ANALYSIS

Access to electricity in the World Energy Council's global energy scenarios: An outlook for developing regions until 2030

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ABSTRACT

Approximately 2 out of 10 people in the world still live without access to electricity. The UN "Sustainable Energy to All – SE4All" initiative aims at eradicating this electricity access deficit by 2030. To estimate the financial effort required to achieve this target we analyse two long-term scenarios developed by the Paul Scherrer Institute and the World Energy Council, which describe two alternative economic and energy system developments. We focus on developing Asia, Latin America and Sub-Saharan Africa, which currently have the largest percentage of population without access to electricity. We couple a long-term energy system model with regional econometric models that forecast population electrification rates. We find that establishing universal electricity access by 2030 requires significant, but attainable investments in power generation infrastructure, and results in low impacts on primary energy demand and CO₂ emissions.

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1. Introduction

Access to electricity is essential to overcome poverty, promote economic growth and employment opportunities and support the provision of social services such as education and healthcare that lead to sustainable human development [1]. The International Energy Agency (IEA) defines electricity access as a first supply connection to a household and then an increasing level of electricity consumption to reach the regional average. This approach reflects the fact that the eradication of energy poverty is a long-term endeavour [2]. Following the IEA definition 1267 million people worldwide did not have access to electricity in 2010 [3]. This figure increased to 1285 million in 2012 [4], implying that population growth outpaced the number of new electricity connections. More than 95% of the population without access to electricity lives in developing Sub-Saharan Africa, Asia and Latin America (Fig. 1).

In September 2011, UN Secretary-General Ban Ki-Moon launched the initiative "Sustainable Energy for All – SE4All" to mobilise action from all sectors of society to promote universal electricity access by 2030 [5]. The initiative has generated significant momentum and more than 100 countries are already participating in it. As global development agendas are increasingly recognising energy access and energy poverty as essential issues for society, it is important to address them in the context of two other significant socio-ecological issues of our time: energy security and environmental sustainability [6]. This triple challenge is referred by the World Energy Council (WEC) as the "energy trilemma" [7].

The Paul Scherrer Institute (PSI) together with WEC developed two energy scenarios to 2050 assessing the energy trilemma at global and regional scales [8]. The two scenarios incorporate a coherent set of key economic, social and political drivers that are quantified and implemented with a detailed energy system model. The WEC/PSI scenarios are exploratory in their nature in the sense that no specific targets were set along the axes of the energy trilemma. The first scenario ("Jazz") is market-facilitated with a focus on achieving economic growth through competitive and low-cost energy. The second scenario ("Symphony") considers stronger policy regulations with priority given to environmental sustainability and energy security. Both scenarios include climate policies and recent technological advances.

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Fig. 1. Population without access to electricity as % of country's population, 2010 (source: own illustration using data from Ref. [3]).

In this paper, we present a detailed analysis of the two WEC/PSI scenarios regarding electricity access in developing and emerging regions. We focus on regions in which a significant share of the population lacks access to electricity: Sub-Saharan Africa, developing Latin America, India, Central Asia, developing Pacific Asia, Middle East and North Africa.³ For each region, we present the outlook of electricity access in WEC/PSI scenarios until 2030, we discuss the key socio-economic drivers affecting it and we evaluate the additional investment effort in power generation infrastructure required to achieve universal electricity access by 2030. In our assessment, we use an analytical approach, in which we couple a large scale bottom-up energy system model that identifies long term cost-optimal configurations of the energy system with regional reduced-form econometric models⁴ that forecast the population with access to electricity.

1.1. Literature review

In general, the majority of research on improving electrification in developing countries, analysing its impacts on energy supply and emissions and identifying drivers and policies with significant contribution to the electricity access, can be divided into four main categories. The first category includes studies that describe current situations of energy demand or consumption and evaluate the outcomes of policy and programs in developing countries. This includes assessments of funding needs and financing mechanisms (e.g. Ref. [9]), evaluations of electrification programmes (e.g. Ref. [10]), policies and reforms required (e.g. Ref. [11]), and case studies at national and regional levels (e.g. Refs. [12–23]). The studies belonging in this category of research include legal, social and fiscal aspects of the policies and programs. However, they are usually highly case-oriented and it is difficult to obtain ideas applicable to other areas.

The second type of research category focuses on the potential of various electricity supply technologies to increase electricity access such as solar photovoltaic systems (e.g. Refs. [24,25]), decentralised generation and micro-grids (e.g. Refs. [26–30]), nuclear power [31],

biomass [32], etc. This type of studies often contains highly disaggregated or highly precise data, but policy implications to promote these technologies are usually not sufficiently discussed.

The third category includes studies investigating relationships between electrification, poverty and economic development on national and regional scales. These studies can be qualitative, based on empirical results from past experiences (e.g. Refs. [33–35]), or quantitative, based on econometric analysis (e.g. Refs. [36–43]). The majority of these studies identify poverty, income, foreign direct investments (FDI), urbanisation, country policy and institutional development, electricity prices, subsidies and average electricity consumption per capita as key factors of electricity access.

Finally the fourth type of research, to which the present study belongs, involves the combined application of top-down and/or bottom-up economic and energy system models with specific micro-economic consumer choice models or econometric models. These studies forecast the population with electricity access by taking into account economic developments, technological parameters and governmental policies. At the same time, they evaluate the broader impacts of increased energy access on energy supply and demand fuel mix, investment requirements and greenhouse gases emissions. Bottom-up modelling frameworks, such as TIMES [44], have been employed in projecting rural electrification (e.g. for Africa in Refs. [45,46], and for other developing regions in Ref. [47]). Top-down approaches have been used for electricity access scenarios for Sub-Saharan Africa [48] and for assessing the impacts of increased energy access on greenhouse gases emissions and global warming [49]. In Ref. [50], a consumer choice model based on micro-economic foundations is implemented within the cost optimisation energy system model MES-SAGE [51]. The model analyses the determinants of fuel consumption choices of heterogeneous household groups by taking into account effects of income distribution, consumer preferences and discount rates. It has been applied to explore response strategies for energy poverty eradication in India [50] and in South Asia [52], and to evaluate pathways to achieve universal electricity access by 2030 [53–55].

The International Energy Agency applies an econometric model to generate projections of electrification rates by developing region. It is based on panel estimation of historical electrification rates of different countries over income, urbanisation, fuel prices and subsidies, electricity consumption, electrification programmes and other variables [56]. The model is interfaced with IEA's World Energy Model (WEM) in the World Energy Outlook series (e.g. Refs. [2–4]).

³ We exclude Brazil and China, since they already display high electrification rates and they are expected to achieve universal electricity access before 2030 ([3], [8]).

⁴ An econometric model is in a reduced-form when it has been rearranged algebraically such that each endogenous variable is on the left side of the equation, and only predetermined variables (exogenous variables and lagged endogenous variables) are on the right side.

Fig. 2. Overview of the modelling framework.

In Ref. [57] a bottom-up residential energy use model was developed, which determines the fuel use in households based on relative differences in perceived costs by following a causal chain from population and income trends to intermediate physical indicators and energy uses. It makes also use of correlations derived from econometric studies and regression analysis to project household energy consumption and electrification rates in urban and rural areas. The model is integrated into the IMAGE/TIMER global energy simulation model [58], and it has been applied to determine the fuel use in households in India [57] and to evaluate universal electricity access scenarios [54].

In Refs. [59], an econometric model for projecting the rural electrification in developing countries is described. The model uses multivariate regression analysis including as statistical significant variables (among others) the electrification level, the population density, the urbanisation, the average per capita income, the exports of goods and services, the fuel exports and the foreign direct investments. The projected rural population electrification rates are then used in a simple power grid expansion model that takes into account the costs of different grid components in order to evaluate the cost of increased electricity access.

We contribute to the existing literature described above by applying a modelling framework that is based on the coupling between a very detailed bottom-up energy system model that assesses cost optimal configurations of the energy system, both at global and regional scales, with a reduced-form econometric model that takes into account key socio-economic factors for the electrification of the population. The same conceptual modelling framework has been applied in assessing long-term electrification rates in Sub-Saharan Africa [60] and it is extended in the current study to cover additional developing regions. Our methodology differs from the methodologies described above in the following aspects: a) the underlying energy system model, which is interfaced with the econometric model for electricity access, is a bottom-up cost optimisation model (in contrast to TIMER and IEA's models that are simulation models) and it has a detailed representation of the energy systems of 15 world regions; and b) we apply a reduced-form econometric model that is estimated using polynomial distributed lags in order to take into account both short-term and long-term effects of key determinants for improving electricity access such as poverty, urbanisation, policy and institutional development for each developing region. To the best of our knowledge this type of modelling framework for electricity access has not yet been applied in literature for all developing regions.

Similar to the approaches presented in [50,56,57,59,60], the modelling framework applied here is suitable to: a) investigate the

critical components affecting the electrification rate of the population; b) assess the different energy supply and demand options; c) estimate the broader implications of increased electricity access on the energy system and on GHG emissions; and d) evaluate the effectiveness of policies and supports designed to achieve universal electricity access. Main strengths of the proposed framework are also: a) its transparency, since it is based on open source modelling using publicly available databases; b) its scalability that allows for higher regional detail to enable in-depth analysis; c) its generic interface, which enables the coupling of the econometric model for electricity access with different underlying energy system models.

