008)
L.School Years			-0.0011	-0.0014
			(0.0035)	(0.0041)
L.Governance				-0.1481**
				(0.0705)
Constant	0.2263***	0.1905***	0.1959***	0.3894***
	(0.0354)	(0.0444)	(0.0516)	(0.0777)
Observations	3261	3261	2949	2274
Adjusted R^2	0.063	0.064	0.075	0.090
Fixed Effects	Yes	Yes	Yes	Yes
Time Dummies	No	No	No	No
Time Trend	Yes	Yes	Yes	Yes

*** p<0.01, ** p<0.05, * p<0.1

Table 4 summarizes the assumptions regarding urbanization, education, and institutions across the five SSP scenarios as described in the SSP narratives in O'Neill et al. (2017). Urbanization and education narratives have already been quantified Jiang and O'Neill (2017) and KC and Lutz (2017)) and therefore we use the scenarios available in the IIASA SSP database (Riahi et al., 2017).

	SSP1	SSP2	SSP3	SSP4	SSP5
Urbanisation	High Well-managed	Medium Continuation of historical patterns	Low Poorly managed	High, high, medium Mixed across and within cities	High Better managed over time, some sprawl
Education	High	Medium	Low	Uneven	High
Institutions	Effective	Uneven, modest	Weak	Effective for elite, not for rest of society	Increasingly effective competitive markets

Table 4: Summary of assumptions regarding urbanization, education, institutions. Source: O'Neill et al. (2017)

Regarding the role of institutions, quantitative pathways implementing the qualitative patterns described by O'Neill et al. (2017) have been developed in (Andrijevic et al., 2020) providing pathways of a broad governance measures combining government effectiveness, control of corruption, voice & accountability, political stability, rule of law, and regulatory quality.

Figure 1 shows the resulting projected trends for education, urbanization, and institutions throughout the century, at the global average level considering the average path across all countries. On average education increases from the 2010 value of around 9.5 years of schooling to more than 12 years in SSP1, SSP2, and SSP5, whereas it even decreases due to population shifts in the other SSPs. Urbanization trends are significant across all SSPs, raising the share of people living in urban centers from the present value of 56% to between 58% in SSP3 to more than 90% in SSP1, SSP4 and SSP5. Institutional quality, here measures as the effectiveness of government, varies across world regions, and is assumed to increases in SSP1 and SSP5, while it declines in SSP3 and slightly increases in SSP4 whereas it is assumed to stay constant in SSP2.

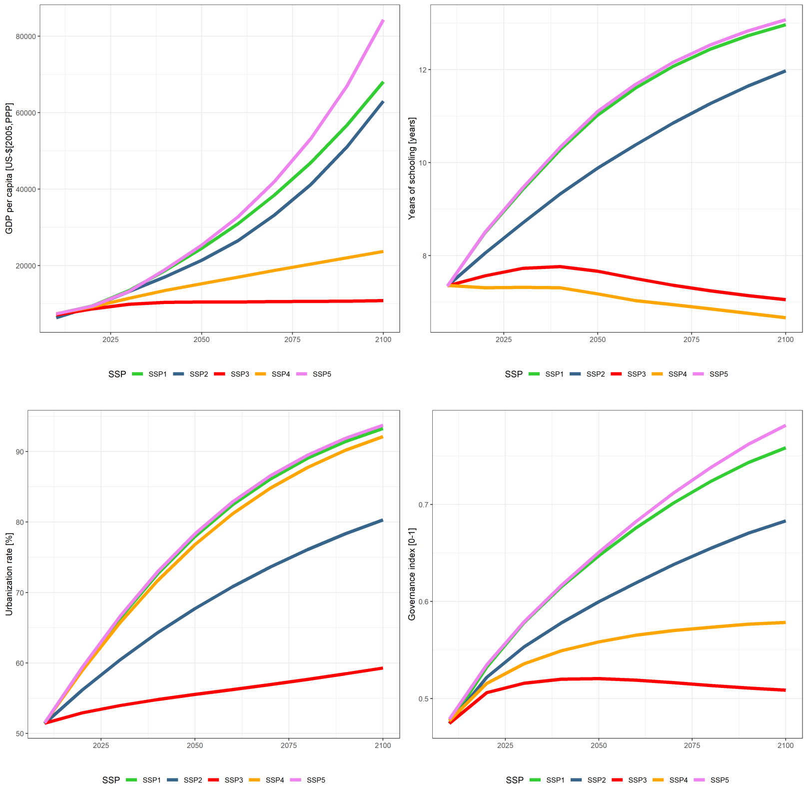

Figure 1: Projections of GDP per capita, Education, Urbanization, and Governance according to the SSPs

Figure 2 displays our preferred specifications Convergence (3) and Panel (3) compared with the SSP IAM model implementations from Bauer et al. (2017) (as shaded grey ribbon showing the range of all maximum six model implementations.[9] All estimated specifications are presented in Figure 3 in the Appendix, and show in general similar results.

