Report on the role of energy efficiency in strengthening the Paris climate agreement

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This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 723791.

Contents

1. Summary for policymakers

Both energy efficiency and greenhouse gas emission reductions are key pillars of the energy transition. Europe energy and climate strategy highlights both as indispensable tools. Similarly, the 1.5 special report of the IPCC has highlighted how low energy demand is key for attaining stringent climate targets without the need for heavy infrastructural changes and negative emissions. Furthermore, energy efficiency can generate significant co-benefits, such as improved air quality, reduced energy expenditures and limited reliance on energy imports.

Despite the clear inter-relation between energy efficiency and GHG reductions, so far most of the model based assessments of the Paris agreement has relied on supply side, technological based transformation. This report focuses on the role of energy demand and energy efficiency when envisioning future trends with and without climate policies. We use mixed methods combining empirical and model based approaches to evaluate how energy demand will evolve in the future, and what can energy efficiency improvements do to help Europe and the world meet the Paris agreement targets.

The results show dramatic variations in future energy trends in the absence of global climate cooperation. Depending on the evolution of socio-economic, behavioural and institutional factors, energy intensity will vary by as much as three times. These different futures bear different consequences for the actions needed to comply with the 1.5-2°C Paris targets. The model based analysis show that energy efficiency induced by price changes and regulation can help achieve the decarbonization objectives at lower social costs. But it also indicates an immediate need to invest in research and development of new, more efficient products and services, as well as to devise policy provisions to limit rebound effects.

2. Executive Summary

The purpose of this deliverable is to analyze the role of energy efficiency in future energy transition scenarios. Mitigation pathways have traditionally focused on the low carbon technological transformation. However, meeting stringent climate objectives will require significant reductions in energy use. Energy efficiency can also provide important co-benefits, in terms of improved air quality and enhanced energy security. This report uses three complementary approaches to evaluate future trends of energy demand, and ways to improve energy efficiency globally and in Europe.

In a first part, we provide an empirical assessment of the drivers of one key indicator of energy efficiency, namely energy intensity. We use these empirically based methods to project energy intensity in the future in different baseline scenarios. We apply our estimates to the the Shared Socio-economic Pathways (SSPs) framework: this distinguishes 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. The results highlight dramatically different future energy intensities across SSPs, driven by different evolution of socio-economic drivers. Between the most and less efficient scenarios, energy intensity forecasts vary by a factor of three.

In a second part, we evaluate the role of energy efficiency and energy demand for meeting the Paris climate accord. We use a leading integrated assessment model (the WITCH IAM), calibrated using the empirical estimates developed in the first part of the report, to evaluate three scenarios of increasing stringency. We identify the energy efficiency gap in the context of the Paris climate and the requirements in investment in R&D to fill these gaps. The intended nationally determined contributions (INDCs) of the main global emitters are evaluated by the models up to 2030, and extrapolated beyond that date with different assumptions about the ramping up of the climate mitigation ambition. We show the importance of energy efficiency in achieving the Paris goals. Already in 2030, global energy intensity should be improved by 25% if the world wants to meet the 2°C long term target. Furthermore, significant investments in research and development for developing new energy efficient products should be ramped up.

In the final part of the report we specifically analyse the impact of energy efficiency (namely efficiency improvements of electric appliances) in the residential sector. We focus on residential electricity demand and investigate the associated impact on production

and CO2 emissions in Germany and Europe. To analyse regional and global demand and supply, we take into account endogenous price changes and the linkages between regions and markets, using a computable general equilibrium model (CGE). Results show that improvements of electric energy services reduce electricity consumption and increase welfare. However, due to rebound effects, the full energy efficiency changes are attained.

The report employs three complementary methodologies which help provide a more comprehensive view of the role of energy efficiency for the energy transition than previously done. Nonetheless, the difficulty of capturing long term uncertainties and including behavioural changes should be acknowledged. Resorting to multiple scenarios and empirically estimated heuristics is an attempt to limit these risks.

3. Patterns of future energy efficiency

3.1 Introduction

Energy demand growth is one of the key challenges for the energy sector [1], and improving energy efficiency is critical for reducing greenhouse gas emissions while addressing the goals of sustainable development related to poverty [16]. 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 [50, 51]. Between 1995 and 2007, world gross output increased by 53.2%, while energy use expanded only by 27%. Thus, resulting in a sharp decline of energy intensity, the total energy consumption over the gross domestic product, by 18%. While annual historical improvement rates have been around 1.3% and 0.99% for non-OECD and OECD countries, respectively[1], mitigation goals require an acceleration in the reduction of energy intensity and improvements of energy efficiency. The IPCC 5th Assessment Report database projects future average annual improvement rates of energy intensity (EI) between 2010 and 2100 up to 2.23% per year.[2] The development of energy intensity and efficiency depends on structural drivers - the composition of economic activities within a specific country, technological factors - diffusion of innovative technologies, as well as behavioral factors - lifestyles as expressed by consumer choices- which are well captured in good governance and institutions. The actual implementation of environmental policies and their effective influence on behaviors and environmental outcomes in fact depend on the broader institutional setting[48]. Good governance and transparency are important, as bureaucrats are the actors ultimately implementing environmental interventions [33], and indeed the influence of institutional quality is apparent even in relation to aggregate outcomes, such as energy intensity and efficiency[14].

How energy efficiency 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

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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/$

[2] In practical energy policy analysis, the typical indicator used at the country level to measure energy efficiency is energy intensity, defined as the ratio of energy consumption to GDP.

Pathways (SSPs) provide the 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 [41]. Several publications have already shown how to translate SSP narratives into assumptions that can be used in Integrated Assessment Models (IAMs) focusing on the quantitative SSP elements (i.e. population, GDP, urbanization and education)[44]. 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 [1].

In this section 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, which is a widely used indicator to measure energy efficiency at the country level. 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 [8], as institutions can affect mitigation costs as well as their distribution [19]. Earlier model-based work, such as those presented in AR5 [4], has already shifted from first-best transition pathways (fully oriented towards cost-optimality under perfect conditions) to second-best transition pathways (exploring sociopolitical and innovative limitations) [29, 28, 27, 47, 44]. Given the rather techno-economic orientation of this type of assessment, contextual factors such as institutions remain rather under-explored due to the rather techno-economic orientation of quantitative integrated assessment models (IAMs). In models, the representation of institutions is limited to the actions of the state or the government for which regulations and policies are generally represented as an exogenous shock/disruption implemented by a social planner. The focus of the quantitative models like IAMs is on institutions such as regulations and policy prescriptions, whereas contextual factors (e.g. governance) are implicitly assumed not influence the implementation and the outcome of those policies. Once the policy is adopted, its effectiveness is generally assumed to be unaffected by the institutional framework, as models assume the same governance style and power structures over centuries. Yet, the increasing focus on implementation of policies and the transition dynamics toward long-term objectives requires more attention on how the changes will take place and ways to accelerate them.

