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Powering the growth of Sub-Saharan Africa: The Jazz and Symphony scenarios of World Energy Council

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ABSTRACT

The energy sector of Sub-Saharan Africa today faces major challenges with total installed electricity generation capacity less than 100 GW and 590 million people lacking access to electricity. We analyse two long-term explorative scenarios, developed together with the World Energy Council, to assess the policy and technology mixes required to achieve long-term energy equity, energy security and environmental sustainability in the region. We find that more than \$55 billion in investments is required in power infrastructure annually until 2050. Access to electricity increases from 31% of the population in 2010 to more than 80% in 2050, but the region remains well behind than the rest of the world. The analysis suggests that a one-size-fits-all solution does not exist: the policy makers need not only to address the design and implementation of suitable energy policies, but also to create an investment climate to mobilise domestic and foreign capital and innovation.

Introduction

The lack of access to a reliable electricity supply stifles income-generating activities and hampers the provision of basic services such as health and education. Especially in Sub-Saharan Africa (SSA), limited electricity access is one of the biggest barriers to development and prosperity, with nearly 590 million people out of a total population of 860 million lacking access to electricity[4] in 2010 (IEA, 2013a); this is almost twice the total population of the USA. Viewed another way, the entire installed electricity generation capacity in Sub-Saharan Africa is 91 GW — no more than that of the UK— and one quarter of this capacity is unavailable because of age and poor maintenance. As a result, at least 30 countries in the region experience chronic power shortages. A key concern is thus how to power SSA's economic and social development along three key dimensions of energy sustainability: energy security, energy equity and environmental sustainability. The World Energy Council (WEC) refers to these three dimensions as the energy trilemma (WEC, 2013).

Together with WEC, we have developed two energy scenarios to 2050 assessing the energy trilemma at global and regional scales (Frei et al., 2013). The scenarios were built through a number of workshops with key energy stakeholders around the world and they incorporate a coherent set of economic, social and political key drivers, which were quantified and implemented with a detailed energy system model. The two scenarios are exploratory,[5] in 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 sustainability and energy security. Both scenarios include climate change policies and recent technological advances.

Under the two sets of scenario assumptions, we have quantified long-term cost-effective configurations of SSA's energy system. To forecast the population with access to electricity we have also developed a

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[4] Based on IEA definition, electricity access is first electricity supply connection to the household and then an increasing level of electricity consumption over time to reach the regional average (IEA, 2011b).

[5] Exploratory scenarios (also known as descriptive scenarios) are those that begin in the present and explore trends into the future. By contrast, normative (or prescriptive or anticipatory) scenarios start with a prescribed vision of the future (optimistic, pessimistic or neutral) and then work backwards in time to visualise how this future could emerge (Alcamo, 2001).

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reduced-form econometric model[6] that takes into account key socio-economic factors affecting the electricity access. This model constitutes also a contribution to the current research on electrification in developing countries.

As summarised in Nanka-Bruce (2010) the majority of the research on electrification in developing countries considers: i) the evaluation of electrification project/programmes (Davidson and Mwakasonda, 2004; GNESD, 2004; Goldemberg et al., 2004; Karekezi and Kimani, 2004; Nouni et al., 2008; Zhong Ying et al., 2006), ii) the progress of electrification projects (GNESD, 2004), iii) the assessment of relations between electrification, poverty reduction and economic development (Winkler et al., 2011; Oseni, 2012; Kooijman-van Dijk and Clancy, 2010; Shiu and Lam, 2004; Yang, 2003; GNESD, 2004) and iv) energy demand modelling describing the relationship between electricity consumption and socio-economic factors (Bhattacharyya and Timilsina, 2009; Kanagawa and Nakata, 2008). To the best of our knowledge there are three studies to date, which have analysed factors influencing electricity access using an econometric approach. One is by Kemmler (2007) and examines the factors influencing household electrification in India, showing that it depends on household characteristics, the electricity tariff and the quality of electricity supply. The second one is by Nanka-Bruce (2010), which analysed the impact of socio-economic factors on rural electrification development. The results indicate that the Human Development Index, the distribution of wealth, the level of institutional development and the urbanisation rate of the population play significant role in the rural population electrification rate. In the third study (Onyeji et al., 2012) the determinants of electricity access in SSA are analysed. The study suggests that the share of poor in population, gross domestic saving rates, corruption, urbanisation and government effectiveness are explaining over 90% of the variation of electricity access levels across emerging countries. However, none of the above studies attempts projections of the electricity access in the longer term and we contribute to the existing literature by developing a tool that is suitable for such projections.

In this paper we provide detailed numerical results for SSA from the two World Energy Council's global scenarios, which have not been published in WEC's special report (Frei et al., 2013). We discuss the energy supply options for the region and their implications in terms of energy access, investment needs, environmental sustainability and energy security. The results help to identify the future energy challenges in Sub-Saharan Africa.

We also provide the scientific background of the study by describing the two models used in it. Additional details about the structure of the econometric model for estimating the electricity access are given in the Appendix for the interested reader. It is worthy to note that the methodology followed in constructing the econometric model is generic enough to be applied also to other developing regions and countries. The interface that links the econometric model to a large scale energy system model is also generic, which allows the use of the model with a wide range of global or regional energy system models.

Thus, the paper contributes both to the literature about the future energy challenges in Sub-Saharan Africa and to the available methodologies and tools for estimating the population with electricity access in developing regions.