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[9] Note that due to different base year calibrations and PPP definitions, historical and base year values sometimes differ.

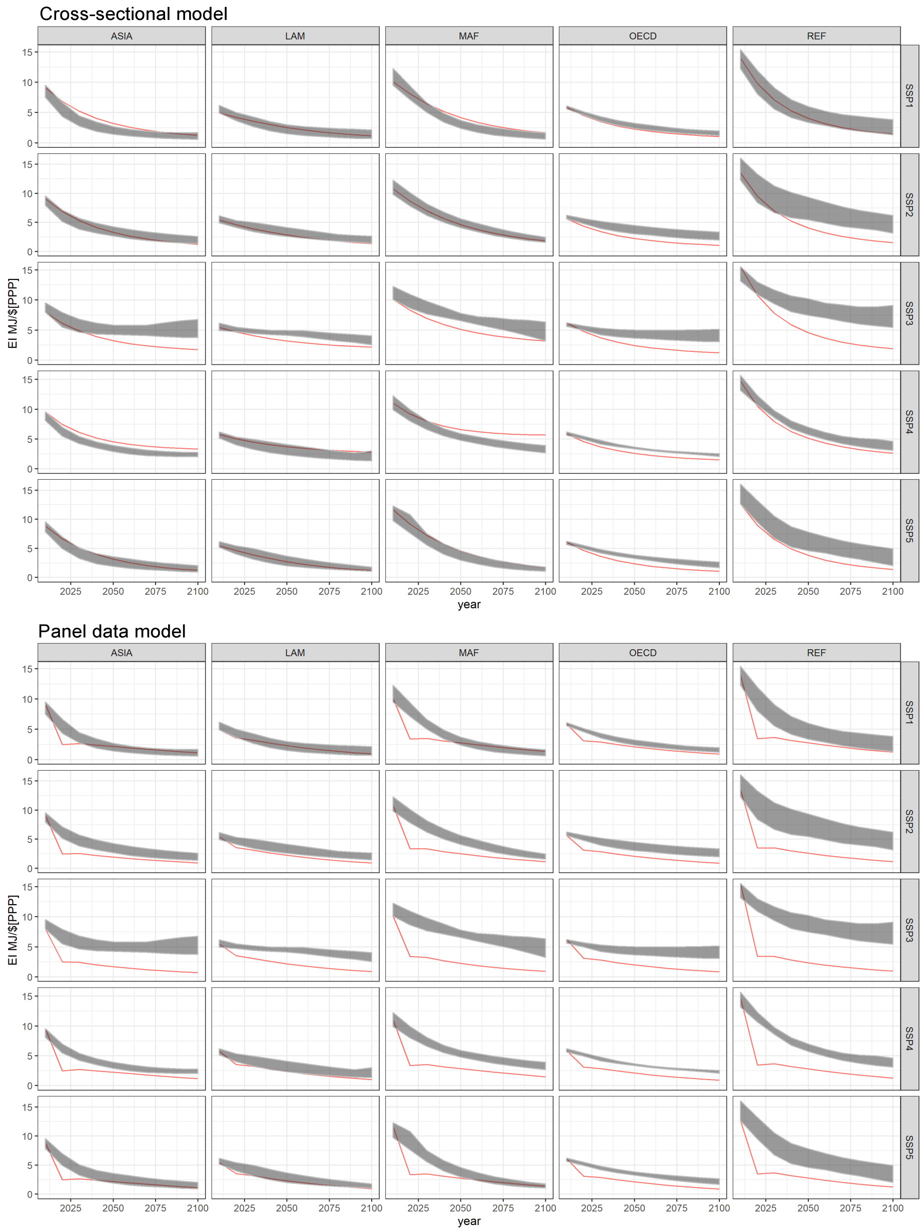

Figure 2: Projected energy intensity across SSPs and regions, cross-sectional and panel specifications and SSP range (shaded).

Across the five different story lines of the SSPs, the implications for energy intensity can now also be based on the underlying baseline assumptions. Firstly, different assumptions about population and productivity growth have a substantial impact on energy demand. Secondly, the projections for educational attainment and urbanization varies significantly across SSPs. The strong convergence pattern across regions is clearly visible in both frameworks. In the case with an exogenous time trend reflecting secular improvements of energy efficiency over time, energy intensity improves significantly reaching consistently values slightly around $1MJ/\$$ by the end of the century in almost all regions.