We focus on energy intensity because this is the most important determinant of uncertain future energy demand and emissions [34], and use a convergence approach to simulate future energy intensity as a process driven by urbanization, education, investments and institutions. Convergence in energy intensity has been already found an important driver of energy demand [7, 6]. We use historical data to estimate both absolute and conditional convergence in energy intensity across world countries and subsequently combine the estimated coefficients with quantitative projections and assumptions of the selected SSP elements to project future energy intensity. This modified representation of energy intensity dynamics has several implications. Calibrating energy intensity

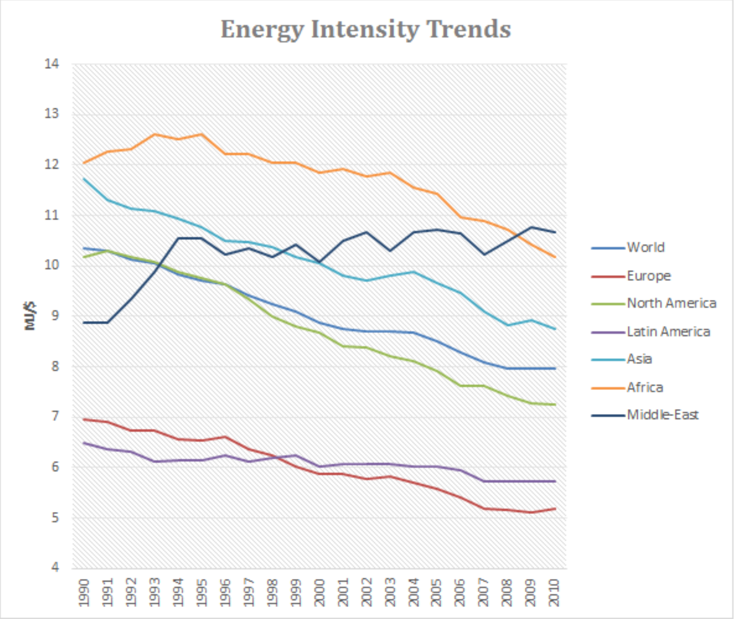

Figure 3.1: Energy intensity for selected regions, 1990–2010

dynamics on conditional convergence leads to *lower* speed of convergence in IAMs, and therefore higher long-run energy intensity levels compared to existing models and projections that tend to overestimate improvement rates [49]. Our approach contributes also an additional "stylized fact" in the context of energy intensity patterns related to [46, 17, 24, 6] in terms of long-run energy required to produce one unit of GDP.

The remainder of the study is organized as follows. Section two describes the method by introducing the theoretical framework of two different models 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.

3.2 Analytical model

Our analytical approach relies on cross-sectional convergence and a panel regression approach to model energy intensity (EI) dynamics. The convergence approach has already been used to calibrate future energy intensity in IAMs, but most models 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 [18, 39, 37] for OECD countries and [35, 38, 20] for developing countries). For example, WITCH calibrates energy demand across regions and over time by estimating energy demand elasticities using historical data, and by assuming that the elasticities fall exponentially[11].

Simulated energy intensity patterns result in a convergence that is stronger than what historical records would suggest, even in the absence of dedicated climate or energy policies. 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 [49]. Comprehending the factors that accelerate or hinder convergence is also important to understand the complementary measures that need to be implemented in order to ensure policy effectiveness. Indeed the empirical literature also find evidence of conditional convergence [30]. 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, energy mix, energy prices, policy, and institutions would experience different improvement rates. Across-countries differences in fundamental characteristics such as investment rates, schooling, natural resources, urbanization rates, institutions affect the convergence process, and lead to different long-run equilibrium in energy intensity [23, 15, 3].

There is empirical evidence suggesting that urbanization, physical and human capital, as well as institutions, which are important elements of the SSP story-lines, affect aggregate energy intensity patterns and energy convergence, which is another SSP dimension [45, 50, 14]. The empirical evidence on the impact of urbanization on energy use and energy intensity is mixed [45, 10] 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 [32]. The extended SSPs story-lines [1] also suggest that the impact of urbanization on energy intensity depends on how the process is managed. In the SSP5 scenario, a fossil-fueled development where energy demand is strongly correlated with economic growth and preferences for intensive material consumption and transportation patterns prevail, urbanization is associated with higher energy intensity[1]. On the contrary, in SSP1, urbanization rates are high, but well-managed, and the combination with adoption of efficient end-use technologies enables a transition to a lower energy intensive economy.

More capital and human capital-intensive economies should be less energy intensive as these inputs substitute for energy [50]. Investments and capital turnover has been shown to be correlated with income convergence [43]. 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 [2, 5]

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 [36], R&D [9], and energy intensity [14]. 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. [13, 14] find that more corrupted countries have less stringent environmental policies.[3] [36, 19] 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. [9] 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. First, we investigate the empirical relationship between these variables and energy intensity using historical data on energy intensity, gross fixed capital formation, years of schooling, urbanization, and institutional quality. Second, we combine the estimated relationship with quantitative projections (urbanization, education, GDP, population, investments) and assumptions (institutions) to project future energy intensity across different SSP scenarios. Before turning to the empirical and modelling results, next section describes the two conditional convergence approaches that can be used to simulate energy convergence over future years.

3.2.1 A conditional convergence approach

A first approach to modelling convergence is to update energy intensity at each point in time, using a model for conditional convergence. First assume to have time interval (0-T) over which to compute the change in energy intensity. Considering that for small changes in country i 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:

$$\frac{\dot{EI_i}}{EI_i} = \{\alpha + f(y_i)\} + \beta \ln EI_{i0} \tag{3.1}$$

where we denote $\dot{EI_i} = \frac{dEI}{dt}$ and $f(y_i)$ represents the factors affecting the long-run limit of convergence, e.g. those factors upon which convergence is conditional, $f(y_i) = \phi_1 Z_i + \phi_2 I_i$. Equation (3.1) is a non-linear non-homogeneous, separable, ordinary differential equation (ODE), which can be solved analytically. The solution of this ODE

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[3] Corruption was captured by the political risk index developed by the ICRG. Democracy index produced by Freedom of House instead was used to represent Democracy.

equation is a variant of the Gompertz curve[4] :

$$EI_{iT} = e^{\left(\ln EI_{i0} + \frac{\{\alpha+f(y_i)\}}{\beta}\right)e^{\beta t} - \frac{\{\alpha+f(y_i)\}}{\beta}} \tag{3.2}$$

The parameters α and β can be estimated with a convergence regression using cross-sectional data (see next section). Equation (3.2) can be used to project energy intensity improvements into the future in each period.[5] For $\beta < 0$, there is a positive long-run limit to the level of convergence defined as follows[6]:

$$lim_{T\to\infty} EI_{iT} = e^{-\frac{\{\alpha+f(y_i)\}}{\beta}} > 0 \tag{3.3}$$

This value can be considered the minimum energy intensity that can be achieved in the long-run.

3.2.2 A panel regression approach

Equation (3.1) can be modified to model the annual growth rate in energy intensity as varying over time. In this framework, the factors affecting the long-run limit, $g(y_{it}) = \phi_1 Z_{i,t-1} + \phi_2 I_{i,t-1} + v_i$, 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 the following modified Gompertz curve:

$$\frac{\dot{EI}_{it}}{EI_{it}} = \{\alpha + g(y_{it})\} + \beta \ln EI_{it} + \gamma t \tag{3.4}$$

Equation (3.4) has the following solutions: :

$$EI_{it} = e^{\left(\ln EI_{i0} + \frac{\{\alpha+g(y_{it})\}}{\beta} + \frac{\gamma}{\beta^2}\right)e^{\beta t} - \frac{\{\alpha+g(y_{it})\}}{\beta} - \frac{\gamma}{\beta^2} - \frac{\gamma}{\beta}t} \tag{3.5}$$

for which we find the following long-term limit as zero:

$$lim_{t\to\infty} EI_i(t) = 0 \tag{3.6}$$

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 (2) and (5) can be taken to the data to estimate the parameters of interest, α, β , andγ using a convergence regression, and subsequently combined with projections for $f(y_i)$ and $g(y_{it})$ to project future energy intensity.