The modelling framework

As mentioned in the introduction two models were used in this study (Fig. 1). The first model is the Global Multiregional MARKAL (GMM) model (Densing et al., 2012; Gül et al., 2009; Krzyzanowski et al., 2008; Rafaj and Kypreos, 2007; Rafaj et al., 2006, 2005; Barreto, 2001), belonging to the family of MARKAL models (Loulou et al., 2004). The GMM model was used in assessing the development of the whole energy system. The second model is a reduced-form econometric model that estimates the population with access to electricity given the economic and demographic assumptions from the scenarios and the output from GMM on the electricity consumption per capita and the level of electrification of demand.

As shown in Fig. 1 the two models are sharing common assumptions regarding the GDP and population projections. The link between the two models is established on the average electricity consumption per capita in the residential sector and the percentage of electrification of the residential demand. When assessing exploratory scenarios the GMM model provides the electricity consumption and the electrification rate of demand to the econometric model and the latter forecasts the population with access to electricity. When assessing normative scenarios, in which specific population electrification rates should be met, the link between the two models is reversed: the average electricity consumption per capita and the electrification rate of demand required to attain the imposed target are calculated from the econometric model and then the updated electricity demands are given to the GMM model as inputs. In this setting, the GMM model finds the cost-optimal configuration of the energy system (technology mix, investments) need to achieve the imposed electrification targets. The two scenarios examined in the present study are exploratory in their nature. Thus, the GMM model is driving the econometric model, by providing to the latter the average electricity consumption per capita and the electrification rate of the residential demand.

In the next sub-sections the two models are described in more details, with emphasis on the design of the new econometric model developed specifically for this study.

The GMM model

The GMM model is a perfect-foresight, bottom-up, technology rich model. It computes an intertemporal partial equilibrium across all energy markets under policy and technical constraints by minimising the total energy system cost (Fig. 2). Equilibrium is established at every stage of the energy system: that is, for primary energy and secondary energy commodities and energy services. The time horizon of the model covers the period 2010 to 2100, with a step length of 10 years. In each period a simplified seasonal and day/night disaggregation is incorporated to account for supply and demand variations.

The spatial resolution of GMM consists of 15 world regions, with Sub-Saharan Africa represented as a single region (Fig. 3). The energy system in each region is represented in detail, from resource extraction to final consumption, using the concept of the “Reference Energy System” (Fig. 4). GMM includes more than 400 technologies from resource extraction to final energy consumption, with the capability of modelling endogenous technology dynamics based on the concept of learning-by-experience (Loulou et al., 2004). The fossil resources in each region are categorised by different extraction costs and by probability of existence: ranging from easily extractable, proven reserves, through more cost-intensive reserves or speculative resources, to unconventional resources (Turton et al., 2013; BGR, 2012; GEA, 2012). Trade of energy carriers across regions is subject to transportation costs.

The energy demand sectors represented in GMM are industry, residential/commercial, transport and non-energy uses. The industry and residential/commercial sector energy demands are disaggregated to thermal and specific uses. Transport includes subsectors for private passenger transport, aviation and other surface transport. The energy demand technology options operate at the level of energy uses. The useful energy demands are derived from the scenario assumptions based on a coherent storyline. The GMM model supplies the useful

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

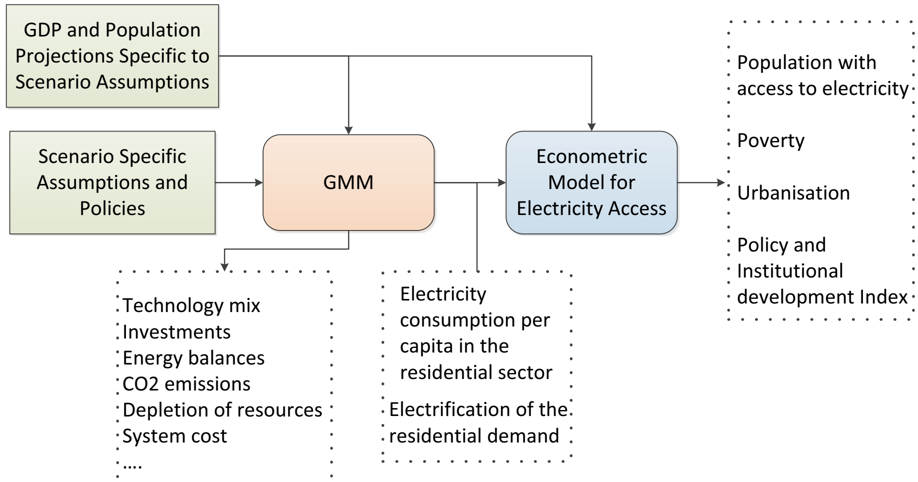

Fig. 1. The modelling framework used in the study (with green colour are represented the scenario assumptions common to both models). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

energy demand by optimising the endogenous equipment choice and production and delivery of energy carriers.

The econometric model for estimating the population with access to electricity

As mentioned in the introduction, relatively few studies have attempted to project future electricity access over the long term using an econometric approach. Accordingly, we have a developed a reduced-form model to explore long-term access for the Jazz and Symphony scenarios. The structure of the model is briefly described in this section and more details are given in the Appendix.

Table 1 presents the variables considered in the model for Sub-Saharan Africa. The selection of the variables was based on two major criteria: a) include at least those variables that are identified in the literature as having a significant impact on electricity access and b) include variables that can be linked both with the results obtained from the GMM model and with the quantification of the scenario assumptions.