Starting from the level of around $6.5MJ/\$$ in 2010, Table 5 shows the projected energy intensities across SSPs for the two baseline specifications Convergence (3) and Panel (3) as well as the SSP Marker scenarios of Riahi et al. (2017).

The resulting energy intensity estimates for 2100 range between 0.8 and $3.1MJ/\$$ by 2100 depending

SSP	EI_conv (3)	EI_panel (3)	SSP Marker Scenario
SSP1	1.314	1.131	1.238
SSP2	1.391	0.987	2.396
SSP3	2.057	0.836	4.406
SSP4	3.126	1.138	2.566
SSP5	1.321	1.114	1.769

Table 5: Projected Energy intensity values in 2100 [MJ/$]

on the scenario and estimation. SSP4 hows the slowest improvement rate, while SSP1 and SSP2 tend to allow energy intensities to drop to a value between 0.9 and 1.4 $MJ/\$$. If the time trend is projected, notably energy intensity falls to around a value of $0.8-1.3 MJ/\$$ by 2100 driven to a large extend by this secular improvement estimated in the data. Based on the simple convergence on the other hand, values between 1.5 and 2.8 are found for the end of century, broadly in line with the results from IAM models as reported in Bauer et al. (2017) and shown in the last column of Table 5. Notably, we make use of the public SSP database that has implemented each SSP within each (attainable) RCP by six different Integrated Assessment Models (IAMs), and we chose the so-called "Marker" model for each SSP.[10]

Our main focus here are the long run attainable minimum values of energy intensity which we analyze in the following. As shown above, we find that a strictly positive limit can be established in the conditional convergence case, while a secular time trend in addition would imply asymptotically approaching an energy intensity of zero. These long-run limiting values at the global level are shown in Table 6.

	SSP1	SSP2	SSP3	SSP4	SSP5
EI_Cronv (3) limit	0.352	0.350	1.076	2.997	0.353
EI_Panel (3) limit	0.000	0.000	0.000	0.000	0.000

Table 6: Long-term EI limits [MJ/$]

In the conditional convergence case, we find a value of around $0.35 MJ/\$$ in the SSPs 1, 2, and 5 - reflecting a rather favorable socioeconomic development. In the SSPs following regional rivalry or inequality (SSP3 and SSP4), much higher limits are found of between 1 and $3 MJ/\$$, showing the importance of economic, institutional, and educational drivers. For the other SSPs, a remarkable similar value of $0.35 MJ/\$$ is found, which moreover is far below projected values by 2100, showing that it takes over one century to reach the theoretical limit and convergence is relatively slow in terms of energy. These results can be thought of an additional "stylized fact" in the context of energy intensity patterns such as the one established in Smulders and de Nooij (2003); Gales et al. (2007); Kander et al. (2014); Csereklyei et al. (2016): in terms of long-run energy required to produce one unit of GDP we find that a strictly positive limit can be established in the conditional convergence case.

We can also compare these results to the scenario database of the IPCC SR15 special report. Based on the full set of scenarios reporting primary energy and GDP (80 scenarios), for 2100, the range of energy intensities ranges from 0.47 to $2.20 MJ/\$$ with an average of $1.29 MJ/\$$. Our results suggest that these values for 2100 could in general be considered as compatible with the range of extrapolating patterns from historical values. Values below unity within 80 years on the other hand seem challenging and will require structural dynamics well beyond historical patterns. An interesting case is the lowest value of $0.47 MJ/\$$, which has been obtained in the Low Energy Demand (LED) scenario (Grubler et al.,

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[10] While several SSPs have been implemented in many models, we chose the marker model to abstract from additional uncertainty due to the use of different models. We did run the results with all models though (results are available from the authors upon request) and the results are very similar and SSP/RCP differences by far dominate model uncertainty in this application.

2018), precisely developed to consider the maximum possible efficiency improvements and energy demand reductions. And in fact, we find that the obtained value is very close to our theoretical long-run limit of $0.35 MJ/\$$ based on the conditional convergence specification, our findings suggest that obtaining such a value within only 80 years goes beyond anything we have seen in the past. This shows that, while conceptually attainable, achieving such efficiency improvements by the end of the century will require economy-wide substantial efforts.

5 Conclusions

We find that based on a conditional convergence model, energy intensity has historically been improved across regions in a rather consistent way. We apply two widely used models based on a cross-sectional and panel data approach. Moreover, additional explanatory variables have been found to affect how energy efficiency changes over time, even though the effect differs in some cases between both econometric models. Both models find a strong convergence effect, and that increasing urbanization rates are shown to have a negative impact on energy intensity improvements. Weaker evidence is found for the level of education leading to faster improvements in energy intensity and improved governance increasing energy intensity improvements.