The present work therefore makes a contribution to research in the direction of coupling large scale energy models with empirical models for estimating energy access, to assess not only future electrification rates of the population in developing regions but also to assess the broader impacts of increased electricity access on the energy system and environment (e.g. demand and supply mixes, investments, greenhouse gases emissions, energy system costs and energy prices). In addition to the methodological aspect, we also contribute to the literature regarding scenarios for increasing electricity access in the developing regions, complementing the studies presented by the International Energy Agency (IEA) in (e.g. Refs. [2–4]), by the International Institute for Applied Systems Analysis (IIASA) in (e.g. Refs. [53–55]), by the Netherlands' National Institute for Public Health and the Environment (RIVM) in (e.g. Refs. [54,58,59]) and by others (e.g. Ref. [48]). The two scenarios describe two different worlds, one with focus on low-cost energy in which the energy markets are fully liberalised and technologies compete on the basis of their production cost and resource availability; and a second one with a focus on sustainability in which the governments set the energy policies and promote technologies.

1.2. Paper structure

In section 2 we describe the two models applied in the study and their coupling. In section 3 we define the two WEC/PSI scenarios and we present their main assumptions regarding economic development, population and climate policy intensity.

In section 4 we focus on the outlook for electricity access in developing regions until 2030 under the assumptions of the WEC/PSI scenarios. We mainly discuss the drivers affecting the electrification of the population as they are assessed by both models. The electricity supply and demand, together with the electricity infrastructure investment requirements and production costs are provided by the

Fig. 3. The fifteen world regions in the GMM model.

energy system model. Additional key socio-economic determinants for increasing access to electricity, such as urbanisation, poverty, policy and institutional development, together with the estimation of the population with access to electricity, are provided by the reduced-form econometric model.

In section 5, we assess the additional effort in power generation infrastructure required in the two WEC/PSI scenarios to achieve the SE4All objective of universal electricity access by 2030. Therefore, we examine two normative variants of the basic WEC/PSI scenarios, in which we set the SE4All target. We discuss the energy supply options, the power generation infrastructure investment requirements, and the implications of the universal electricity access case on CO₂ emissions

and energy demand. We conclude by assessing the robustness of our results through a series of sensitivity analyses: i) on the economic and demographic assumptions of the two WEC/PSI scenarios; ii) on the initial levels of electricity consumption for the newly connected population; and iii) on the transmission and distribution (T&D) electricity grid extension costs.

2. Modelling framework

As mentioned in the introduction, two models are used in this study. The first model is the Global Multiregional MARKAL (GMM) model [61–64] belonging to the MARKAL family of models [65]. The GMM

Fig. 4. A simplified Reference Energy System in GMM for a single region.

model was used in assessing the development of the energy system. The second model is a regional reduced-form econometric model that estimates the population with access to electricity. The two models share common scenario assumptions regarding GDP and population projections. They are coupled at the electricity consumption in the residential sector as shown in Fig. 2.

In the case of exploratory scenarios the GMM model first finds the cost-optimal configuration of the energy system. The calculated electricity consumption is then given to the econometric model as an input in order to project the electrification rate of the population together with the main drivers affecting it.

In the case of normative scenarios, the econometric model is used in a backward calculation to find the levels of useful energy demands in the residential/commercial sector that are necessary to meet the imposed electrification targets. This backward calculation requires an assumption regarding the initial electricity consumption level of the newly connected households. The updated demands are then fed back into the GMM model in order to calculate the least-cost pathway to achieve the desired electrification rates. The convergence of the two models can require a number of iterations, in which the useful energy demands calculated by the econometric model are adjusted such that the electricity consumption of the GMM model is sufficient to meet the universal electricity access target.

2.1. The GMM model

The GMM model is a linear programming perfect-foresight, bottom-up, technology rich model, covering the period 2010 to 2100 with a time step of 10 years. The model computes an intertemporal partial equilibrium across all energy markets, under policy and technical constraints, by minimising the total energy system cost. The spatial resolution of GMM covers 15 world regions (Fig. 3), which have been defined according to criteria such as economic influence, level of economic development, energy resource endowments, level of intra-regional integration, geography, policy and political situation [64]. The model represents more than 400 demand and supply technologies using the concept of the “Reference Energy System – RES” (Fig. 4), the dynamics of which are influenced by the scenario assumptions. International trade of energy carriers is also represented and subject to transportation costs.

The energy demand sectors in GMM are industry, residential/commercial, transport and non-energy uses. The energy demands in industrial and residential/commercial sectors are further disaggregated

Table 1
List of the variables used in the econometric model.

Type of Variable	Variable Name	Unit	Source
Input	Income	Average income per capita in USD2005 (PPP)	IMF [66], World Bank [67]
Input	Electricity per capita	Average KWh per capita in residential/commercial demand	IEA [68]
Input	Electrification Programmes	Targeted % of population with access to electricity	IEA [2], World Bank [5]
Output	Urbanisation	% Of population in urban areas	UNPD [69]
Output	Poverty	% Of population living with less than \$2 (PPP 2005) per day	World Bank [67]
Output	Institutional development	Average of Country Policy and Institutional Assessment (CPIA) indices for public sector management, economic management, social inclusion and structural policies	World Bank [67]
Output	Electricity access	% Population with access to electricity	IEA [3], World Bank [5], World Bank [67], UNDP [70]

Box 1. Mathematical formulation of the econometric model:

Equation 1: Population with access to electricity:

$$\begin{aligned} \ln(\text{elcaccess}_{r,t}/(1 - \text{elcaccess}_{r,t})) \\ = \beta_{r,0} + \beta_{r,1} \cdot \sum_{k_r} (\gamma_{r,k_r,1} \cdot \text{poverty}_{r,t-k_r}) \\ + \beta_{r,2} \cdot \sum_{\lambda_r} (\gamma_{r,\lambda_r,2} \cdot \text{urbanisation}_{r,t-\lambda_r}) \\ + \beta_{r,3} \cdot \sum_{\mu_r} (\gamma_{r,\mu_r,3} \cdot \text{elccap}_{r,t-\mu_r}) + a_{r,t} + \varepsilon_{r,t} \end{aligned} \quad (1)$$

Equation 2: Population living with less than \$2 PPP (2005) per day:

$$\begin{aligned} \ln(\text{poverty}_{r,t}/\text{poverty}_{r,t-1}) \\ = \beta_{r,0} + \beta_{r,1} \cdot \sum_{k_r} (\gamma_{k_r} \cdot \ln(\text{income}_{r,t-k_r}/\text{income}_{r,t-k_r-1})) \\ + \beta_{r,2} \cdot \sum_{\lambda_r} (\gamma_{r,\lambda_r} \cdot \ln(\text{cpia}_{r,t-\lambda_r})) + \varepsilon_{r,t} \end{aligned} \quad (2)$$

Equation 3: Country Policy and Institutional Assessment Index (CPIA):

$$\begin{aligned} \ln(\text{cpia}_{r,t}/(6 - \text{cpia}_{r,t})) = \beta_{r,0} + \beta_{r,1} \cdot \sum_{k_r} (\gamma_{k_r} \cdot \text{gdp}_{r,t-k_r}) \\ + \varepsilon_{r,t} \end{aligned} \quad (3)$$

Equation 4: Percentage of internal migration of population from rural to urban areas:

$$\begin{aligned} \ln(\text{migration}_{r,t}/(1 - \text{migration}_{r,t})) \\ = \beta_{r,0} + \beta_{r,1} \cdot \sum_{k_r} (\gamma_{k_r} \cdot \text{income}_{r,t-k_r}) + \varepsilon_{r,t} \end{aligned} \quad (4)$$

Equation 5: Percentage of urban population in total population:

$$\begin{aligned} \text{urbanisation}_{r,t} = \text{urbanisation}_{r,t-1} \cdot (\text{pop}_{r,t}/\text{pop}_{r,t-1}) \\ + \text{migration}_{r,t} \cdot \text{pop}_{r,t} \cdot ((\text{pop}_{r,t-1} \\ - \text{urbanisation}_{t-1})/\text{pop}_{r,t-1}) \end{aligned} \quad (5)$$

to thermal and specific uses. Transport includes subsectors for private passenger transport, aviation and other surface transport. The energy demand technologies operate at the level of useful energy. The useful energy demands are derived from the scenario assumptions based on a coherent storyline. The GMM model supplies the useful energy demand by optimising the endogenous equipment choice and the corresponding production and delivery of energy carriers.

2.2. Econometric model for estimating the population with access to electricity

In order to forecast the population with access to electricity in the WEC/PSI scenarios, we have developed a reduced-form regional econometric model with the same spatial resolution as in GMM. The model takes a number of variables into account that have been

Fig. 5. Historical evolution of the population electrification rates in selected world regions (source: IEA world energy outlooks and own compilation).

identified in the literature as statistically significant in affecting the electrification rate of the population, and – at the same time – they can be linked with the results obtained from the GMM model and the WEC/PSI scenarios assumptions. The electrification programmes promoting energy access, though in general neither sustainable nor adequately contributing to development [10], are included in the model specification as exogenous adjustments that shift the curve for the rate of electrification of the population towards the expected outcomes foreseen by these programmes (Equation (1)). The model was estimated using time-series for the period 1970–2012. The short- and long-term effects of the explanatory variables are captured with distributed lag estimation⁵ [71,72]. Table 1 summarises the input and output variables of the model for each region, together with the data sources used in the estimation.