The data were collected for the period 1970–2010 for Sub-Saharan Africa as a whole. The correlation coefficients between the input variables (presented in Table 2) provided guidance in designing the model.

Electricity access is positively correlated with urbanisation, since around 85% of the population without access to electricity lives in rural areas (IEA, 2012, 2011a). This is attributed to both the low income levels in rural settings and the reluctance of utilities (due to high costs)

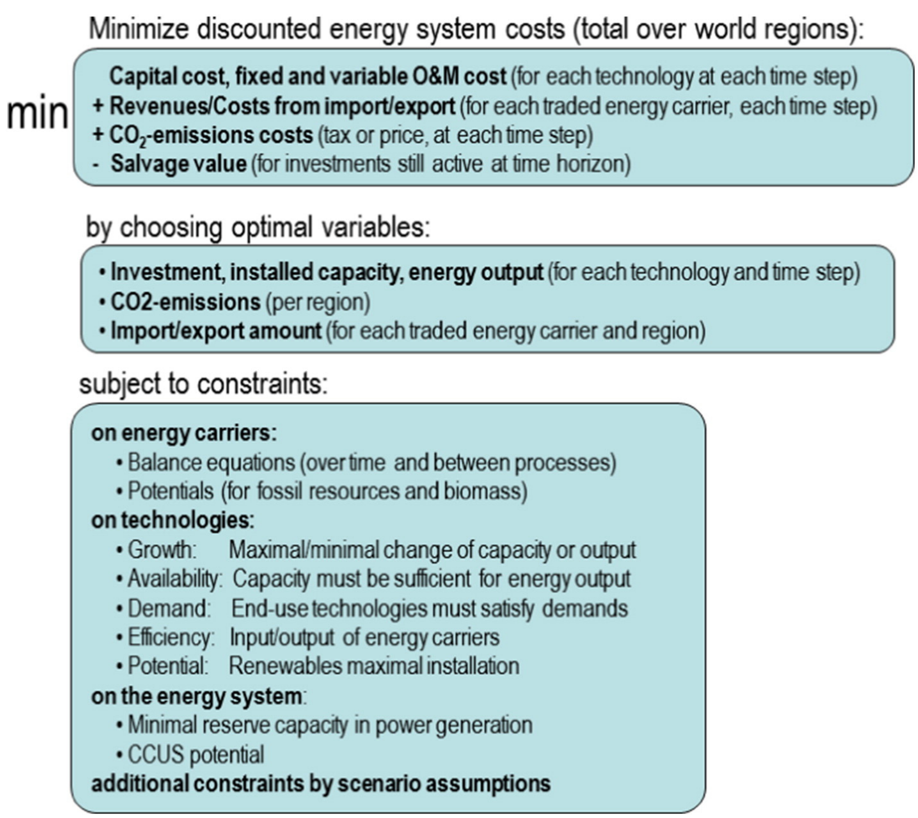

Fig. 2. The cost-minimisation problem solved by GMM to supply the energy demand services.

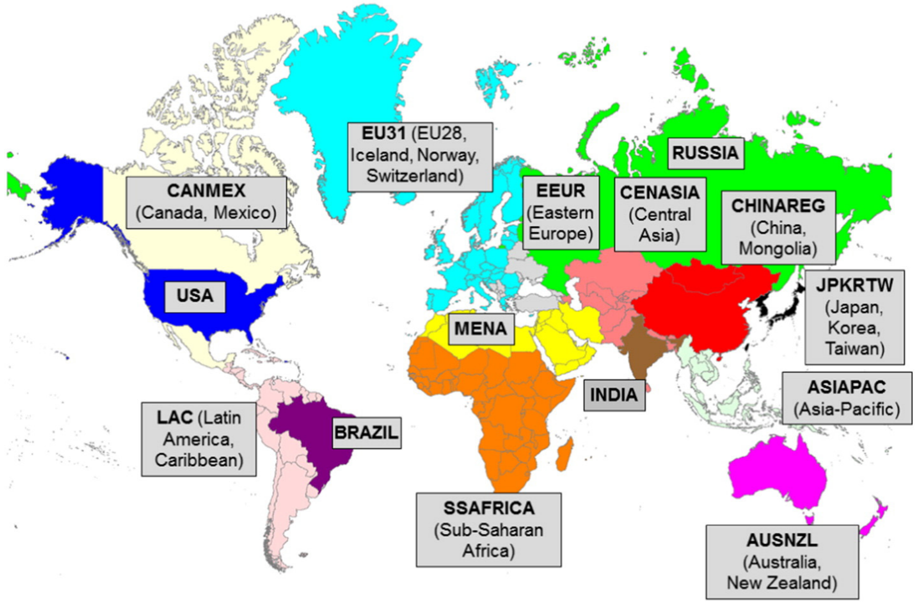

Fig. 3. The 15 world regions of the GMM model.