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[4] 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 $lim_{t\to\infty} EI_i(t) = -\{\alpha + f(y_i)\}/\beta > 0$.

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

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

3.3 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 equation (2) using a cross sectional convergence regression for energy intensity in country i between time 0 and T:

$$\frac{1}{\mathrm{T}}\Delta lnEI_{i,T} = \alpha + \beta lnEI_{i,0} + \phi_1 Z_i + \phi_2 I_i + \epsilon_i \tag{3.7}$$

where $EI_{i,0}$ 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 , $\frac{1}{\mathrm{T}}\Delta lnEI_{i,T}$, is defined over the period from 1990 until 2010. This equation is the empirical counterpart of (3.1), where $f(y_i) = \phi_1 Z_i + \phi_2 I_i$, are a set of control variables that affect the long-run level of energy intensity. The β coefficient is expected to be negative, in line with the hypothesis of absolute convergence. The coefficients ϕ_1 and ϕ_2 will determine whether the hypothesis of conditional convergence is supported by the data.

We estimate equation (5) using conditional convergence regression with panel data. The dependent variable is the the annual growth rate of energy intensity, $\Delta lnEI_{i,t} = lnEI_{i,t} - lnEI_{i,t-1}$:

$$\Delta lnEI_{i,t} = \alpha + \beta lnEI_{i,t-1} + \phi_1 Z_{i,t-1} + \phi_2 I_{i,t-1} + \gamma t + +\nu_i + \epsilon_{it} \tag{3.8}$$

Here, the conditioning function is specified as follows: $g(y_{it}) = \phi_1 Z_{i,t-1} + \phi_2 I_{i,t-1} + \nu_i$. It comprises region and time specific control variables, as well as country-specific fixed effect ν_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 investments in physical capital, years of schooling, and urbanization rate, while I refers to a measure of institutional quality. While the existing literature suggests that the coefficients of physical and 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.

Equations (3.7) and (3.8) are estimated using Ordinary Least Squares. When estimating Equation (3.8), we include country-fixed effects to control for unobserved country-specific factors and a time trend to control for shocks that affect all cross sectional units, such as oil prices. For inference we use standard errors that are robust to heteroscedasticity. Next section discusses the data sources used to estimate equations (3.7) and (3.8).

3.3.1 Data

We construct a country panel data set for the period 1990 - 2010. 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 IEA (2016)[7] and Gross Domestic Product (GDP) from the World Development Indicators (WDI, World Bank, 2015) measured in USD[PPP] of 2005.[8]

Investment is proxied by the percentage of gross investments over GDP at the beginning of the period as gross fixed capital formation, using WDI data. Years of schooling (WDI) is the average years of schooling in the population over 25. Years of schooling is available every five years. We create a new variable schooling as linear interpolation of the original variable. Urbanization, is the share of population living in urban centers from the WDI.

Institutional quality is measured using the World Governance Indicators (WGI) [25]. The WGI institutional quality indicators are measured on a normalized scale from -2.5 to +2.5, where the highest value indicate better institutions. We focus on control of corruption and government effectiveness. Control of corruption measures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. A lower score indicates a higher level of corruption (or a lower level of corruption control). Governance effectiveness is an indicator of bureaucratic quality and speed. Low levels of government effectiveness (low score) can be associated with excessive regulations, lengthy processes, and lower transparency in the form of flow of information. Table 3.1 summarizes the main variables used on the analysis and shows the energy intensity growth rate over different time windows and the initial values.

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[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 [31] 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.

Variables	N	Mean	sd	Min	Max	Source
Energy intensity (MJ/$)	2,351	14.23	14.32	0.365	113.8	IEA (2016) and WDI (2015)
Energy intensity, log	2,351	2.333	0.772	-1.007	4.735	IEA (2016) and WDI (2015)
Energy intensity, growth rates	2,187	-0.0159	0.0694	-0.608	0.530	IEA (2016) and WDI (2015)
Urbanisation (%)	3,553	56.07	24.87	7.211	100	WDI, World Bank, 2015
Schooling (n. of years, interpolated)	2,304	7.309	3.089	0.650	13.42	WDI (2015)
Years of schooling (n. of years)	576	7.311	3.109	0.650	13.42	WDI (2015)
Investments (% of GDP)	2,958	23.48	11.15	-2.424	219.1	WDI (2015)
Government effectiveness(index)	3,075	-0.0196	1.003	-2.454	2.431	WB WGI (Kauffman et al. 2010)
Control of corruption (index)	3,078	-0.0201	1.009	-2.057	2.586	WB WGI (Kauffman et al. 2010)

Table 3.1: Summary statistics for the period 1990-2010.

3.4 Results

3.4.1 Empirical results

	Δ EI (1990-2010)			
Variables	(1)	(2)	(3)	(4)
ln Energy Intensity	-0.00672**	-0.01184***	-0.01333***	-0.01266***
	(0.023)	(0.000)	(0.000)	(0.000)
Urbanisation		0.00006	0.00007	0.00008
		(0.592)	(0.477)	(0.427)
Control of corruption			-0.00329	
			(0.192)	
Schooling		-0.00314***	-0.00251***	-0.00271***
		(0.000)	(0.005)	(0.003)
Investments		-0.00039*	-0.00033	-0.00035
		(0.095)	(0.203)	(0.181)
Government Eff.				-0.00268
				(0.348)
Constant	0.00705	0.04383***	0.04203***	0.04170***
	(0.272)	(0.000)	(0.000)	(0.000)
Observations	90	90	90	90
R-squared	0.075	0.307	0.326	0.316

Robust p values in parentheses
*** p<0.01, ** p<0.05, * p<0.10, + p<0.15

Table 3.2: Conditional convergence results.

Table 3.2 shows the result for the conditional convergence regressions using cross sectional data considering the growth rate in energy intensity between 1990 and 2010.

Table 3.3 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 section 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 and physical 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, investments are never significant, whereas schooling becomes significant when the original data at five year time step are used (specifications (2) and (3) use the annual interpolation of the original education data). Regarding the role of institutions, we test two indicators, corruption control and government effectiveness. Both significantly contribute to accelerate the reduction in energy intensity. Based on the empirical fit and significance, we consider the specifications Panel regression (5) and Conditional convergence (3) as our baseline estimates for developing future projections.

3.4.2 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 from 2015 onwards. We combine the central point estimates of the coefficients associated with the three SSP elements of interest from 3.2 and with quantitative projections of urbanization, education and institutions, to simulate EI improvements using equation 3.8. 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 3.4 summarizes the assumptions regarding urbanization, education, and institutions across the five SSP scenarios as described in the SSP narratives in [42]. Urbanization and education narratives have already been quantified [21] and [26]) and therefore we use the scenarios available in the IIASA SSP database [44]. Note that investment/saving rates have not been explicitly modelled in the SSP scenarios, we use an historical broad average of 20% of GDP for all scenarios.