The mathematical formulation of the econometric model is given in Box 1. Equation (1) projects the population electrification rate ($elcacc_{r,t}$) in region r and time t as a function of the percentage of population living with less than \$2 per day ($poverty_{r,t}$), the population urbanisation rate ($urbanisation_{r,t}$) and the average electricity per capita in residential sector⁶ ($elccap_{r,t}$). This is a sigmoid function representing increasing efforts to electrify the remaining segments of the population living in small or dispersed communities, often with low income levels. This is also justified by the fact that the electricity supply in remote rural areas is characterised by peaky electricity consumption profiles, and therefore it can be up to seven times more costly compared to urban settings [73]. Thus, utilities are reluctant to serve these areas unless remote consumers are able or willing to pay at least for operating costs [74]. The equation also includes an exogenous adjustment factor ($a_{r,t}$) to account for electrification programmes. This

factor can shift the curve of the share of population with electricity access upwards, reflecting in this way the expected outcomes of electrification support policies in place. Fig. 5 presents the historical trends in population electrification in various world regions, in which the sigmoid shape of the electrification rate can be observed in almost all regions.

Equation (2) projects the population living with less than \$2 per day ($poverty_{r,t}$) as a function of the average per capita income ($income_{r,t}$) and the Country Policy and Institutional Assessment (CPIA) index ($cpi_{r,t}$) that is used as a proxy for the government effectiveness and corruption.⁷ Equation (3) links the CPIA index with the GDP ($gdp_{r,t}$) in region r . Equation (4) forecasts the percentage of population migrating from rural to urban areas ($migration_{r,t}$) due to income differences. Equation (5) projects the urbanisation rate of the population ($urbanisation_{r,t}$) based on the work of [75] and the theory of population mobility presented in Ref. [76].

In all equations described above, the coefficients $\beta_{r,i}$ are the ordinary least squares (OLS) estimators and the terms $\varepsilon_{r,t}$ are the error of the regressions. The coefficients of a polynomial distribution lag i with degree k_r are denoted as $\gamma_{r,k_r,i}$. Where necessary the econometrically estimated equations include an additional term for first order autocorrelation correction. Table 2 presents the estimated coefficients obtained,⁸ together with their statistical significance (p-values).

3. WEC/PSI global energy scenarios: “Jazz” and “Symphony”

The WEC/PSI global energy scenarios have been built through a number of workshops in collaboration with a range of partners and stakeholders including international energy suppliers and energy technology companies from WEC’s extended network of 93 member committees and 3000 member organisations. Table 3 gives a short overview of the two scenarios and the interested reader is directed to [8] for additional information. Further to the WEC/PSI scenarios we examine two normative variants aimed at achieving universal electricity access by 2030 in section 5. In the same section additional

⁵ A simplified equation for PDL is $y_t = a + b(L)x_t + u_t = a + \sum b_s x_{t-s} + u_t$ where u_t is the stationary error term. This form is very similar to the infinite-moving-average representation of an ARMA process, except that the lag polynomial on the right-hand side is applied to the explanatory variable rather than to a white-noise process. The individual coefficients b_s are called lag weights and they collectively comprise the lag distribution, constrained to lie on a polynomial of known degree. They define the pattern of how x affects y over time.

⁶ The average electricity consumption per capita is linked with the results from the GMM model and it is influenced by energy prices and taxes, population and total electricity consumption in the residential sector.

⁷ The CPIA index has a scale from 1 = worse to 6 = best [67].

⁸ The sum of lags is reported for the polynomial distribution lags, which corresponds to the total elasticity.

Table 2
Estimated coefficients and their corresponding p-values for each equation and region.

	C	p-val	POV	p-val	URB	p-val	ELC	p-val	INC	p-val	CPIA	p-val	R-sq
Pacific Asia													
Eq. (1): Electricity access			−0.990	0.000	0.988	0.005	2.687	0.000					0.964
Eq. (2): Poverty									−0.277	0.043	−0.026	0.084	0.812
Eq. (3): Institutional development									0.055	0.000			0.431
Eq. (4): Population migration	0.008	0.000							0.001	0.016			0.753
Central Asia													
Eq. (1): Electricity access			−3.520	0.000	1.891	0.007	8.070	0.000					0.915
Eq. (2): Poverty									−0.225	0.005	−0.012	0.000	0.754
Eq. (3): Institutional development									0.176	0.000			0.609
Eq. (4): Population migration	−0.003	0.000							0.007	0.000			0.866
India													
Eq. (1): Electricity access			−2.574	0.000	2.571	0.009	10.461	0.000					0.999
Eq. (2): Poverty	0.567	0.001							−0.184	0.064	−0.450	0.001	0.857
Eq. (3): Institutional development									0.387	0.000			0.746
Eq. (4): Population migration	0.004	0.000							0.002	0.000			0.699
Latin America													
Eq. (1): Electricity access			−3.238	0.000	1.665	0.000	3.156	0.000					0.953
Eq. (2): Poverty									−1.521	0.026	−0.039	0.022	0.778
Eq. (3): Institutional development									0.068	0.000			0.650
Eq. (4): Population migration									0.002	0.000			0.559
Middle East & North Africa													
Eq. (1): Electricity access			−0.899	0.097	0.421	0.005	1.754	0.000					0.936
Eq. (2): Poverty									−2.107	0.000			0.897
Eq. (3): Institutional development									0.013	0.001			0.537
Eq. (4): Population migration	0.001	0.093							0.002	0.000			0.938
Sub-Saharan Africa													
Eq. (1): Electricity access			−3.393	0.000	1.701	0.000	5.425	0.000					0.998
Eq. (2): Poverty	0.779	0.027							−0.145	0.010	−0.692	0.027	0.879
Eq. (3): Institutional development									0.061	0.000			0.595
Eq. (4): Population migration									0.005	0.000			0.943

C = Constant.

POV = Population living with less than \$2 per day.

URB = urbanisation.

ELC = Electricity consumption per capita in residential.

INC = Average GDP per capita.

CPIA = Country policy and institutional assessment index.

p-val = p-value.

Table 3
The WEC/PSI scenarios at a glance.

Jazz	Symphony
Focus on economic growth via low cost energy and using the best available resources: <ul style="list-style-type: none"> Economy liberalisation, opening of upstream energy markets, increased participation of the private sector → high economic growth Lower fertility is driven by higher incomes and education that reduce the opportunity cost for raising children for women Technology choice is based on energy markets: limited government support for nuclear, CCS, large hydro, renewables Energy efficiency is market driven Delayed climate policy action with no global agreements and diverse regional responses 	Focus on environmental sustainability and energy security: <ul style="list-style-type: none"> Market regulation with policies set by governments, energy policies financed and coordinated by governments, regulatory hurdles, limited Foreign Direct Investments (FDI) and limited participation of the private sector into the economy → lower economic growth than "Jazz" Medium fertility in line with UN Population Division; lower incomes result in higher opportunity costs for raising children for women Technology choice is driven by energy policies implemented by governments: increased government support for low-carbon technologies: CCS, nuclear, hydro, renewables Efficiency measures policies are implemented by governments Strong climate policy with global convergence; emission trading schemes are developed by 2030, which are replaced by a global CO₂ market in the longer term

sensitivity analyses of these two normative variants are also considered regarding: i) the economic and demographic assumptions of the two scenarios; ii) the initial electricity consumption levels for the newly connected population; and iii) the T&D electricity grid expansion costs.

Table 4 presents the assumptions regarding GDP and population in the developing regions in the WEC/PSI scenarios. The future economic growth shifts from developed countries to developing economies and it is assumed that developing regions implement structural economic reforms that also lift domestic constraints related to monetary and fiscal policies. Infrastructure investments and improved labour relations increase foreign direct investments (FDI) and buoyant services

and at the same time contribute to increased integration of developing regions into the global value chains. Although the main drivers for the economic development are common in the two scenarios, the assumed GDP growth in "Jazz" and "Symphony" is not the same because of the different market structures (liberalisation versus regulation), which affect the participation of the private sector into the economy, the FDI infusions and the capital and labour flows.

The assumptions on population growth are based on the premise that higher incomes and education levels facilitate women's access to the labour market and result in increased opportunity costs of raising children. Compared to the UNPD population projections [69], "Jazz" is

Table 4
GDP per capita and population assumptions in “Jazz” and “Symphony”.

	Jazz				Symphony			
	2010	2020	2030	2010–2030	2020	2030	2010–2030	
GDP per capita (\$2010 MER)								
Pacific Asia	3150	6380	10,470	6.2%	5690	8620	5.2%	
Central Asia	1340	2040	3430	4.8%	1910	2950	4.0%	
India	1330	2270	4230	6.0%	2080	3500	5.0%	
Latin America	6190	8810	12,230	3.5%	8310	10,930	2.9%	
Middle East & North Africa	6650	7690	9940	2.0%	7510	9300	1.7%	
Sub-Saharan Africa	1350	1680	2530	3.2%	1620	2280	2.7%	
Average in the above regions	2508	3721	5704	4.2%	3470	4917	3.4%	
Population (millions)	2010	2020	2030	2010–30	2020	2030	2010–30	
Pacific Asia	604	664	707	0.8%	669	721	0.9%	
Central Asia	475	545	600	1.2%	551	618	1.3%	
India	1225	1374	1485	1.0%	1387	1523	1.1%	
Latin America	278	309	333	0.9%	312	342	1.0%	
Middle East & North Africa	381	442	490	1.3%	448	507	1.4%	
Sub-Saharan Africa	857	1070	1281	2.0%	1089	1354	2.3%	
Total in the above regions	3819	4405	4897	1.3%	4456	5066	1.4%	

Table 5
Correlations between electricity access and its key drivers based on time series analysis over the period 1970–2012.