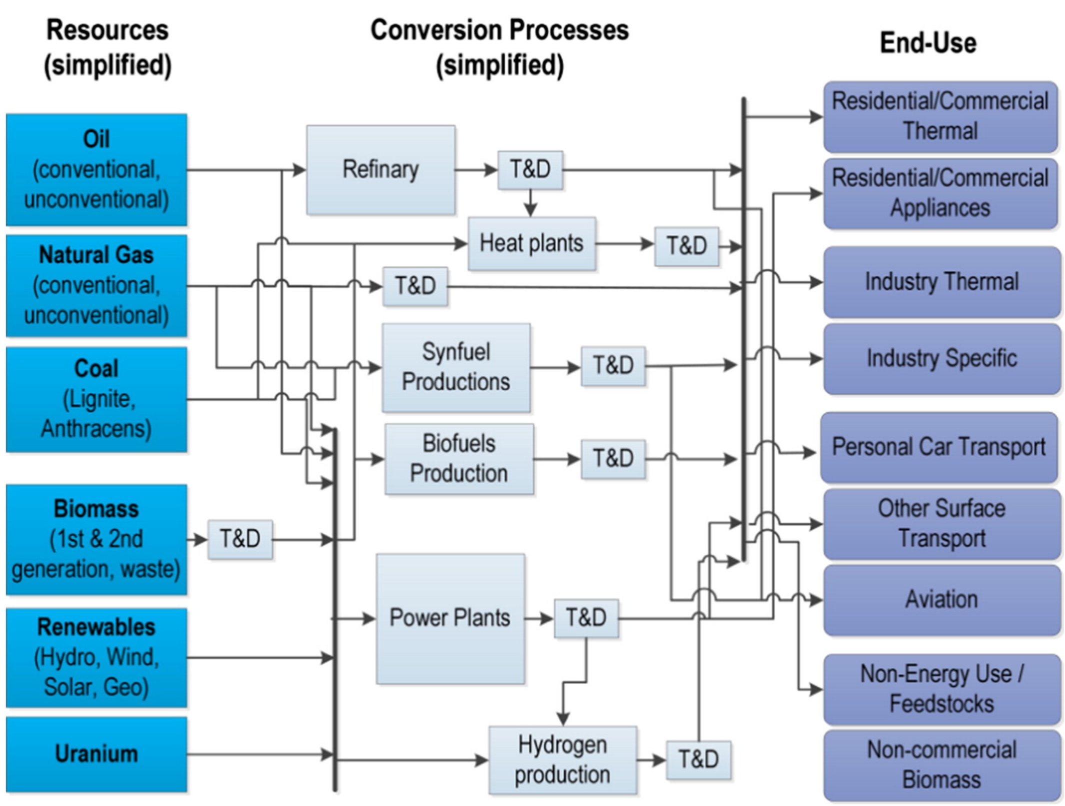

Fig. 4. A simplified representation of the Reference Energy System (RES) in the GMM model.

to serve areas with low population densities and low demand levels with a peaking profile.[7] Electricity access is negatively correlated with poverty (IEA, 2002; Zhong Ying et al., 2006), as more than 80% of people without access to electricity are located in the poorest regions, despite possible electrification programmes in place. This is because unless consumers are able or willing to pay at least for operating costs, energy access programmes are unlikely to be sustainable (Brew-Hammond, 2010). The positive correlation of the institutional development with electricity access suggests that the government effectiveness is related to electricity levels in SSA as corruption seems to have an adverse impact on electricity access outcomes (Onyeji et al., 2012).

Based on the above correlations, the general structure of the model is specified as in Fig. 5. The main input variables are the GDP and population projections from the scenario assumptions and the electricity consumption per capita and electrification rates of residential/commercial

[7] Supplying electricity in rural areas can be up to seven times more costly compared to supplying urban settings (Goldemberg, 2000).

Table 1
List of variables and the corresponding data sources used in the estimation.

Variable	Unit	Source
Income	Average income per capita in USD2005 (PPP)	World Bank indicators' database (WB, 2013)
Urbanisation	% of population in urban areas	United Nations Population Division (UNPD, 2013)
Poverty	% of population living with less than $2 (PPP 2005) per day	World Bank indicators' database (WB, 2013)
Institutional development	Average of CPIA indices for public sector management, economic management, social inclusion and structural policies	World Bank indicators' database (WB, 2013)
Electricity per capita	KWh per capita in residential/commercial demand	IEA World Energy Balances (IEA, 2013a)
Electrification of demand	% electricity in final consumption in residential/commercial demand	IEA World Energy Balances (IEA, 2013a)
Electricity access	% population with access to electricity	IEA World Energy Outlook series (IEA, 2013b, 2012, 2011a, 2010, 2009, 2006, 2004, 2002)

Table 2
Correlation coefficients between population with electricity access and its drivers considered in the model for Sub-Saharan Africa, using the data sources mentioned above.

	Income per capita	Urbanisation rate	Poverty rate	Institutional development	Electricity per capita	Electrification of demand
Urbanisation rate	0.85					
Poverty rate	−1.00	−0.85				
Institutional development	0.33	0.32	−0.30			
Electricity per capita	0.76	0.85	−0.73	0.39		
Electrification of demand	0.66	0.79	−0.63	0.37	0.99	
Electricity access	0.88	0.97	−0.87	0.29	0.85	0.79

demand from the GMM output. Via estimated reduced-form equations (which are described in more detailed in Appendix A), urbanisation, poverty and institutional development are linked with the economic and demographic developments. Then, together with the outputs from the GMM model, they enter into the estimated equation for electricity access. The estimation method used is Ordinary Least Squares (OLS) using time series data for the Sub-Saharan Africa region as a whole. The short- and long-term effects of the explanatory variables are captured via polynomial distributed lag estimation (Box et al., 2008; Pindyck and Rubinfeld, 2000; Romer, 2012). The estimations were made in Eviews software (QMS, 2009).