We link the estimated econometric models to an iterative projection model based on ordinary differential equations, allowing us to compute projected energy intensities for the year 2100, which vary between 0.8 and 3.1 $MJ/\$$. Moreover, we show that based on the cross-sectional model we find a the strictly positive long-term limit of global energy intensity, which we estimate to be about $0.35 MJ/\$[2005, PPP]$, down from its value in 2010 of about $6.5 MJ/\$$. Only in very challenging scenarios including SSP 3 and SSP4, the long-term limit lies much higher around 2 to 3 $MJ/\$$. In the conditional convergence case, this level of energy used per dollar of GDP thus provides a lower limit of energy intensity, while in the panel regression model with time trend, the lower limit equals zero, even though it is only reached several centuries into the future. We are thus the first to quantify this potential long term techno-economic level based on purely historical observations, and find it to be not too far away from the Low Energy Demand scenario of Grubler et al. (2018) recently developed and discussed in the IPCC's SR15 report.

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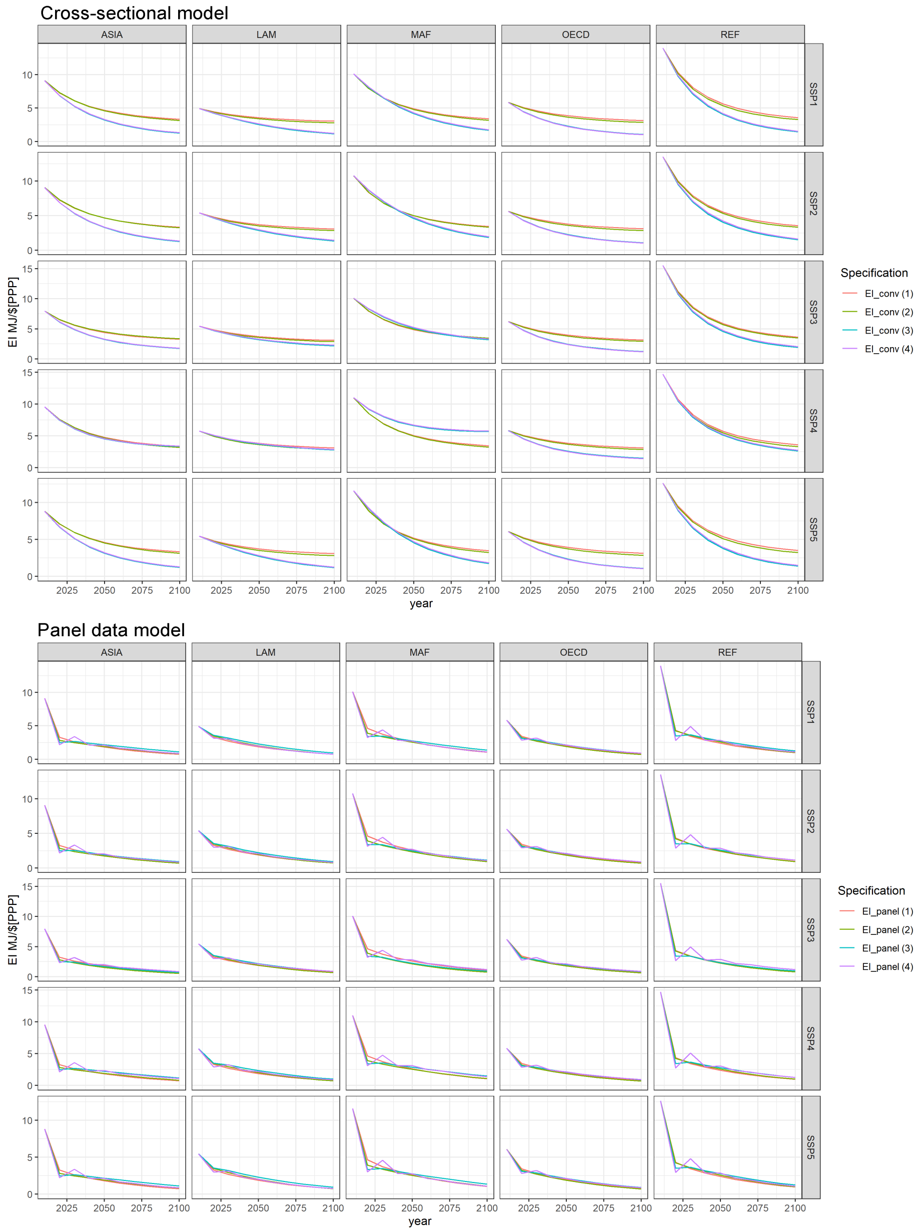
A Additional Figures


Cross-sectional model

Panel data model

Figure 3: Projected energy intensity across SSPs and regions, all specifications

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