	Poverty	Urbanisation	CPIA Index	Electricity per capita
Pacific Asia	−0.96	0.99	0.89	0.98
Central Asia	−0.97	0.97	0.34	0.58
India	−0.97	0.99	0.98	0.96
Latin America	−0.41	0.99	0.76	0.96
Middle East and North Africa	−0.68	0.83	0.74	0.77
Sub-Saharan Africa	−0.82	1.00	0.45	0.83

close to the “Low Fertility” variant, while “Symphony” is close to the “Medium Fertility” variant.

The climate policy intensity in the developing regions is very modest in “Jazz” reaching \$5 per tonne of CO₂ in 2030.⁹ In “Symphony” it is assumed that the developing regions join the international effort led by the developed countries in the longer-term and the CO₂ price is \$23 per tonne of CO₂ in 2030 [8]. The same CO₂ prices are applied to all energy demand sectors in both scenarios.

4. Outlook for electricity access in “Jazz” and “Symphony” in 2030

In this section an outlook is presented regarding the population’s access to electricity in the exploratory WEC/PSI scenarios for the developing countries until 2030. As already mentioned in the methodology section, the GMM model finds the cost-optimal configuration of the energy system. Subsequently, the econometric model, which takes the electricity consumption from GMM as an input, provides results for key socio-economic drivers affecting the households’ electrification and the population with access to electricity in each region. Therefore, we first discuss the outlook for the key factors affecting electricity access, and then we present the projection of the population that still remains without electricity access in 2030.

⁹ All monetary units in the current text refer to real US Dollars of 2010.

4.1. Development of the key drivers of electricity access until 2030

Based on the literature we have identified as the main drivers for affecting electricity access, the electricity consumption per capita (which in turn is influenced by the electricity supply mix and the cost of the delivered energy to consumers) and a number of socio-economic indicators such as the population living with less than \$2 PPP (2005) per day, the urbanisation rate and the policy effectiveness (CPIA index). The assessment of the electrification of the households requires the application of the coupled framework due to the multitude of determinants. As already stated, the GMM model provides the energy system configuration together with the electricity consumption per capita, while the econometric model provides the development of the rest of the socio-economic drivers and the ultimately the population electrification rates.

The correlations of these drivers with the electricity access are presented in Table 5. Poverty is negatively correlated with electricity access, as more than 80% of the people without access to electricity are living in the poorest regions. The correlation with urbanisation is positive, since around 85% of the population without access to electricity live in rural areas. The CPIA Index is also positively correlated with electricity access with higher correlations suggesting higher probability of success of national electrification programmes. Finally, the correlation with the average electricity consumption per capita is also positive, with stronger correlations implying higher levels of energy equity.

4.1.1. Urbanisation

Fig. 6 presents the urban population in developing Pacific Asia, India, Central Asia, developing Latin America, Sub-Saharan Africa, Middle East and North Africa by 2030. In “Jazz” the urban population increases by 873 million people from 2010 to 2030. More than half of this increase, around 495 million people, is attributable to internal migration from rural to urban areas because of income disparity. In “Symphony” the urban population increases by 889 million people between 2010 and 2030, of which 477 million people migrate from rural to urban areas. The urbanisation rate in “Symphony” is lower than in “Jazz” because of the lower economic growth. In both scenarios, much of the increase in urban population takes place in Sub-Saharan Africa and India implying significant challenges in meeting the needs of housing and urban support infrastructure in these regions.

4.1.2. Poverty

Poverty is reduced in both scenarios due to the positive economic development (Fig. 7). The number of people who are living with less than \$2 PPP per day declines from 1947 million in 2010 to 1047 million in “Jazz” and 1163 million in “Symphony” by 2030. In both scenarios much of the reduction in poverty occurs in developing Asia and particularly in India. On the other hand, in Sub-Saharan Africa the growth of the population absorbs the economic growth and the remaining poor population in the world becomes increasingly concentrated in this region: half of the poor population worldwide lives in Sub-Saharan Africa in 2030 in both scenarios.

4.1.3. Policy and institutional development

Table 6 presents the projections of the Country Policy and Institutional Assessment (CPIA) index¹⁰, reflecting developments in the quality of public management, as well as the implementation of

¹⁰ Projections of the CPIA index were obtained from equation (3), which was calibrated to the projections of the International Futures modelling system of the University of Denver [77]. This takes into account factors other than the economic development, which are not fully captured by our modelling framework, such as political stability, economic and structural reforms already implemented and in progress etc.

Fig. 6. Urban population by region and scenario, in millions and as % of region's total population.

Fig. 7. Population living with less than \$2 (2005, PPP) per day, in millions and as % of region's total population.

economic and social structural changes. In both scenarios the index improves in all regions, implying a reduction in corruption and an increase in the efficiency of public administration.

4.1.4. Electricity demand and supply

In both WEC/PSI scenarios the final electricity consumption in developing regions doubles in 2030 relative to 2010 levels, growing on average by 4.1% p.a. in "Jazz" and 3.8% p.a. in "Symphony" (Fig. 8). More than the half of this growth takes place in residential and commercial sectors because of the increased use of electric

appliances at the expense of traditional fuels (e.g. kerosene, non-commercial biomass). Average electricity consumption per capita in the residential and commercial sectors reaches 858 kWh in "Jazz" and 760 kWh in "Symphony" in 2030 compared to 531 kWh in 2010. The electrification rate of final energy demand is on average higher in "Symphony" than in "Jazz" (16.7% versus 13.8%). This is driven by the emphasis on efficiency and the stronger climate policy assumed in this scenario, which increase the use of electricity in the demand sectors.

The electricity supply mix in the two scenarios reflects underlying energy policies and market structures (Fig. 9). In "Jazz" investments in power generation are towards flexible projects with short construction times. Capital intensive projects, such as nuclear and hydropower, are not financially attractive. In the absence of supporting policies, solar and wind power are competitive only in regions with good resource quality ensuring high utilisation rates. In "Jazz", each region tries to make the best possible use of available resources with the lowest possible cost: coal dominates electricity production in India and Central Asia; gas is a major fuel for electricity supply in the Middle East & North Africa; gas becomes important for Latin America due to limited investment in hydropower; and coal and gas are the main options for electricity supply in Pacific Asia and Sub-Saharan Africa.

Table 6
Country Policy and Institutional Assessment Index (CPIA index).

CPIA (1 = worst, 6 = best)	2010	Jazz		Symphony	
		2020	2030	2020	2030
Pacific Asia	3.30	3.40	3.69	3.37	3.56
Central Asia	3.32	3.41	3.72	3.39	3.62
India	3.72	4.04	4.84	3.98	4.60
Latin America	3.61	3.73	4.01	3.71	3.91
Middle East & North Africa	3.07	3.13	3.15	3.12	3.14
Sub-Saharan Africa	3.12	3.16	3.19	3.16	3.18

Fig. 8. Electricity consumption by region and sector.

Fig. 9. Electricity generation mix by fuel and region.

On the other hand, the electricity generation mixes in the “Symphony” scenario are more uniform across regions and more diversified in terms of technology choice than in the “Jazz” scenario. Low-carbon technologies account for a share in total electricity production from 17% (in the Middle East) to 53% (in Latin America) in 2030, driven by effective climate policy and the presence of supportive measures (e.g. subsidies). Solar based generation is more competitive than wind, as it is an off-grid solution with high utilisation rates in developing regions.

The investments in new power generation capacity and grid expansion are significant in both scenarios (Fig. 10). In “Jazz”, around 1265 GW of new capacity is added over the period of 2011–2030, with India accounting for around one third of it. The annual undiscounted investment expenditure in “Jazz” sums up to \$165 billion, of which \$94 billion are directed to new power generation capacity and \$71 billion in electricity T&D grid expansion and refurbishment.¹¹ It should be noted

that the electricity power plants specific investment costs (Table 7) are different in the two scenarios because of different technology learning dynamics arising from the endogenous learning by experience mechanism of the model [65].

In “Symphony”, around 1429 GW of new capacity is installed between 2011 and 2030, with one quarter of it in India. The annual undiscounted investment expenditure over the period of 2011–2030 sums up to \$208 billion, of which \$131 billion are invested in new generation capacity and \$77 billion in electricity T&D grid. The “Symphony” scenario is more expensive than “Jazz” because of its capital intensive pathway towards long term environmental sustainability.

4.2. Population without access to electricity in 2030

The population with electricity access increases in both scenarios because of positive developments in the key drivers affecting it (as discussed in the previous section) and the electrification programmes in place (Table 8 presents an overview of the electrification programmes taken into account in the current study). In the WEC/PSI scenarios we do not consider additional policies to expand energy access other than those in place today. However, as it is mentioned by both [2] and [10], while the adoption of national targets and

¹¹ The MARKAL family of models does not have a spatial representation of the grid. The model assumes that grid expansion occurs when 1 GW of new capacity is added to the electricity system. In our analysis we also adjusted the investment costs for electricity grid expansion to reflect different population densities of developing regions based on data provided from IEA [3]. The investment costs for electricity grid expansion are shown in Table 7.

Fig. 10. Cumulative investment in capacity (left) and annual expenditure (right), 2011–2030.

programmes for electricity access is important, in practice it has been relatively commonplace for initial ambitions to be subsequently downgraded.

It should be noted that the prospects of improvement in electricity access is fragile in both scenarios: it can still be upset by changes in economic development, higher energy prices or the failure to implement policy actions to increase electrification rates of the population. Therefore, we also perform sensitivity analyses regarding the GDP and population growth in the next section, in order to assess the robustness of our projections regarding the population with access to electricity and the required investment in power generation infrastructure to support increased levels of electricity access.