The specification of the equation estimating the population with access to electricity does not take into account the effect of electrification programmes, because: a) they are neither always sustainable nor adequately contributing to the development[8] (Bhattacharyya, 2012) and b) their introduction as a possible explanatory variable would require additional scenario assumptions about future implementation (and effectiveness), which were not explicitly considered in the present study. However, the specification can be extended to include electrification programmes, provided suitable assumptions for future electrification programmes are available.[9] The historical data (Fig. 6) suggest a sigmoid function for electricity access, implying a greater effort to electrify the last part of the population.

Notwithstanding the estimation of the econometric model by using datasets for Sub-Saharan Africa, its methodology is generic enough to be applied to other developing regions or countries. In addition, the required inputs from a large-scale energy system model are only the electricity consumption per capita and the electrification rate of residential demand, which imply that it can be interfaced with other energy system models as well (see also the Appendix for a relevant discussion).

The “Jazz” and “Symphony” scenarios

The Paul Scherrer Institute (PSI) and the World Energy Council (WEC) have built two scenarios, in collaboration with a range of partners including international energy suppliers, distributors and energy technology companies. from the extended network of WEC's 93 member committees and 3000 member organisations around the world. The scenarios correspond to two narrative storylines about future trajectories of the energy system. They are explorative in their nature, since no specific targets were set in them (e.g. regarding CO_2 emissions or population electrification rates), and they were quantified for each one of the 15 world regions of the GMM model. The results were aggregated to the World Energy Council's eight regions,[10] to ensure consistency with other publications from WEC. Below the two scenarios are described in brief and the interested reader may find their full description in (Frei et al., 2013). Table 3 gives a quick overview.

“Jazz” scenario

“Jazz” focuses on achieving economic growth through low-cost energy. The economy is liberalised, there are no barriers in international trade, and there is minimal government intervention in energy markets. The deregulation of the economy and the opening of the upstream energy market attract Foreign Direct Investments (FDI) in Sub-Saharan Africa. Under these assumptions high economic growth is anticipated in SSA, which also leads to an increased demand for energy services. Subsidies and support programmes promoting specific technologies are phased-out and market prices reflect the true cost of energy. In this context, energy technologies compete on price, quality and resource availability. The scenario also assumes limited government support for large-scale capital intensive power production options, particularly nuclear power and large hydropower projects.

[8] Two examples supporting this statement are India and China, in which the electrification programmes produced different results.

[9] In the current model specification the electrification programmes can be included implicitly by imposing constraints on the level of electricity consumption per capita in the GMM model, which correspond to the electrification targets set by the corresponding programme; they can be also included as adjustments (constants) in the electricity access equation of the econometric model.

[10] The WEC regions are: North America (USA, Canada, Mexico), Europe (EU, Eastern Europe and Russia), Middle East & North Africa, East Asia (including China), Latin America (including Brazil), Southeast Asia & Pacific (including pacific OECD countries), South & Central Asia (including India and former USSR states in Asia) and Sub-Saharan Africa.

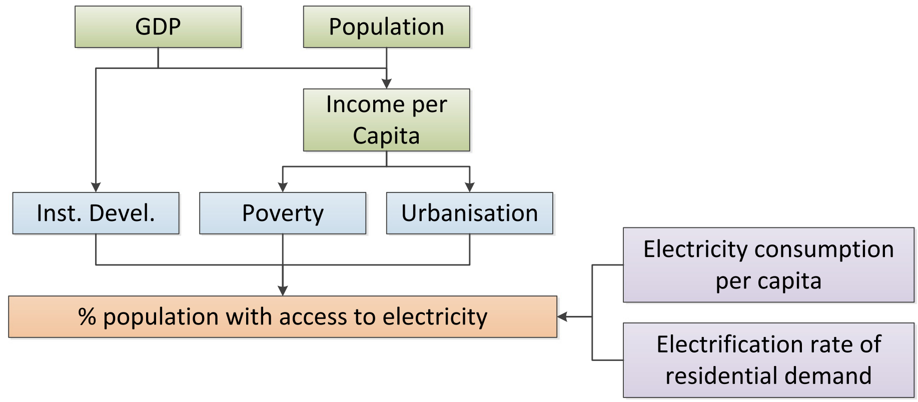

Fig. 5. Overview of the econometric model structure for forecasting the population with access to electricity.