	Δ EI					
Variables	(1)	(2)	(3)	(4)	(5)	(6)
Lag ln EI	-0.14159***	-0.15800***	-0.16635***	-0.10110**	-0.11680***	-0.11794***
	(0.000)	(0.000)	(0.000)	(0.018)	(0.004)	(0.007)
Lag Urbanisation		0.00262*	0.00255*		0.00306	0.00265
		(0.086)	(0.086)		(0.157)	(0.207)
Lag Schooling		-0.00695	-0.00546			
		(0.254)	(0.379)			
Lag Investments		-0.00031	-0.00033		-0.00065	-0.00067
		(0.502)	(0.488)		(0.556)	(0.528)
Lag Control of corruption		-0.02252**			-0.02840	
		(0.018)			(0.139)	
Time	-0.00181***	-0.00213**	-0.00231**	-0.00366***	-0.00231	-0.00209
	(0.002)	(0.047)	(0.030)	(0.001)	(0.194)	(0.237)
Lag Gov. Eff.			-0.03472***			
			(0.002)			
Lag Years of schooling					-0.02334**	-0.02255**
					(0.012)	(0.014)
Constant	0.38965***	0.34716***	0.37200***	0.38057***	0.37497***	0.38945***
	(0.000)	(0.000)	(0.000)	(0.006)	(0.008)	(0.009)
Observations	1,740	1,740	1,740	355	355	355
R-squared	0.079	0.089	0.092	0.078	0.109	0.107
Number of id2	125	125	125	125	125	125
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time dummies	No	No	No	No	No	No
Time trend	Yes	Yes	Yes	Yes	Yes	Yes

Robust p values in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 3.3: Panel regression results.

	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 3.4: Summary of assumptions regarding urbanization, education, institutions[42].

Regarding the role of institutions, quantitative pathways implementing the qualitative patterns described by [42] are described in Table 3.4. To put things in perspective, historically institutional quality, measured either in terms of corruption control or government effectiveness, has ranged between very low values close to -2 in countries such as Afghanistan or Somalia, to very high values in Nordic European countries, New Zealand and Singapore. For a given country, changes in institutional quality over time are in the order of 0.2 standard deviation, suggesting that, for example, a standard deviation increase in institutional quality is a large change that during the historical period considered (1990-2010) has been observed only in the United Arab Emirates or in Qatar, where the control of corruption indicator rise from -0.09 in 1990 to 0.93 and to 1.5 in 2010, respectively. We differentiate the assumptions on future development of institutions by OECD and non-OECD regions. The SSP2 scenario is called Middle of the Road because it follows a path that does not significantly shift from historical patterns. Institutional quality is also assumed to remain equal to the present level across all countries. In the SSP1, the sustainability scenario, institutions are effective at national and international level. We model this narrative by assuming that OECD countries converge to the highest level of institutional quality.[9] In SSP3, the Regional Rivalry scenario characterized by a resurgent nationalism and concerns about competitiveness and security, institutions are generally weak. We model this assuming their quality remain constant in OECD countries, while there is convergence to the lowest quartile in non-OECD regions. In SSP4, the Inequality scenario, characterized by increasing disparities in economic opportunity as well as political power, institutions are effective for the elite of internationally-connected societies, leaving behind lower-income and poorly educated population. In SSP5, the fossil-fueled development scenarios, institutions are highly effective and aimed at enhancing human and social capital. Table 3.5 summarizes our assumptions about the level of institutions.

Figure 3.2 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 2015 value of 6.7 years of schooling to more than 13 in SSPs 1 and 2, whereas it remains lower than 11 years 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 70%

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[9] Which is Canada, given we consider the seventeen regions of the WITCH model to aggregate basically across 17 (sub)continents and large countries, see [11].

SSP	OECD	non-OECD
SSP1	Convergence to highest value (+1.71)	Convergence to highest value (+1.71)
SSP2	Constant at 2005 levels	Constant at 2005 levels
SSP3	Constant at 2005 levels	Convergence to lowest quartile (-0.90)
SSP4	Convergence to highest quartile (+1.45)	Constant at 2005 levels
SSP5	Convergence to highest quartile (+1.45)	Convergence to highest quartile (+1.45)

Table 3.5: Assumptions about institutional development across SSPs

in SSP3 to more than 90% in SSP5 and SSP4. Institutional quality, here measures as the effectiveness of the control of corruption, 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.

Combining the projected trends of the SSP elements with the estimated elasticities, Figure 3.3 compares the resulting pattern in global average energy intensity with patterns resulting from the qualitative implementation of the extended SSPs as in [1]. The figure displays all specifications we estimate, and compares it with historical values over the last two decades (in pink), and the model range from the SSP database (in shaded grey). Energy Intensity predictions vary substantially across regions and specifications. Based on the empirical results reported above, we consider the specifications Convergence (3) and Panel (5) as our baseline empirical models and discuss these specifications further.

Across the five different story lines of the SSPs, the implications for energy intensity can now also be based on the underlying baseline assumptions, plus additional assumptions about the explanatory variables of energy demand. 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.

Given the empirical analysis in this analysis, we find based on our base specification that the level of energy intensity in 2010 globally was $7.5MJ/\$$. As the long-run limit, based on the estimation in this analysis, we can compute the long-run minimum energy intensity (averaged across regions). Across regions, the following table shows the resulting energy intensity projected for 2100 based on the two baseline specifications Convergence (3) and Panel (5). Note that 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, reflected in the estimated values for the year 2100.

The resulting energy intensity estimates for 2100 range between 0.8 and 5.6 depending on the scenario and estimation. SSP4 shows the slowest improvement rate, while SSP1 and SSP2 tend to allow energy intensities to drop to a value between 0.8 and 2.5 $MJ/\$$.

Note that the theoretical limit in the conditional convergence scheme equals $2.06MJ/\$$

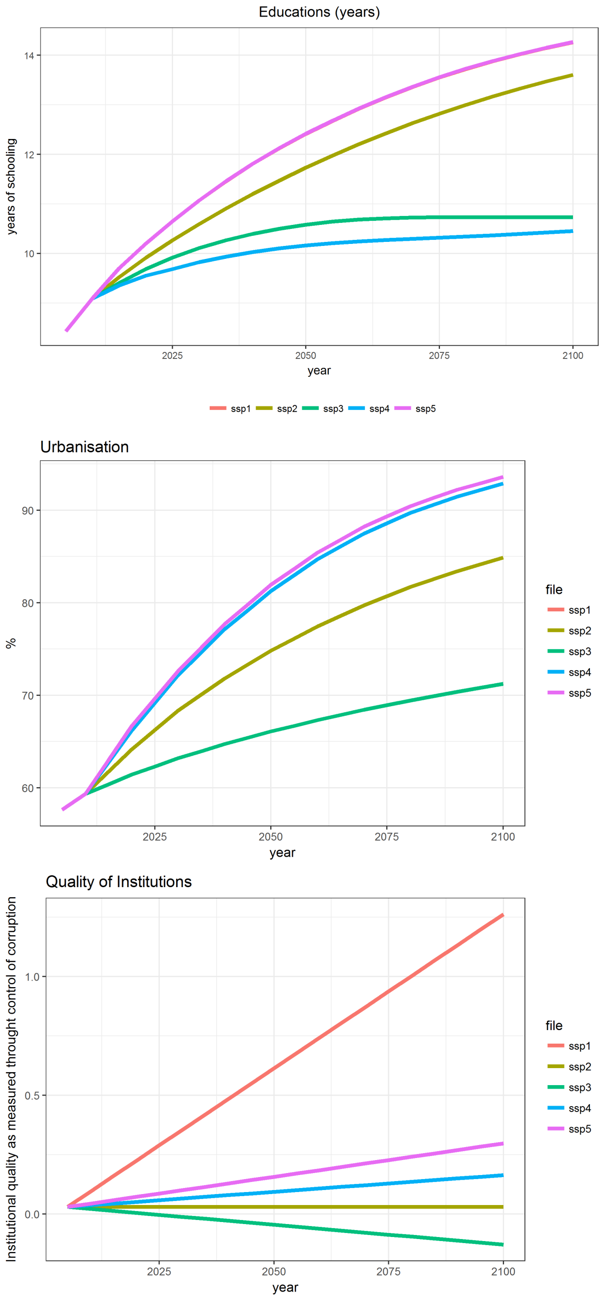

Figure 3.2: Projections of education, urbanization, and institutions according to the SSPs (note that SSP1 and SSP5 are virtually identical in terms of demographic assumptions)