In both scenarios Latin America and the Middle East and North Africa achieve universal electricity access by 2030, while developing Asia and Sub-Saharan Africa continue to have a significant electricity access

deficit (Fig. 11). In the “Jazz” scenario around 733 million people lack access to electricity in 2030. In developing Asia the number of people without access to electricity is halved, going from around 605 million in 2010 to 275 million in 2030. India accounts for a large proportion of the increased access to electricity, continuing an already positive trend initiated by its rural electrification programmes. However, India is still the country with the largest population without electricity access in 2030. In Sub-Saharan Africa the number of people without access to electricity is reduced only by 134 million, and this reduction is achieved mainly after 2020.

In the “Symphony” scenario the global electrification rate of the population is slightly lower than in “Jazz”. The population growth in “Symphony” outpaces the number of new electricity connections. At the same time the expansion of the infrastructure required to provide electricity access to large parts of the rural population is hampered by the lower economic growth assumed in this scenario. As a result, around 885 million people still lack access to electricity in 2030 in “Symphony”. Much of the reduction in the number of people without access to electricity occurs in developing Asia. On the other hand, in Sub-Saharan Africa the population lacking access to electricity reduces by only 47 million between 2010 and 2030.

The trajectories in the population electrification between developing Asia and Sub-Saharan Africa are different in the WEC/PSI scenarios. While developing Asia achieves electrification rates above 60%, Sub-Saharan Africa accounts for more than 60% of the global population without electricity access in 2030 in both scenarios. Some of the contributing factors that could explain the high concentration of the remaining global population without access in Sub-Saharan Africa include: a) the current state of electricity infrastructure; b) the nature and the extent of expected flows of investment to different parts of the power sector; c) the large size of many African countries; and d) demographic stress due to the high population growth rate that outpaces the growth of new electricity connections.

The size of the challenge that remains in our projections in both scenarios should not obscure the progress that is being made. The annual investment expenditure in power generation infrastructure that is directed to increase electricity access at a global scale amounts to close to \$16 billion in “Jazz” and \$18 billion in “Symphony” over the

Table 7

Specific investment costs in electricity infrastructure assumed in the present study, USD2010.

T&D expansion costs in \$/kWe		2010–2030	
Asia Pacific		1399	
Central Asia		842	
India		674	
Latin America		999	
Middle East and North Africa		978	
Sub-Saharan Africa		1177	
		Jazz	Symphony
Specific investment cost \$/kWe	2010	2030	2030
Gas turbine combined cycle	686	627	657
Coal conventional	1473	1473	1473
Coal advanced	2222	2222	2222
Hydro (average of different scales)	3015	3015	3015
Solar PV	3296	1732	2430
Wind turbines	1370	1262	1370
CHP gas	1052	1052	1052
Geothermal	6486	4410	4410
Biomass thermal	3717	3717	3717
Biomass gasification	3144	2990	3121
Nuclear power (average of regions)	2805	2805	2805

Table 8

Major electrification programmes and targets for improving electricity access, taken into account in WEC/PSI scenarios (source IEA [2]).

Country	Programme name	Objective
North & South Latin America	Enabling Electricity – ENEL	Implementing more than 30 projects in 20 Latin America Countries to improve electricity access in isolated communities [78]
Brazil	Luz para Todos	Aiming at increasing rural electrification in Brazil (2003–2014) [79]
India	Rajiv Gandhi Grameen Vidyutikaran Programme	Electrification of more than 17 million rural households [80]
Bangladesh	Master Plan for Electrification	Electricity for all by 2020 [81]
Nepal	Rural Electrification Programme	Electricity for all by 2027 [82]
Philippines	Philippines Energy Plan	Electrification of 90% of households by 2017 [83]
Indonesia	Rural Electrification Programmes	Electricity access for 95% of the population by 2020 [84]
Vietnam	National energy development programme	Universal electrification by 2020 [85]
Ghana	National Electrification Scheme	100% Electricity access by 2020 [86]
South Africa	Integrated National Electrification Programme	100% Electricity access by 2020 [87]
Zambia	Rural Electrification Master Plan	Electricity access for 78% in urban and 15% in rural areas by 2015 [88]

Fig. 11. Population without access to electricity by region, in millions and as % of total population.

period of 2011–2030.¹² This is almost twice as high as the \$9 billion spent on electricity access in 2009 [2]. The investment for increasing the electricity access is higher in “Symphony” than in “Jazz” due to the capital intensive pathway of the power generation sector to achieve long-term environmental sustainability. Fig. 12 presents the annual investment to increase electricity access by region. In both scenarios, India accounts for more than 25% of the global investment for electricity access, reflecting the increasing need of the country to provide electricity access to its rural population. The above numbers imply that the average connection cost per capita is \$370 in “Jazz” and \$460 in “Symphony” for every person gaining electricity access during the period of 2011–2030.

5. Achieving universal electricity access in “Jazz” and “Symphony”

As shown in the previous section, the level of projected investments in the “Jazz” and “Symphony” scenarios is insufficient to achieve

universal electricity access by 2030. In this section we estimate the investment in power generation infrastructure required to meet the SE4All objective in the two WEC/PSI scenarios.

5.1. Definition of the universal electricity access case

In the universal electricity access case we assume that new policies and electrification programmes are implemented from 2015 that result in increasing the electrification rates to 100% of the world’s population by 2030.¹³ In a first step, the annual additional number of people gaining access to electricity by region is estimated based on equation (1), in which we apply the adjustment factor $a_{r,t}$ in order to shift the electricity access curves towards the 100% electrification by 2030. To assess the additional electricity demand (and hence the additional generating capacity) required to attain universal electricity access by 2030, we follow the same approach as IEA in Ref. [2]. We assume that once the initial basic consumption of electricity is achieved, the level of consumption rises gradually over time reaching the average regional consumption level after five years; this is a time dynamic assumption since the average regional consumption is calculated for every year over the projection period. This approach reflects the fact that the

¹² To calculate the investment directed to increase electricity access we first estimate the need for electricity generation by matching the additional electricity demand from people gaining access over time to the existing residential electricity demand, total electricity generation and power capacity. The investments in generating access are then a straightforward calculation, based on the share of the total electricity generation capacity that corresponds to the increase in electricity access of the population. This is similar to the methodology applied by IEA [4].

¹³ In our analysis we abstain from identifying or suggesting policies that could increase the electricity access in developing regions.

Fig. 12. Annual investment by region to increase electricity access, 2011–2030.

Table 9
Additional electricity consumption to achieve universal electricity access by region in 2030.

	Jazz (in TWh)		Symphony (in TWh)	
	Base	Additional	Base	Additional
Pacific Asia	922	69 (+7%)	788	90 (+11%)
Central Asia	301	59 (+20%)	302	66 (+22%)
India	942	88 (+9%)	815	91 (+11%)
Latin America	543	2 (+0%)	489	4 (+1%)
Middle East & North Africa	1109	3 (+0%)	1086	4 (+0%)
Sub-Saharan Africa	387	285 (+74%)	369	329 (+89%)
Total in the regions above	4203	507 (+12%)	3848	585 (+15%)

eradication of energy poverty and the achievement of energy equity is a long term activity.

We set the initial level of annual electricity consumption to 120 kWh per capita¹⁴ as suggested in Ref. [89]. However, different threshold levels are adopted in other analyses. IEA for example assumes an initial consumption of 250 kWh per year for a rural household of five people and 500 kWh per year for an urban household of the same size [2]. As another point of reference, according to the Government of India [90] the electricity consumption in 2009 was 96 kWh per capita in rural areas and 288 kWh per capita in urban areas. In Refs. [54] and [91] the minimum annual electricity consumption threshold is set to 420 kWh per household gaining electricity access, which is enough to run some small appliances. This threshold translates into 84 kWh per capita if we assume a household of five people. Nevertheless, in our study, the assumption of initial electricity consumption per capita is the subject of additional sensitivity analyses in a following sub-section.

We abstain from assessing a possible feedback of the increased electricity access to the rest of the economy, mainly due to the absence of unanimity across studies looking at the direction of causality between electricity consumption and economic growth (see for example Refs. [92–95]). However, some studies for developing countries (for example Refs. [96–98]) have shown that increased electrification rates of population lead to increased electricity supply, which in turn enhances productivity and enables the creation of new enterprises.

¹⁴ This level of consumption is equivalent to the use of a floor fan, a mobile telephone, an efficient refrigerator, a small TV and two bulbs for about 5 h per day in an average household of five people.

5.2. Additional electricity demand needed to achieve universal electricity access

We estimate that the total incremental final electricity consumption required to achieve universal electricity access by 2030 is 507 TWh in “Jazz” and 585 TWh in “Symphony” (Table 9). This corresponds to an increase in electricity demand by 12% in “Jazz” and 15% in “Symphony” compared to the base case.¹⁵ The average level of electricity consumption per capita across newly connected households over the period is 691 kWh in “Jazz” and 660 kWh in “Symphony”. More than the half of the additional electricity demand takes place in Sub-Saharan Africa.

The definition of the universal electricity access case that we use in our analysis implies that although the starting consumption per capita is the same across regions, there is a regional difference depending on the average consumption per capita of each region. Hence, the effort to achieve energy equity is higher in those regions with high average electricity consumption per capita. For example the number of people in Pacific Asia without access to electricity is smaller than in Central Asia, but the additional electricity consumption in Pacific Asia required to eradicate energy poverty is higher, in order to bring the newly-connected households to consumption levels of the already-connected ones.