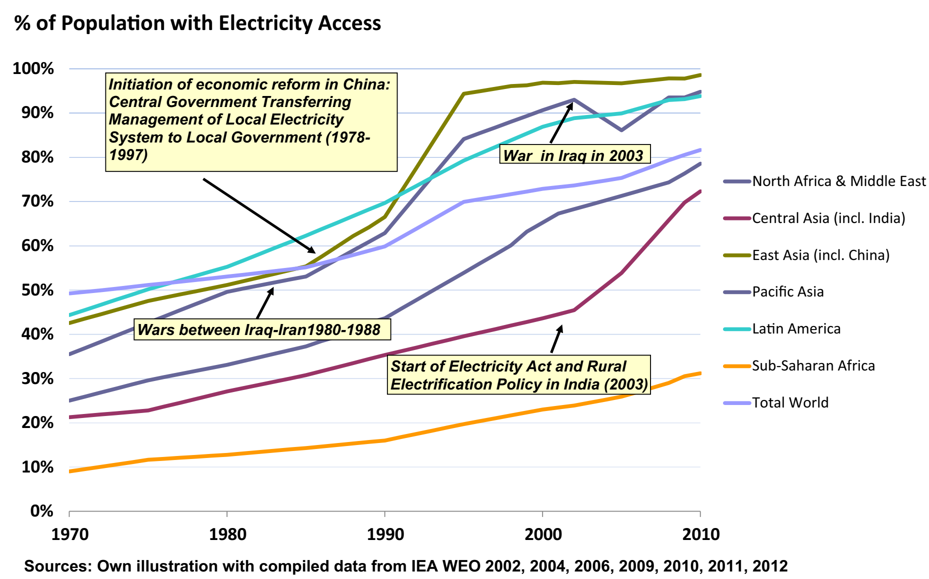

Fig. 6. The historical evolution of population with access to electricity in major world regions.

"Jazz" assumes that there is a delayed action in climate policy with no global agreement on emission targets, but more diverse regional responses. SSA is assumed to implement a carbon market only in the second half of the projection period with limited abatement intensity.

"Symphony" scenario

"Symphony" focuses on environmental sustainability and energy security. The economy is more regulated in this scenario than in "Jazz" and energy policies are set by more coordinated government action. The level of privatisation of the economy is assumed to remain at the current levels, which leads to a restrained participation of the private sector. As a result the FDI in the SSA region are more limited, targeting fewer sectors of the economy, which in turn leads to lower economic growth in SSA compared to "Jazz".

"Symphony" assumes that regional emission trading schemes are being developed by 2030, which are replaced by a global CO_2 market in the longer term. SSA fully joins the globally coordinated action by 2050. Governments seek to support energy technologies with lower GHG emissions and reduced import dependency. Technology leapfrogging enables SSA to avoid a lock-in to carbon-intensive options in electricity generation and to adopt low-carbon options in demand sectors.

Quantification of the main assumptions of the scenarios for SSA

Table 4 presents the quantification of the scenarios regarding population growth, economic development and climate policy intensity. In both scenarios, economic growth is assumed to be higher in the second half of the projection period as a result of the benefits of current economic reforms (IMF, 2013).

The quantification of the population growth assumption is based on the premise that the higher incomes and education levels facilitate access of women in labour market and result in increased "opportunity cost" of children.[11] Hence, in the "Jazz" scenario the fertility rates are lower compared to "Symphony". In this context, the "Jazz" scenario is closer to the "low fertility" variant of the UN projections (UNDP, 2012),

[11] The increase of the earning potential, associated with higher educational attainment, encourages women to invest more time in labour market participation than caring for children. However, after a certain stage of economic development is attained the fertility is increased again, but this level of economic growth is not attained in the two scenarios in SSA according to the stakeholders.

Table 3
The WEC's scenarios at a glance: "Jazz" and "Symphony".

Jazz	Symphony
Focus on economic growth via low cost energy and using the best available resources	Focus on environmental sustainability and energy security
• Economy liberalisation, opening of upstream energy markets, increased FDI, high economic growth	• Market regulation with policies set by governments, regulatory hurdles, limited FDI, lower economic growth than "Jazz"
• Lower fertility driven by higher incomes and education	• Medium fertility in line with UN Population Division
• Technology choice based on energy markets = > limited support for nuclear, CCS, large hydro	• Government support for low-carbon technologies = > CCS, nuclear, hydro, solar, wind
• Efficiency is market driven	• Efficiency measures taken by governments
• Delayed climate policy action	• Strong climate policy with global convergence

Table 4
Main assumptions used in "Jazz" and "Symphony" scenarios.

Quantification of the two scenarios		Jazz					Symphony				
	2010	2020	2030	2040	2050	% CAGR (2010–50)	2020	2030	2040	2050	% CAGR (2010–50)
Population (in million)	857	1070	1281	1478	1648	1.6	1089	1354	1648	1961	2.1
GDP (in billion USD2010 MER)	1160	1800	3239	6405	12001	6.0	1768	3090	5903	10843	5.7
Per capita income (USD2010 MER)	1354	1682	2528	4334	7282	4.3	1624	2282	3582	5529	3.6
CO_2 price (USD2010/tn CO_2)	0	0	5	10	23	–	10	23	42	70	–

while the "Symphony" scenario is closer to the "medium fertility" variant. In both scenarios however, the region becomes the most populated among the fifteen GMM regions by 2050, exceeding both China and India.

Average incomes increase significantly in both scenarios, compared to the current levels, but are still rather modest in a global context, with SSA remaining the poorest region in the world (Frei et al., 2013).

Regarding climate policy, the regional carbon market of modest intensity assumed in "Jazz" is reflected in lower carbon prices compared to "Symphony", in which SSA joins the global effort in the second half of the projection period and adopts more stringent goals.

Results and discussion

Urbanisation rate, poverty and institutional development

The econometric model was used to obtain the projections for the urbanisation rate, poverty and institutional development, based on the demographic and economic assumptions of each scenario. Table 5 summarises the results.

Currently (2010) the urbanisation rate of the SSA region is well below than the global average of 52%. During the projection period, the urbanisation rate increases in both scenarios reaching a higher level in "Jazz". In terms of absolute numbers the urban population in "Jazz" reaches 950 million in 2050, while in "Symphony" exceeds 1 billion (mainly because of the higher overall population). In "Jazz", about 30% of this increase is attributed to population migration to urban areas (due to higher incomes) and the rest is attributed to natural population growth. In the "Symphony" scenario, around 20% of the increase in urban population is attributed to migration.