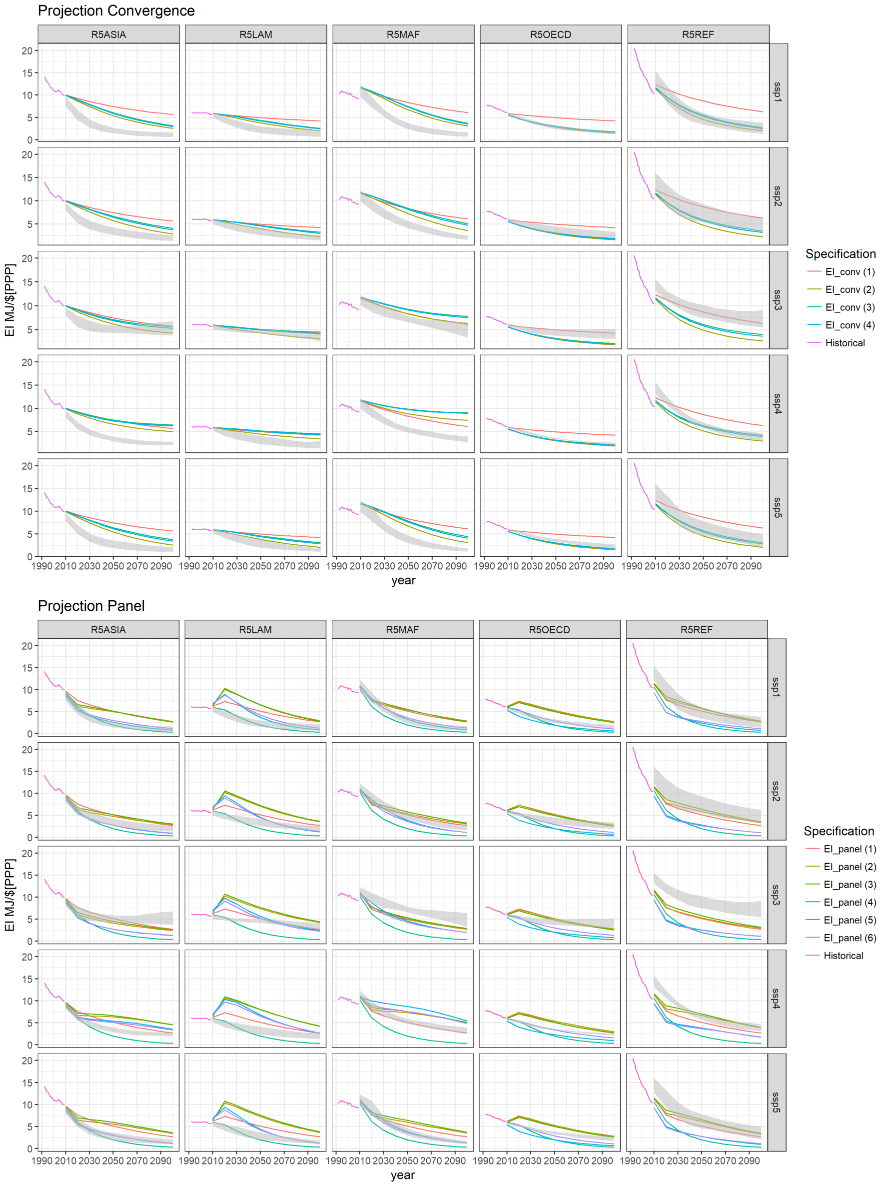

Figure 3.3: Projected Energy Intensity across SSPs and regions, all Convergence (top) and Panel (bottom) specifications.

SSP	Convergence (3)	Panel (5)	SSP marker scenario
SSP1	$2.23MJ/\$$	$0.79MJ/\$$	$1.24MJ/\$$
SSP2	$2.52MJ/\$$	$0.98MJ/\$$	$2.40MJ/\$$
SSP3	$3.87MJ/\$$	$1.50MJ/\$$	$4.41MJ/\$$
SSP4	$5.68MJ/\$$	$3.58MJ/\$$	$2.57MJ/\$$
SSP5	$3.12MJ/\$$	$1.02MJ/\$$	$1.77MJ/\$$

Table 3.6: Projected Energy intensity values in 2100

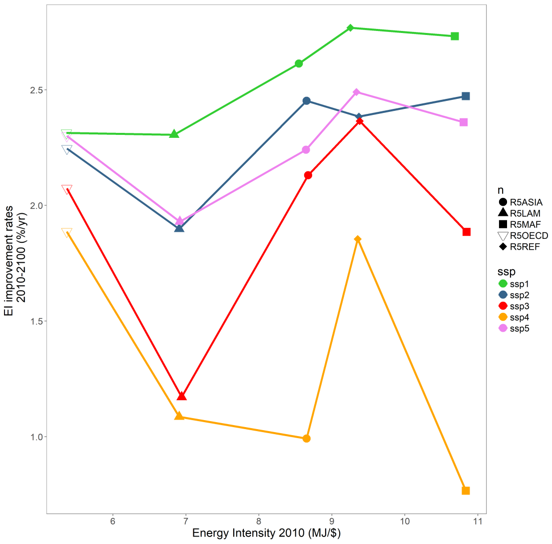

Figure 3.4: Projected average energy intensity improvements across SSPs and regions (Panel Specification 5)

Variable	SSP1	SSP2	SSP3	SSP4	SSP5
Urbanisation (%)	92.1	79.4	58.5	91.4	92.5
Years of schooling (n. of years)	13.9	12.99	8.5	8.1	13.99
Control of corruption (index)	1.18	-0.38	-0.75	-0.49	0.05
Investments (% of GDP)	20	20	20	20	20
$lim_{t\rightarrow\infty} EI_i(t)$ based on Convergence (3) $[MJ/\$]$	**1.26**	**2.06**	**4.71**	**5.66**	**1.64**

Table 3.7: Values in 2100 (global population-weighted averages) and long-term EI limits

based on the SSP2 "middle of the road" baseline projection.[10] While this (theoretical) limit is not yet met in 2100, the SSP2 and SSP1 scenarios close the gap almost fully from today's value of $7.5 MJ/\$$. When looking at the regional results, Figure 3.4 shows a mixed result of convergence: Asia, Latin America, and the Reforming economies show the highest expected improvement rates. Moreover, the projected rates are higher in all regions for SSP1 and lowest for SSP4.

3.5 Conclusion

Understanding the implications of modeling conditional convergence as opposed to absolute convergence in future socio-economic pathways is important for the accuracy of future energy scenarios, and can help to identify the complementary measures that need to be implemented in order to ensure policy effectiveness.

We found that based on a panel regression and conditional convergence approach, energy intensity has historically been improved across regions in a rather regular way. Besides an exogenous time trend capturing technical progress and convergence across countries, additional explanatory variables have been found to affect how energy efficiency changes over time. Notably, we find that education and investment rates lead to a faster improvement in energy intensity, while urbanisation tends to decrease energy intensity improvements. When considering institutional variables, we find than notably an effective control of corruption or effective government also increases energy intensity improvements, confirming some earlier literature on institutional impacts on energy demand. We link the estimated econometric models to an iterative projection model based on ordinary differential equations. Across regions, our projected energy intensities vary between 0.9 and 5.7 $MJ/\$$. At the global level, finally we compute for the conditional convergence case a long-term limit of global energy intensity of about $1.9 MJ/\$$, down from its value in 2016 of about $7.5 MJ/\$$. 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. These results can be thought of an additional "stylized fact" in the context of energy intensity patterns such as the one established in [46, 17, 24, 6]: in addition to the steady improvement in energy intensity, 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, while a secular time trend in addition would imply asymptotically approaching an energy intensity of zero.