5.3. Investments needed to achieve universal electricity access

The GMM model quantifies the effort needed in terms of electricity generation capacity and T&D grid expansion to achieve universal electricity access by 2030. It takes as input the updated useful energy demands from the econometric model corresponding to the increased levels of electricity consumption required to attain the target of universal electricity access. Subsequently the model finds the cost-optimal configuration of the energy system to meet these new demands.

Fig. 13 presents the cumulative total investment in power generation capacity required to achieve universal electricity access by region and the breakdown of the incremental power generation capacity by fuel. In “Jazz” the power generation capacity increases by 133 GW (+11% from the base case), of which 76 GW is fossil fuel based generation (+15%), 28 GW is hydropower (+32%) and 21 GW solar power (+24%). In “Symphony” the additional investment in power generation capacity is 192 GW (+13% from the base case), of which 54 GW is fossil fuel based (+13%), 46 GW is hydropower (+22%), 60 GW is solar power (+19%), 18 GW is wind power (+24%) and 7 GW is nuclear (+14%). These results suggest that renewables play a significant role in achieving universal electricity access. In both scenarios, more than half of the additional investment takes place in Sub-Saharan Africa. India alone accounts for one third of the incremental investment in developing Asia.

Fig. 14 presents the undiscounted annual investment expenditure required to achieve universal electricity access by region, as well as its breakdown terms of power generation capacity and electricity T&D grid. The cumulative undiscounted investment expenditure over the period of 2011–2030 amounts to \$710 billion in “Jazz” and \$978 billion in “Symphony”. This implies that the annual undiscounted outlays to achieve the SE4ALL objective are \$36 billion in “Jazz” and \$49 billion in “Symphony” over the period of 2011–2030. These amounts are equivalent to less than 4% of the global investments in power generation infrastructure attained in WEC/PSI scenarios [8]. The undiscounted connection costs per person gaining electricity access between 2011 and 2030 are on average of \$450 in “Jazz” and \$590 in

¹⁵ The base case of “Jazz” and “Symphony” in the text refers to the original WEC/PSI scenarios without the target of universal electricity access by 2030.

Fig. 13. Cumulative investment in electricity generation capacity in the universal electricity access case, 2011–2030.

Fig. 14. Undiscounted annual investment expenditure in power generation infrastructure in the universal electricity access case, 2011–2030.

“Symphony”. The connection costs per capita increase by 22% and 25% compared to the base case in “Jazz” and “Symphony” respectively, which is attributed to the higher effort required connecting remote and sparsely populated areas (Fig. 15). It should be noted that the connection costs are also influenced by the average level of the electricity consumption per capita, to which the consumption of the newly connected population convergences. Thus, Sub-Saharan Africa has the lowest connection costs per capita among all regions because of the very low average consumption per capita. On the other hand, Pacific Asia and Latin America display much higher connection costs per capita.

More than half of the additional investment expenditure occurs in Sub-Saharan Africa, with the region needing an annual investment of \$14 billion in “Jazz” and \$23 billion in “Symphony” to achieve universal electricity access by 2030. Developing Asia requires \$19 billion in “Jazz” and \$24 billion in “Symphony” on annual basis over the period of 2011–2030 to meet the SE4ALL objective, the bulk of which is directed to India and Pacific Asia. Pacific Asia requires the largest additional

investment per capita gaining electricity access among the developing regions, because of its high average electricity consumption per capita that increases the effort to eradicate energy poverty and to achieve energy equity in the region.

Table 10 presents the undiscounted cumulative investment expenditure in new power generation capacity by fuel that is required to achieve universal electricity access in developing regions.¹⁶ To raise this investment, a combination of different financing options is necessary depending on the electricity supply technology. For

¹⁶ The substantial investment in coal is due to the absence of stringent climate change targets and due to limits in the infrastructure expansion required to supply electricity from lower carbon intensive sources, e.g. gas pipelines required for gas turbine combine cycle plants and hydropower projects. In our analysis, in order to come up with plausible infrastructure expansion rates, we have taken into account the fact that the infrastructure to support the transition of the energy supply sector to low-carbon technologies is not currently fully in place in developing regions. This assessment was done in collaboration with the WEC members and the WEC scenario team.

Fig. 15. Average undiscounted costs per newly capita in the universal electricity access case during the period 2011–2030.

Table 10
Cumulative investment expenditure in power generation capacity in billion USD2010 to achieve universal electricity access, 2011–2030.

	Total to achieve electricity access		Incremental from the base case	
	Jazz	Symphony	Jazz	Symphony
Coal	846	375	66	16
Gas	386	425	23	30
Nuclear	56	154	6	19
Hydro	346	776	83	139
Biomass	90	135	4	4
Wind	69	143	5	25
Solar	204	925	37	147
Geothermal	120	77	12	22
Total	2117	3010	236	402

example, solar PV as an off-grid option is in general less financial attractive for the private sector.¹⁷ Possible solutions for raising the required funds can include: a) government programmes that improve the capacity of solar systems providers to finance end consumers (examples are found in Philippines [99] and Kenya [100]); b) local banks, government and concessional funds that support the provision of financial services to low-income population (examples of this approach include India Solar Programme [99] and some African countries [101]); c) sustainable solar marketing packages (SSMP) based on a service contract to install and maintain solar PV systems to public services sector and include exclusive rights to provide such services to private customers as well [102]; d) the development of solar home systems (SHS) that provide electricity to end users on a fee-for-service basis [103]; and e) solar portable light business models [104].

On the other hand, hydropower is a mature technology that can supply electricity at low costs, but hydropower projects can face significant financial and social risks. Successfully raising the required investment in hydropower depends on risk mitigation strategies addressing the high upfront capital expenditures and the lead times for planning, permitting and construction. Social risks include the relocation of people, which could start deep social disruption due to expropriations, asset condemnation and other losses. The mitigation of social risks needs to be addressed constantly throughout the entire project,

and involves timely and continuous communications between developers and those affected, adequate compensation, support and long term contacts, and efforts to ensure that population relocation and land transformation is balanced by some direct benefits.

Fossil-based generation can increase electricity access in urban agglomerations that favour on-grid electrification options, but the grid expansion required is less profitable for the private sector.¹⁸ Financing schemes to raise investments in on-grid electrification could consider: a) public-private partnerships through which a local utility extends the grid to provide access in an agreed area by including generation and transmission together [104]; b) sourcing loans from the private sector to supplement internal financing of state-owned utilities; and c) partial risk guarantees, targeted government subsidies to low income households, equity investments, cross-subsidisation, etc.

The role of nuclear power in the universal electricity access case is constrained by issues related to technical capacity and safety, grid interface, legal and regulatory infrastructure and high upfront investment, especially in developing countries that start from green fields. A promising direction for nuclear development might be to downsize reactors from gigawatt scale to less-complex smaller units. Small modular reactor (SMR) technology could be a part of the solution [31].

The above discussion regarding the financing options of the different technologies suggests that the governments alone cannot fully finance the universal electricity access case. The participation of the private sector in the investment needs for the universal electricity access case depends on the ability of the investors to charge electricity tariffs that could return a reasonable profit. To this extent the biggest challenge is the electrification of low-income households, which can be financed from government budgets, multilateral and bilateral guarantees, concessional loans and grants through development banks (e.g. the World Bank, the African Development Bank) [105].

5.4. Implications of universal electricity access in primary energy supply and CO₂ emissions

Achieving universal electricity access is projected to increase the primary energy consumption in developing regions by 4.2 EJ in “Jazz” (+1.8% from the base case) and by 3.8 EJ in “Symphony” (+1.9%) in

¹⁷ Investors compare the levelised cost of electricity from solar PV with the wholesale price and they also use a market-based weighted average cost of capital. Households instead compare the levelised cost of electricity from solar PV with the residential retail price, and they often use an interest rate based on their savings account.

¹⁸ Electricity transmission infrastructure needs high upfront investment in view of future electricity demand growth. It requires a high level of electricity consumption per capita, strong growth of retail electricity prices and adequately high transmission tariffs in order for the investment to be attractive to private investors. These conditions are hard to meet in developing regions with low incomes and low levels of electricity consumption per capita.

Fig. 16. Total global primary energy supply (left) and CO₂ emissions in 2030 (right) in the base and universal electricity access cases of the two WEC/PSI scenarios.

2030. This translates to a global increase in primary energy supply of 0.6% in “Jazz” and 0.7% in “Symphony” in 2030 (Fig. 16). These small impacts on primary energy demand can be explained by the low level of energy per capita consumed by the people provided with electricity access. The intra-scenario comparison shows that “Symphony” requires 13% lower primary energy consumption in developing regions than “Jazz” (205 EJ versus 234 EJ).