The results from the econometric model also suggest a significant reduction of poverty. In 2010, the budgets of households in Sub-Saharan Africa were very limited, with a monthly average of less than $180 for a 5-person household (WB, 2013), with more than half spent on food. In the "Jazz" and "Symphony" scenarios, the percentage of the population in poverty is reduced by roughly 50 percentage points (see Table 5). In absolute numbers the population living on less than $2 per day is reduced from 603 million in 2010 to 307 million in "Jazz" and to 409 million in "Symphony" in 2050. The "Symphony" scenario lags behind "Jazz" by around 10 years in poverty mitigation measured in absolute terms[12] (i.e. number of people living with less than $2 per day).

The Country Policy and Institutional Assessment CPIA index presented in Table 5 seeks to capture the quality of public sector management, economic management and the social and other structural reforms. In both scenarios the index improves, consistent with a reduction in corruption and an increase in public administration efficiency. Despite the significant improvement from the 2010 level, the average CPIA index in the region remains at low levels compared to other parts of the world, remaining below current levels in developing European and Central Asian countries (WB, 2013).

Final energy consumption

In 2010, Sub-Saharan Africa was characterised by relatively low levels of industrialisation, low demand for transport services and significant use of traditional fuels in the residential sector. Industry is mainly oriented towards mining and raw material processing activities. Transport services are met mainly by road transport (or non-motorised forms which are not represented in energy statistics). The demand for energy services in the residential/commercial sectors is supplied mostly by non-commercial biomass, which is used in appliances with low efficiencies (and high levels of local and indoor pollution). This implies that the final energy demand in the residential sector is much higher than it would be if all households had access to – and could afford – modern fuels and efficient equipment (IEA, 2013a). Table 6 presents the final energy consumption by sector in 2010 and the long-term projections from the two scenarios.

According to the scenario assumptions, economic growth and significant industrialisation is anticipated in SSA by 2050. The share of the industrial sector in total final energy consumption increases from 16% in 2010 to more than 40% in both scenarios by 2050. The energy consumption for industrial specific uses increases by a factor of seven during the projection period. The increase in industrial thermal uses is much lower compared to specific uses, due to the choice of more efficient equipment.

The positive economic developments also increase the replacement of traditional biomass with modern equipment for supplying

[12] In relative terms, i.e. percentage of population living with less than $2 per day, "Symphony" lags behind "Jazz" by around 3 years.

Table 5
Projections of the econometric model for urbanisation, poverty and government efficiency.

		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
Urbanisation rate (%)	36%	39%	42%	47%	58%	39%	42%	46%	53%
Poverty (% of pop living < $2 per day)	70%	56%	41%	28%	19%	56%	43%	30%	21%
CPIA index (1 = low, 6 = high)	3.18	3.22	3.28	3.35	3.41	3.22	3.27	3.34	3.40

Table 6
Final consumption by sector in PJ.

TFC by sector in PJ		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
Industry	2763	4300	6952	10314	15410	4244	6487	9476	13850
Of which:									
Thermal uses	2033	3110	4771	6717	9509	3072	4388	6149	8512
Specific uses	730	1190	2180	3597	5901	1172	2099	3327	5338
Residential/Commercial	12156	10099	9721	10646	12853	10181	9736	10467	12235
of which:									
Thermal uses	11730	9430	8564	8537	9166	9524	8631	8521	8900
Specific uses	426	669	1157	2109	3688	657	1105	1946	3335
Transport	2112	2528	3807	5194	7372	2421	3440	4568	5657
Of which:									
Private transport	887	1031	1667	1838	2248	987	1523	1833	1963
Aviation	245	380	682	1338	2436	350	561	948	1412
Other transport	981	1118	1457	2018	2687	1084	1356	1787	2283
Total	17031	16927	20479	26154	35636	16846	19663	24511	31742

space and water heating in the residential/commercial sectors. In this context, the energy consumption for thermal uses declines by 22% in "Jazz" and by 24% in "Symphony" scenarios in the period from 2010 to 2050. The electricity consumption in specific uses increases substantially driven by the increase in per capita incomes. The overall electrification of the residential/commercial final energy consumption reaches 30% in both scenarios by 2050. This is comparable to current average global[13] levels of electrification. Due to the above developments, efficiency gains and increased access to modern energy carriers, the share of the residential/commercial sector in total final energy consumption declines from 71% in 2010 to below 40% in 2050.

The demand for transport services also increases during the projection period, pulled by the economic activity. Road transport remains the most important sector in terms of energy consumption. Regarding private road transport, technology choice diverges between the two scenarios (Fig. 7). In "Jazz", a large share of conventional cars remains, as the efficiency of internal combustion engines continues to improve, with limited support for alternative technologies. On the other hand, in "Symphony" the passenger car fleet becomes more diverse, due to more stringent climate policy and promotion of alternative technologies, with an increased share of hybrid vehicles. Despite these differences, in both scenarios energy consumption in the transport sector shows signs of decoupling from economic activity, due primarily to improvements in energy efficiency.

Table 7 presents the total final energy consumption by fuel for all demand sectors, with both scenarios displaying similar trends. In this context, oil consumption increases driven by the higher transport activity. Gas penetrates in the industrial and residential/commercial sectors, although the rate of expansion is limited to the development of distribution infrastructure. Finally, the share of demand supplied by electricity is similar in the two scenarios, driven by higher economic growth in Jazz and a stronger emphasis on efficiency in Symphony.