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[10] This theoretical lower bound is computed based on equation (3.3) using the world average values for all variables in 2100 in the SSP2 (which shows a leveling-off in many variables anyhow). In the conditional convergence case, the limit is zero, which is approached however very slowly.

4. Energy Efficiency gap in the context of the Paris climate Agreement

4.1 The IAM modelling framework

WITCH (World Induced Technical Change Hybrid) is an integrated assessment model (IAM) designed to assess climate change mitigation and adaptation policies [11]. It is developed and maintained at the Centro Euro-Mediterraneo sui Cambiamenti Climatici. WITCH is a global dynamic model that integrates into a unified framework the most important drivers of climate change. An inter-temporal optimal growth model captures the long-term economic growth dynamics. A compact representation of the energy sector is fully integrated (hard linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables. Land use mitigation options are available through a linkage with a land use and forestry model. WITCH represents the world in a set of fourteen representative native regions; for each, it generates the optimal mitigation strategy for the long- term (from 2005 to 2100) as a response to external constraints on emissions. A modelling mechanism aggregates the national policies on emission reduction or the energy mix into the WITCH regions. Finally, a distinguishing feature of WITCH is the endogenous representation of R&D diffusion and innovation processes that allows a description of how R&D investments in energy efficiency and carbon-free technologies integrate the mitigation options currently available. Further documentation is available at `http://doc.witchmodel.org`.

One of the main features of the WITCH model is the characterization of endogenous technical change. Albeit difficult to model, technological innovation is key to the decoupling of economic activity from environmental degradation, and the ability to induce it using appropriate policy instruments is essential for a successful climate agreement, as highlighted also in the Paris climate agreement.

Both innovation and diffusion processes are modeled. We distinguish dedicated R&D investments for enhancing energy efficiency from investments aimed at facilitating the competitiveness of innovative low carbon technologies (backstops) in both the electric and non-electric sectors. R&D processes are subject to stand-on-shoulders as well on neighbors effects. Specifically, international spillovers of knowledge are accounted for to mimic the flow of ideas and knowledge across countries. Finally, experience processes via Learning-by-Doing are accounted for in the development of niche technologies such as renewable energy (Wind&Solar) and the backstops. International spillovers of knowledge and experience Learning processes via knowledge investments and experience are not likely to remain within the boundaries of single countries, but to spill to other regions too. The effect of international spillovers is deemed to be important, and its inclusion in integrated assessment models desirable, since it allows for a better representation of the innovation market failures and for specific policy exercises.

The WITCH model is particularly suited to perform this type of analysis, since its game theoretic structure allows distinguishing first- and second-best strategies, and thus to quantify optimal portfolios of policies to resolve all the externalities arising in global problems such as climate change. WITCH features spillovers of experience for Wind&Solar in that the Learning-by-Doing effect depended on world cumulative installed capacity, so that single regions could benefit from investments in virtuous countries, thus leading to strategic incentives. An enhanced version was developed to include spillovers in knowledge for energy efficiency improvements.

Energy knowledge depends not only on regional investments in energy R&D, but also on the knowledge stock that has been accumulated in other regions. Similarly to the Learning-By-Doing for Wind&Solar, WITCH assumes experience accrues with the diffusion of technologies at the global level. We also assume knowledge spills internationally. The amount of spillovers entering each world region depends on a pool of freely available knowledge and on the ability of each country to benefit from it, i.e. on its absorption capacity. Knowledge acquired from abroad combines with domestic knowledge stock and investments and thus contributes to the production of new technologies at home. The energy service demand is part of the Constant Elasticity of Substitution production function. Energy services have endogenous improvements in energy efficiency. Energy efficiency increases with investments in dedicated energy R&D, which build up the stock of knowledge. The stock of knowledge can then replace (or substitute) physical energy in the production of energy services. As a result, the energy demand is mainly determined by the economic growth, which is calibrated from the growth rate of total factor productivity.

4.2 Scenarios

The aim of the the Paris Climate Agreement is *to hold average global warming to well below 2C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5C*. These long-term climate target are formulated at the global scale, but the agreement's capability to enforce effectively national climate policies is crucial. That's why, in the agreement, every country have to submit Nationally Determined Contributions (NDCs), revised every five years. To assess the gaps between current policy to NDCs and between NDCs and long-term target, we modeled the following scenarios:

- *Current Policies*: "National policies" scenario shows the impact of currently implemented climate and energy policies of the G20 economies for the period 2010 to 2030.
- *NDC*: "NDC" scenario has the implementation of conditional NDC targets in addition to *Current Policies*.
- *2C*: the climate target scenario explores the requirements after 2020 to keep global warming below 2C with a probability of 66%, equivalent to cumulative CO2 emissions (carbon budget) of 1,000 GtCO2 in the period 2011–2100.

To explore future uncertainties in socio-economic developments, we run the scenarios for the five the shared socio-economic pathways (SSPs).

4.2.1 Assessment gaps

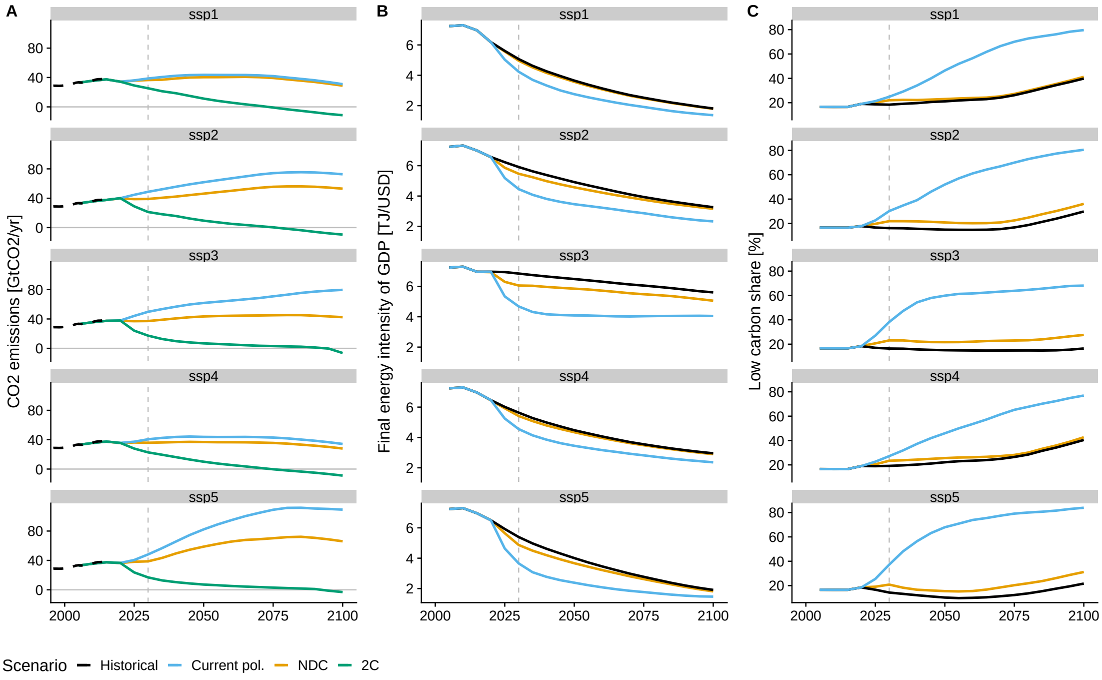

Figure 4.1: **SSP overview**. Panel A: CO2 emission in GtCO2 per year, Panel B: Final energy intensity of GDP in TJ per USD, Panel C: Low carbon share in total primary energy supply.