The energy-related CO₂ emissions in the universal electricity access case in developing regions are 12.3 Gt in “Jazz” (+2.1% from the base case or +250 Mt) and 9.3 Gt in “Symphony” (+1.2% from the base case or +110 Mt) in 2030 (Fig. 16). This translates to a global increase in energy-related CO₂ emissions of around 0.5% in “Jazz” and 0.7% in “Symphony” in 2030. The small increase in emissions is because of the high shares of renewable options implemented. However, the pathway to achieve universal electricity access in “Jazz” is based on investments in fossil fuel based generation with long lifetimes that result in 25% higher cumulative CO₂ emissions than in “Symphony” in developing regions.¹⁹ However, the diversity of factors involved implies that the total impact on greenhouse gas emissions from achieving universal electricity access and using modern cooking and lighting facilities needs to be treated with caution, especially as these factors are not fully captured by the present study. It is accepted in literature that advanced stoves and greater conversion efficiencies result in a reduction in CO₂ emissions and thereby can lower our projection [2]. This might be the case even if access is provided entirely from fossil energy resources, because the transition to such fuels displaces large quantities of traditional biomass that is associated with significant emissions of non-CO₂ Kyoto gases (e.g. CH₄ and N₂O) [54]. For comparison IEA estimates that achieving universal electricity access by 2030 would raise CO₂ emissions by 0.7% as compared to their “New Policies” scenario [2], while [54] estimates an increase of GHG emissions of about 2–4% above the baseline in 2030. In Ref. [49], it is calculated that the additional CO₂ emissions due to energy poverty eradication are in the range of 44–183 Gt CO₂ over the 21st century with the maximum warming contribution of increased energy access estimated to 0.13 °C.²⁰

¹⁹ As it is mentioned in Ref. [8], the “Jazz” scenario follows a trajectory consistent with a long term atmospheric concentration between 590 and 710 ppm CO₂-eq, which corresponds to a more than 66% probability of a warming of 4 °C according to [106], while “Symphony” is on track for 490–535 ppm CO₂-eq that corresponds to a probability of 33–50% of meeting the 2 °C target [106].

²⁰ This evidence is also supported by looking at retrospective analyses which show that in India, for example, increased electricity access has contributed 3–4% of the national emissions growth over the past 30 years [107].

5.5. Sensitivity analyses

In order to further enhance the analysis and assess the robustness of the results discussed in the previous sections, we perform a number of sensitivity analyses regarding: a) the initial level of electricity consumption per capita for the newly-connected population; b) the electricity T&D grid expansion cost; and c) the GDP and population assumptions.

5.5.1. Sensitivity on initial level of electricity consumption per capita

The initial electricity consumption for newly-connected population constitutes a key assumption in the model that affects the level of investment required to attain universal electricity access. Different studies consider different levels above which access to electricity is assumed to be established. Therefore, we perform a sensitivity analysis regarding the annual starting electricity consumption for newly-connected population in the range of 60–180 kWh per capita for both scenarios. This range includes the initial electricity consumption levels reported in the majority of the studies in literature.

Fig. 17 presents the annual undiscounted investment in power generation infrastructure required to achieve universal electricity access by 2030. The investment in the “Jazz” scenario ranges from \$33 billion (–6.1% compared to the base case of 120 kWh per capita) to \$37 billion annually (+5.1% from the base case of 120 kWh per capita). “Symphony” displays lower volatility in initial consumption levels than “Jazz”, with the annual investment of the scenario ranging from \$46 billion (–5.3% compared to 120 kWh per capita case) to \$51 billion (+3.9% compared to 120 kWh per capita case). This is attributable to the more capital intensive pathway of “Symphony” because of the emphasis on sustainability. In “Jazz”, the capital demanding investment options are considered last in the merit order of supply due to the focus in this scenario on low-cost energy; this increases the sensitivity of “Jazz” to higher initial electricity consumption levels.

5.5.2. Sensitivity on electricity T&D grid expansion costs

The electricity T&D grid expansion costs assumed in the study depend on the population density and urbanisation levels of each region and are shown in Table 7. In the universal electricity access case the investments in the T&D grid represent about 43% of the total annual expenditure in power generation infrastructure in “Jazz” and 37% in “Symphony”. In order to assess the sensitivity of the annual investment expenditures with respect to the electricity grid costs, we perform additional analyses by varying these costs by ±50%, ±25% and ±10% from the base case. This type of analysis also provides insights about

Fig. 17. Annual investment to achieve universal electricity access in billion US\$ for different levels of initial electricity consumption compared to the base case (high-lighted) of 120 kWh per capita and year, 2011–2030.

the trade-off between decentralised generation and electricity grid expansion. High T&D grid expansion costs can favour the adoption of decentralised options to supply electricity in rural areas, but at the same time these options have significantly higher specific investment costs compared to centralised technologies due to differing economies of scale.

Fig. 18. Annual investment to achieve universal electricity access in billion US\$ for different levels of electricity T&D grid expansion costs, 2011–2030.

Table 11

Variants examined in the sensitivity analyses.

Variant name	Policies from	Assumption(s) modified	Total Population (millions)	Average income (\$2010)
Jazz	Jazz	WEC/PSI Jazz scenario	4897	5704
Jazz (GDP from Symph)	Jazz	GDP growth from Symphony	4897	5086
Jazz (POP from Symph)	Jazz	Population growth from Symphony	5066	5514
Jazz (POP&GDP from Symph)	Jazz	GDP & population growth from Symphony	5066	4917
Symphony	Symphony	WEC/PSI Symphony scenario	5066	4917
Symph (GDP from Jazz)	Symphony	GDP growth from Jazz	5066	5514
Symph (POP from Jazz)	Symphony	Population growth from Jazz	4897	5086
Symph (POP&GDP from Jazz)	Symphony	GDP & population growth from Jazz	4897	5704

By changing the T&D costs by $\pm 50\%$ we find that in “Jazz” the annual investment in power generation infrastructure ranges from \$31 billion (–13% from the base case) to \$43 billion (+21% from the base case) over the period 2011–2030, while for “Symphony” the obtained interval is from \$43 billion (–12% from the base case) to \$55 billion (+13% from the base case) for the same period (see Fig. 18). This implies that a significant part of the reduction or the increase in the T&D electricity grid expansion costs is traded-off with reduced or increased decentralised generation respectively. The investment expenditures in the decentralised generation capacity in “Jazz” are between 16.6% (in the –50% case) to 22.4% (in the +50% case) of the total investments in power generation capacity in developing regions. In “Symphony”, the investment expenditures in decentralised generation capacity are between 32.4% (in the –50% case) to 36.4% (in the +50% case) of the total investments in power generation capacity.

Compared to the base case more than half of the additional investment in decentralised generation in the variants with higher T&D electricity grid costs is directed to solar photovoltaics. The remaining investments are in small scale gas CHP plants (around 30–40% of the investment in decentralised generation in “Jazz”, but less than 15% in “Symphony”), biomass thermal/gasification units (around 6% of the investment in decentralised generation in “Jazz” and about 20% in “Symphony”) and small scale run-of-river hydro projects (around 2–3% of the investment in decentralised generation in “Jazz” and less than 15% in “Symphony”).

The analysis shows that the “Jazz” scenario exhibits higher sensitivity to electricity grid expansion costs than “Symphony”. This is attributable to the centralised model of electricity generation that is followed in this scenario, which aims at providing low-cost energy through large economies of scale. On the other hand, the “Symphony” scenario already in the base case displays doubled shares of decentralised generation compared to “Jazz”. Therefore it is less sensitive to the changes in T&D electricity grid expansion costs assumptions.

5.5.3. Sensitivity on economic and demographic assumptions

Economic and demographic developments affect investments in attaining universal electricity access: a) by influencing the number of people that do not have access to electricity in the base case; and b) by influencing the level to which the average electricity consumption per capita for the newly-connected population converges (after 5 years of their initial consumption), in order to eradicate the energy poverty.

Fig. 19. Population without access to electricity in "Jazz" and "Symphony" and in their variants, 2030.

The different sensitivity analyses on GDP and population assumptions of the two scenarios are shown in Table 11.

Fig. 19 compares the population without electricity access across all scenarios and variants in 2030. In a "Jazz-like" world²¹ the number of people without access to electricity in 2030 ranges from 733 million in "Jazz" to 1020 million in "Jazz (POP&GDP from Symph)". In a "Symphony-like" world²² the number of people without access to electricity in 2030 ranges from 654 million in "Symph (POP&GDP from Jazz)" to 885 million in "Symphony". Looking at the population electrification rates, in a "Jazz-like" world they range from 80% to 85%, while in a "Symphony-like" world they range from 80% to 87%. These results suggest that for the same level of population and economic growth a "Symphony-like" world achieves higher population electrification rates than a "Jazz-like" world.

There are a number of contributing factors that can explain why "Symphony" performs better than "Jazz" for the same level of average income per capita. The electricity access in "Jazz" is linked with the ability and/or willingness of consumers to pay for connection and operating costs in a liberalised market without energy subsidies. This implies that the "Jazz" scenario is imbalanced with respect to electricity access between urban and rural areas, since utilities can supply on-grid electricity at low costs to urban areas, while they are reluctant to serve rural areas. Moreover the off-grid generation is not subsidised in this scenario. On the other hand, electricity access in "Symphony" is linked with the capacity of governments to invest or support off-grid distributed generation to combat energy poverty in rural areas. This implies that "Symphony" is more balanced with respect to electricity access between urban and rural areas than "Jazz". In addition, in the "Symphony" scenario there are also policies for supporting efficiency and reducing the CO₂ emissions in the demand sectors. These policies increase the share of electricity in final energy consumption and consequently the investments in power generation infrastructure and electricity access.

Fig. 20 presents the electricity consumption in the residential sector and the cumulative undiscounted annual investment expenditure in power infrastructure required to achieve universal electricity access in all variants under consideration. In a "Jazz-like" world the annual outlays range from \$34 billion to \$38 billion, while in a "Symphony-like" world they are between \$46 billion and \$50 billion.