In the Current Policies scenario, the CO2 emissions increases at global level in all SSPs, and decreases in the second half of the century for SSP1 and SSP4 (Figure 4.1). In order to achieve NDC, the efforts vary a lot according to the SSP, from high effort (SSP3 and SSP5) to very low effort (SSP1 and SSP4). In 2030 and SSP3, this represents a decrease of 20% of the CO2 emissions in comparison to Current Policies (Table 4.1). The 2C scenario requires a large decarbonization efforts for all SSPs, even going negative at the end of the century for almost all SSPs. In particular, Emissions reduction are required for many countries for NDC between 21% (Mexico) to 41% (Brazil). India does not need to reduce emission for NDC. To reach 2C, all countries have to mitigate more than 50% in 2030. Brazil can decabornize to 93% with afforestation. At world level, optimal abatment emission in 2030 is equivalent to 56% of the current policies level (table 4.1).

Final energy intensity is decreasing over time in the current policies scenario with different convergence values according to the socio-economic developement. At world level, NDC and 2C policies require a faster decrease in final energy intensity, especially in the 2C scenario. At country-level, high decrease in final energy intensity are required in most of the economies, from 8% to 15% in the OECD. Brazil and Canada have a different profile as they can mitigate quickly earlier, this is also reflected in the low carbon share (Table 4.1).

Low carbon share is not much different between the NDC and the current policy scenario at global scale. However, for the 2C scenario, the low carbon share has to reach high value and overcome 75%. This is for all socio-economic development. At country-level, this gap is quite heterogeneous across countries as it is reflected by the national capability to decarbonize. Many countries have to double the level of low carbon share projected for the Current policies scenario: Brazil, Chine, Mexico, USA. At global level, from current policy to 2C, the gap is equal to 87% increase in the share (table 4.1).

	CO2 emissions		**Final energy intensity**		**Low carbon share**	
	NDC	2C	NDC	2C	NDC	2C
Brazil	41	93	30	18	113	113
Canada	39	44	18	14	52	52
China	28	58	8	19	91	186
Europe	22	53	5	19	23	54
India	0	53	–	26	2	51
Mexico	21	53	16	22	43	108
USA	29	63	15	28	57	123
World	20	56	7	25	35	87

Table 4.1: **Assessment gaps at country-level in 2030**. Values are expressed in % change relative to the current policies trajectory in 2030. SSP2, middle of the road, socio-economic development.

4.3 Requirements in R&D developments

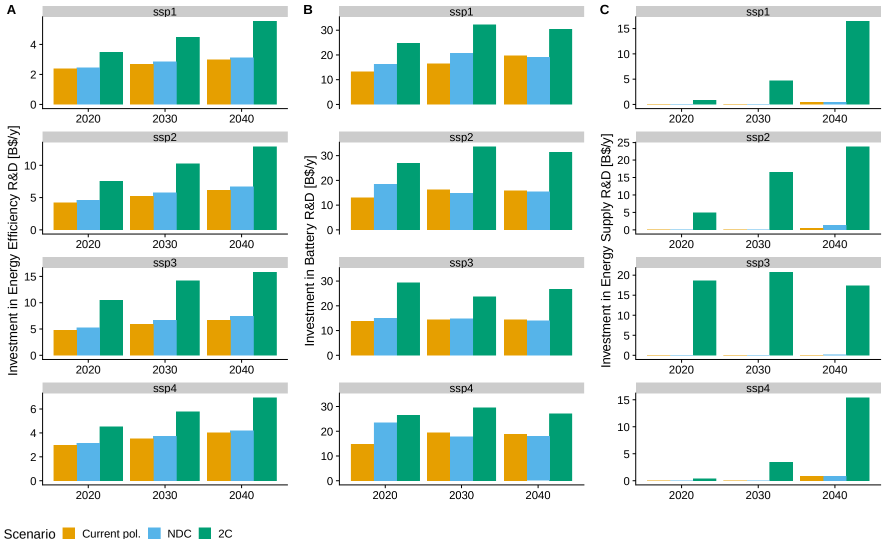

Figure 4.2: **Investment in R&D requirements**. Investments are in Billions USD per year. Panel A: Investment in Energy efficiency, Panel B: Investment in battery technologies, Panel C: Investment in energy supply (advanced biofuels).

The WITCH model can assess the requirements in investment in R&D to fill the gaps between Current Policies, NDC, and 2C climate target. At world level, R&D investments in energy efficiency are estimated to be between 3 to 5 billions USD in 2030 in the current policies scenario. A slightly increase of this amount is required to implemnent the NDC of the order of 0.2 billions USD. For the 2C scenario, these investments should increase by 50% to 100% according to the socio-economic development.

In comparison, the investments in R&D for battery are of another order of magnitude, still being very close between current policies and NDC, between 15 to 20 billions USD in 2030. A relatively smaller increase is necessary for the 2C scenario.

Concerning, investment in energy supply R&D, mainly concerning the development of advanced biofuels, no much investments are required in 2030 for the current policies and NDC scenarios, while a large amount of investment in required to reach the 2C climate target.

5. Energy efficiency improvement in the residential sector

5.1 The CGE modelling framework

Human-induced climate change is considered one of the most pressing problems of our time. Besides industry, households contribute to this problem through their daily behaviour, such as the (inefficient) use of energy-intensive products and services. Because the European Union identified increasing energy efficiency to be one of the cheapest and most effective route to cut climate-harming emissions and protect citizens from climate change, it has become of one of the central objectives to achieve the Paris Agreement. To this end, the EU wants to increase energy efficiency by at least 30% until 2030 to bring about this transition, reduce its dependency on energy imports and meet its climate targets [40]. More recently, the Commission reached a political agreement which includes a binding energy efficiency target for the EU for 2030 of 32.5% , with a clause for an upwards revision by 2023.[1]

In 2016 residential energy consumption accounted for 25% of the total final energy consumption in the EU28 region. While electricity demand accounts for a rather small part of energy demand, there exists potential to increase energy efficiency and reduce energy demand. The final residential electricity consumption in the EU-29 has grown by 12.63% in the period between 2000 and 2016 and the specific consumption per dwelling from the total electrical appliance stock increased on average by 1.2% /year [12]. This increase has partly been offset by the diffusion of newer, more efficient appliances that reduced the specific electricity consumption per dwelling. Furthermore, expected gains from increasing energy efficiency from new technologies are reduced by rebound effects.

The level of electricity consumption per household in Europe is very unequal. This heterogeneity is mainly due to different thermal uses (e.g. electricity as main source of space heating in some countries, such as in France, Norway) and different levels of energy efficiency.

Implementing energy efficiency measures in the residential sector will contribute to decrease EU final energy consumption. The idea of these policies is that households

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[1] http://europa.eu/rapid/press-release_STATEMENT-18-4155_en.htm

might adjust their consumption plans to obtain potential energy savings. These adjustments in the energy consumption plans of consumers are supposed to have a significant effect on the EU energy system as the producers need to take into account the changes in energy demand.

In our model, we analyse the impact of energy efficiency improvement in the residential sector focussing on electricity demand. Using the CGE Model developed in D4.1 we are able to investigate the associated impact on production and CO_2 emissions in Germany and Europe. The CGE model allows us to take into account endogenous price changes and the linkages between regions and markets to analyse regional and global demand and supply.

5.2 Simulation

We investigate the impact of efficiency improvements of electric appliances on the economy and energy levels in Germany and the EU. The increasing electricity demand per dwelling can only be partly offset by efficiency improvements of appliances. Increasing energy efficiency of electric appliances always changes the consumption structure and can lead to rebound effects. In our model, we simulate different energy efficiency improvement scenarios of households in Germany and the EU. By accounting for different behavioural parameters, we are able to identify the most important channels and factors that influence energy consumption behaviour.

Elasticities of substitution in CES production functions are of great importance for CGE based policy modelling, since the results of counterfactual policy analyses and the comparative static behaviour of these models can be highly sensitive to the values used for elasticity parameters [22]. Therefore, we apply different elasticities in our main efficiency improvement scenarios.

In order to get a more in-depth picture of the impact of the technological efficiency gains, we make a sensitivity analysis simulating efficiency improvements ($\theta_{(r)}$) in a range between 10 and 30% . We account for sensitivity in the adjustment process of electric appliance stock changes. Price changes that are due to efficiency improvements can trigger investments in new, potentially more efficient appliances. A certain degree of inertia in the consumption response and the fact that expensive new appliances like washing machines or televisions are no every day purchases is taken into account. To accomplish that we include different degrees of substitutability in energy service consumption in our sensitivity analysis ($\sigma_{(r)}^{ela}$). Furthermore, by varying the elasticity of substitution in consumption ($\sigma_{(r)}^{SZ}$), we take into account changes in the willingness to substitute energy services by other consumption goods. The scenarios are displayed in Table 1.

- $\theta_{(r)}$: Increase in energy efficiency in region r
- $\sigma_{(all)}^{ela}$: Elasticity of substitution between electricity and electric appliances in all regions

Scenario	$\theta_{(GER)}$	$\theta_{(EU)}$	$\sigma^{ela}_{(all)}$	$\sigma^{SZ}_{(all)}$
S1	1.1	1	0	0
S2	1.2	1	0	0
S3	1.3	1	0	0
S4	1.1	1	0.2	0
S5	1.2	1	0.2	0
S6	1.3	1	0.2	0
S7	1.1	1	0.4	0
S8	1.2	1	0.4	0
S9	1.3	1	0.4	0
S10	1.1	1.1	0.2	0
S11	1.2	1.2	0.2	0
S12	1.3	1.3	0.2	0
S13	1.1	1.1	0.2	1
S14	1.2	1.2	0.2	1
S15	1.3	1.3	0.2	1

- $\sigma^{SZ}_{(all)}$: Elasticity of substitution between energy services and other consumption in all regions

5.3 Results

We start simulating efficiency improvements in energy services in Germany (S1-S9) to analyse the impact on other sectors. Increasing energy efficiency by 10% reduces electricity consumption of households by 8.97% . Due to rebound effects, not the full 10% are transferred into electricity savings, as it also results in an increase of 14.50% in the consumption of energy services by households in Germany. An increase of 20% reduces the consumption of electricity by 16.46% , an increase of 30% by 22.81% . GDP in Germany is increasing in all scenarios. In S1, S2 and S3, GDP is increasing by 0.14% , 0.26% and 0.36% respectively. Looking at the environmental aspects of this analysis, compared to the benchmark scenario without efficiency improvements, CO_2-emissions in Germany decrease by 1.50% in the case of a 10% efficiency improvement. A 20% (30%) efficiency improvement in the consumption of energy services reduces emissions by 2.75% (3.81%). There is also a reduction in CO_2-emissions in Europe in the first 7 simulations (S1-S7) with the largest reduction in S3 (-0.02%).

In Scenario S4-S9, we increase the substitutability between electricity and appliances in the energy service consumption. Thereby we take into account that households might change the way they consume the energy services. If it's easier to substitute electricity and electric appliances, households tend to shift their consumption to the consumption of electricity as it has become much cheaper due to the efficiency shock. While purchases of electric appliances increase by 0.73% (S1), 1.33% (S2) and 1.84% (S3) when we did not allow for substitution in energy service consumption, households tend to reduce new purchases if we allow for it. With a elasticity of substitution ($\sigma^{ela}_{(r)}$) of 0.2 , households increase purchases of new electric appliances by only 0.19% in case of a 10% efficiency shock and even reduce purchases of new appliances by 0.34% if we assume a higher substitutability of 0.4. However, these are special cases, as we assume a costless efficiency improvement of the existing appliances and new appliances in our simulations. Impacts of this costless efficiency improvement in household appliances in Germany on other European countries are rather small. Relative changes in GDP are negative, but below -0.01% for S1 to S9.

In S10-S15 we simulate the efficiency shock in all European Countries. Each country increases energy efficiency in the consumption of energy services in the household sector by 10% (S10 & S13), by 20% (S11 & S14) or 30% (S12 & S15). The impact on GDP is positive and much higher in these scenarios. A 30% increase in energy efficiency of households' electric energy services increases GDP in Europe by 0.33% . The 10% efficiency shock reduces total electricity consumption in the EU by 7.31% . A 20% (30%) efficiency shock decreases electricity consumption by 13.51% (18.86%). In terms of emissions, we see a total CO_2-emission reduction of 0.92% in S10, a reduction of 1.69% in S11 and a reduction of 2.36% in S12. It should be kept in mind that in our scenarios, we abstract from an emissions trading system and look at the pure changes in emission levels as production sectors are only indirectly affected by households efficiency improvements. However, the impact of households' efficiency improvements in energy service consumption in the presence of emission trading systems can be investigated in future research.

The last scenarios take into account that households preferences might change towards more or less energy service consumption. However, we assume that in these scenarios households spend a constant share of their income on energy services and other goods. To accomplish that, we assume a Cobb-Douglas utility function instead of a linear-limiting Leontief function (i.e. we change the elasticity of substitution in consumption from zero to one). This assumption results in slightly higher GDP levels of 0.14% (S13), 0.26% (S14) and 0.36% (S15) but on the other hand slightly higher CO_2-emissions of -0.85% (S13), -1.58% (S14) and -2.22% (S15) compared to a situation without substitution in consumption. This is mainly due to the fact that the reduction in electricity costs that comes with the efficiency shock makes it more attractive to consume more energy services. Therefore, households shift their consumption towards more energy services. In the cases of a 10% , 20% and 30% energy efficiency improvement in the consumption of energy services in Europe, energy service consumption increases by 0.51% , 0.95% and 1.33% .

5.4 Conclusion

In our model, we analyse the impact of energy efficiency improvement of households focussing on electricity demand in energy service consumption. Using the CGE Model developed in D4.1, we are able to investigate the associated impact on production and CO_2-emissions in Germany and Europe. The CGE model allows us to take into account endogenous price changes and the linkages between regions and markets to analyse regional and global demand and supply. We find that energy efficiency improvements in the consumption of electric energy services reduce electricity consumption and looks to increases welfare, as GDP and CO_2-emissions are decreasing. However, we also see that not the full energy efficiency changes are transferred into electricity savings as rebound effects lead to an increase of energy services. The results show that although electricity consumption accounts for a rather small part of household income and consumption, it can still play a role in strengthening the Paris climate agreement.

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