5.6. Comparison with other studies

In the WEC/PSI "Jazz" and "Symphony" scenarios, we estimate that 733 million and 885 million people lack access to electricity in 2030 respectively. In order to achieve the SE4ALL target, the required annual undiscounted investments in power generation infrastructure is \$36 billion in "Jazz" and \$49 billion in "Symphony" over the period of 2011–2030. The universal electricity access case increases the primary energy supply from 1.8% to 1.9% from the base case in both scenarios in 2030, while the CO₂ emissions increase by 1.2% in "Jazz" and 2.1% in "Symphony" in the same period. In addition, the sensitivity analyses suggest that the annual investment expenditures can be as low as \$31 billion and as high as \$55 billion over the period of 2011–2030, depending on the underlying assumptions of initial electricity consumption levels, electricity T&D grid expansion costs, economic developments and population growth.

These findings are generally in line with results from similar studies. IEA estimates that 1036 million people lack access to electricity by 2030 and that an annual investment of \$45 billion over the period of 2011–2030 is required to achieve universal electricity access by then [2]. It is also estimated that the universal electricity access case increases the primary energy supply by 1.1% and the additional impact on CO₂ emissions is +0.7% in 2030 compared to IEA's base case of "New Policies" scenario. In Ref. [3] IEA updated these numbers to 991 million people without access to electricity in 2030 and to \$49 in billion annual investment expenditure over the period of 2011–2030 in order to achieve universal electricity access by 2030. In Ref. [53], it is estimated that without additional policies to increase electrification, between 795 million and 822 million people living in rural areas in Sub-Saharan Africa and South and Pacific Asia will remain without access to electricity by 2030 and that \$36 billion to \$41 billion will need to be spent annually until 2030 to ensure universal access to clean cooking fuels and electricity by 2030. In Ref. [54] it is estimated that without policies to accelerate electrification 600 million to 850 million people in rural Sub-Saharan Africa and South and Pacific Asia could remain without electricity by 2030. It also suggests that around \$65 billion to \$86 billion²³ would be required annually worldwide to achieve universal access to clean cooking fuels and electricity by 2030. This corresponds to approximately 3%–4% of global investments in electricity generation

²¹ Refers to the "Jazz" scenario and all variants with policies from "Jazz".

²² Refers to the "Symphony" scenario and all variants with policies from "Symphony".

²³ The costs are expressed in real USD of 2005. By applying a GDP deflator of approx. 1.11 to change the base year from 2005 to 2010, the resulting annual investments is \$72 to \$95 billion of USD2010 over the period 2011–30.

Fig. 20. (a) Electricity consumption in TWh and (b) Annual investment to achieve universal electricity access in billion US\$, 2011–2030.

and transmission and distribution infrastructure. The same study estimates that universal modern energy access increases greenhouse gases emissions by about 2%–4% over the baseline in 2030. In Ref. [59] it is estimated that around 650 million people will lack access to electricity in rural areas by 2030. Achieving universal electricity access by then would require \$24 billion to \$43 billion,²⁴ which corresponds to a range of 3.6%–6.5% of global investments in the power sector in the period of 2011–2030.

In Ref. [108] a compilation of studies assessing the cost of universal electricity access by 2030 is presented. The study finds that the annual investment expenditure in power generation infrastructure ranges from \$35 billion to \$55 billion over the period of 2011–2030.

The findings of the abovementioned studies indicate the robustness of our results and constitute a positive outcome for the methodology that we apply. They also indicate a general consensus that despite the different methodologies applied in studies and the different policy scenarios assessed in them, the annual investment outlays in power generating infrastructure required to achieve universal electricity access range between \$30 billion to \$60 billion USD2010 over the period of 2011–2030.

²⁴ The costs are expressed in real USD of 2005. By applying a GDP deflator of approx. 1.1 to change the base year from 2005 to 2010, the resulted annual investments range from \$26 to \$48 billion over the period 2011–2030.

6. Conclusions

Modern energy services are crucial to economic and social development, yet this is out of reach of the people most in need. The latest statistics from IEA and the World Bank show that the population without access to electricity has increased in recent years as natural population growth outpaces the number of new electricity connections [4]. This imposes significant challenges in meeting the UN “Sustainable Energy For All – SE4ALL” objective of achieving universal electricity access by 2030.

In order to provide insights regarding population electrification rates in 2030 and the additional investment effort in power generation infrastructure required to meet the SE4ALL objective, we analyse two explorative scenarios developed by the World Energy Council and the Paul Scherrer Institute that describe alternative configurations of the economy, population and energy policies. We find that in the absence of new policies 733 million to 885 million people lack electricity access by 2030 in the two WEC/PSI scenarios, which corresponds to a reduction of about 400–500 million people compared to 1285 million in 2012. This is equivalent to an increase in the population electrification rate in developing regions from 67% in 2012 to 85% in “Jazz” and 83% in “Symphony” by 2030. Poverty, urbanisation and government effectiveness constitute key socio-economic drivers that affect population electrification rates. In our projections the population without access to electricity becomes increasingly concentrated in Sub-Saharan Africa due to factors relating to demographic trends, the current state of

electricity infrastructure, the nature and extent of expected flows of investments to different parts of the power sector and the large size of many African countries.

In order to achieve universal electricity access we estimate that the total annual investment expenditure in power generation infrastructure is on the order of 36–49 billion dollars depending on energy policies and developments in the economy and demography in the two WEC/PSI scenarios. The size of this investment corresponds to less than 4% of the global investment in power generation infrastructure over the same period in the two WEC/PSI scenarios. A significant share of the investment required to achieve universal electricity access is directed towards renewable options: solar and hydropower play an important role in providing electricity at low costs. Fossil fuel based generation is considered to be a near-term solution and nuclear power is constrained by issues related to high capital costs, safety, legal and regulatory investments.

The participation of the private sector is important in order to raise the necessary funds to achieve universal electricity access. The governments of developing countries not only need to address the design and implementation of suitable policies, but also create an investment climate to mobilise domestic and foreign capital and innovation. As political momentum is building and energy access is becoming a political priority, governments also need to start adopting staged energy access targets and allocating funds to achieve them.

In the WEC/PSI scenarios the universal electricity access case increases the global primary energy demand by 0.6–0.7% compared to the base case. This is because newly-connected people exhibit low levels of energy consumption per capita. The impact of universal electricity access on the increase of cumulative global CO₂ emissions is 0.3% compared to the base case over the period of 2011–2030. This is mainly because of the relatively high shares of renewables options (solar, hydro, etc.) that are chosen in order to achieve universal electricity access. However, if the global electricity access agenda is not paired more robustly with the climate agenda, the energy poor will be left behind. Empirical evidence from Bangladesh, Bolivia and Rwanda shows capable manpower in the energy access space to be extremely limited. Meaningful and sustainable approaches to energy access remain largely unfamiliar to most actors in the energy sector and the only way to deliver on them is to radically and urgently ramp-up broad-based capacity building on decentralised approaches to energy service provision amongst practitioners, policymakers and the finance community [109].

In order to gain more insights regarding the financial effort required to meet universal electricity access until 2030 we also perform a series of sensitivity analyses on key assumptions regarding: i) the initial electricity consumption levels for the newly connected population; ii) the electricity T&D grid expansion costs; and iii) the main economic and demographic assumptions of the two scenarios. The sensitivity analyses suggest that the investment cost in power generation infrastructure required for the universal electricity access case can range from \$31 billion to \$55 billion. The investment expenditures in increasing electricity access are more sensitive to the electricity T&D grid expansion costs than to the initial electricity levels of consumption, because the grid cost significantly affects the cost of delivered electricity and hence the choice of technologies that supply remote rural areas. In addition, for the same level of income the electrification rates of the population are likely to be higher when policies supporting efficiency and environmental sustainability are in place. In general, the range of investment expenditure required to achieve universal electricity access in the current analysis is in-line with estimates reported in similar studies, such as those from IEA, IIASA, RIVM and from others. This result constitutes a positive outcome for the methodology we applied and for the robustness of our analysis.

The two scenarios analysed in this paper can facilitate the exploration of different strategies and policy mixes that balance low-cost

energy and environmental sustainability in order to meet the goals of the SE4ALL objective. The results obtained from this work help in identifying the major opportunities and challenges in achieving universal electricity access in a global context of unprecedented uncertainty regarding international energy prices and patterns of energy trade, global competition for investment capital, technical progress and international interactions in environmental aspects.

Beyond these broad findings, it is of course critical to emphasise that the developing Asia, Latin America and Sub-Saharan Africa are very diverse regions with different sub-challenges and respective solutions. This heterogeneity is not directly addressed in our analysis. To tackle this we aim at enhancing the regional detail of the two models and performing regional deep-dives in collaboration with WEC. This can also include a more complete representation of the current infrastructure networks (for example length and quality of the electricity grid lines). Additional sensitivity analyses of key scenario drivers can further enhance the findings of this study as well.

Finally, the econometric model that we apply in our analysis for estimating the population with access to electricity takes into account only few of the factors that have been identified as statistically significant in the relevant literature (e.g. in Refs. [43,50,57,59]). This is mainly because this model is coupled with a bottom-up model, like GMM, which does not consider variables at macro-economic level. A coupling with a top-down general equilibrium model, or even better with a hybrid top-down/bottom-up framework, would require an extension of the econometric model to include additional variables such as: human development index, Gini index, net aid inflows, consumer expenditure to energy and goods, fuel prices, fuel taxes, fuel subsidies, fuel exports and imports, share of industry and services in GDP, levels of household consumption (in monetary units), external balances of good and services, public sector consumption relative to GDP, population access to education, etc. Such an expansion can provide additional insights and capture better the complexity of the problem of increasing electricity access in developing regions. Therefore, it can substantially improve the findings of this study and their quality.

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