Power generation

Electricity generation in Sub-Saharan Africa is currently dominated by fossil fuels, with a large share of coal in the south, and oil and gas in the west. Two nuclear power stations are currently in operation in South Africa, but expected to be decommissioned by 2024–25 (WNA, 2013). The technical potential for generating electricity from renewables in the region is vast (Turton et al., 2013), but as of today only hydropower has been developed on a large scale: however, it is estimated that only 7.6% of the hydro potential is now exploited (mainly in the basins of the Blue Nile, Zambezi and Congo rivers), well below the world average of 24%. Biomass, wind, solar and geothermal electricity generation are still underdeveloped in most countries, with the exception of geothermal energy in Kenya.

Out of the currently installed generation capacity of 91 GW in SSA, around 20 GW is planned to be decommissioned by 2025. On the other hand, 25 GW of coal-fired generation (Yang and Cui, 2012) and another 10 GW of hydropower is planned to be installed. The Grand Inga Dam with a potential power of 39 GW is still an uncertain project (Taliotis et al., 2014). The above imply that there is a significant under-investment in the region in terms of infrastructure, which can also be verified by a brief comparison of SSA with other world regions in terms of power capacity per capita and power capacity per unit of GDP (Table 8).

The developments in the power generation in the two WEC scenarios are presented in Fig. 8, while Table 9 presents a set of indicators in the power sector.[14]

[13] The electrification rate of demand is influenced by the climatic conditions, so a cross-regional comparison may be not appropriate; for instance Switzerland in 2010 had an electrification rate of the residential/commercial demand of 31%.

[14] In the context of the present study we assume a copper plate electricity market in Sub-Saharan Africa, with a single electricity price, and not four different power pool regions as they stand today.

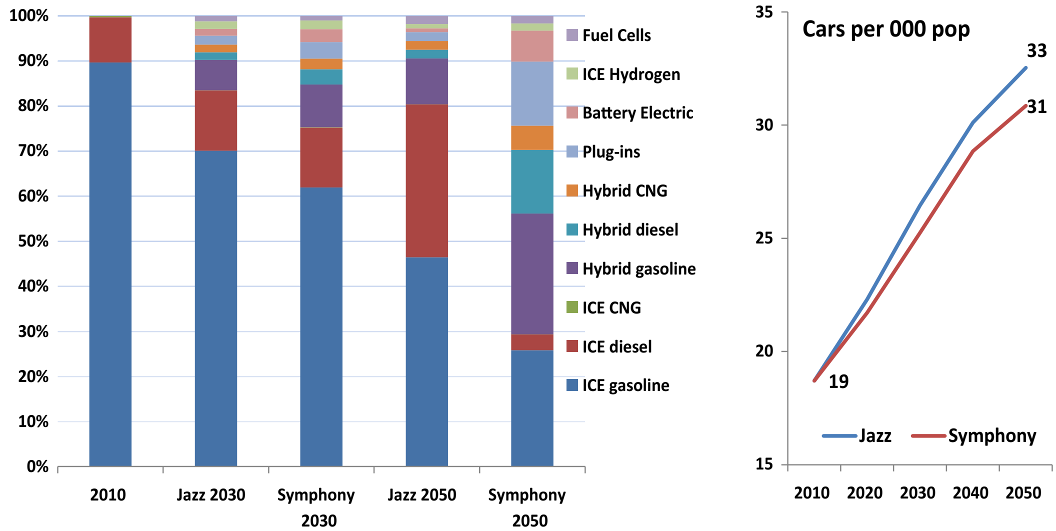

Fig. 7. Shares of technologies in passenger private transport and car ownership per thousand capita.

In "Jazz" the choice of electricity generation technologies is market driven and the investments are oriented towards flexible projects with short construction times, avoiding capital intensive alternatives. In this context, gas turbine combined cycle (GTCC) plants have a competitive advantage because of their low capital cost, high efficiency, short construction times and generation flexibility. Solar PV constitutes a competitive choice mainly in the second part of the projection horizon, due to the anticipated continuing decline in investment costs, the good quality of the solar resource in much of SSA and the ability of PV to supply electricity in remote areas, where there may be barriers to grid expansion. Coal attains high shares in electricity generation until the mid-term horizon because of the relatively low cost and limited climate change policy; the share of coal drops later in the projection period because of increasing CO_2 prices, and the increased cost-effectiveness of solar and gas. New hydropower projects are focused mainly on small hydro and run-of-river options. Nuclear power is not expanding due to limited government support and capital costs. Biomass use for electricity production accelerates after 2030 when the more efficient gasification technology matures. The share of wind turbines in electricity generation increases, but wind lacks behind solar as the competitive advantages of PVs in the second half of horizon are quite significant. Finally geothermal energy grows fast, facilitated by the good quality of resource, and its penetration in the electricity mix is limited mainly by the expansion of the required infrastructure (e.g. exploration, drilling, grid connection).

In "Symphony", the supply of electricity is more diversified. Carbon capture and storage (CCS), solar PV and hydropower are the main options for producing electricity in the long term. Coal-based generation adopts CCS technology after 2030 due to the more stringent abatement policy in this scenario. On the other hand, GTCC with post-combustion CO_2 scrubbers become the main option in gas-based generation only at the end of projection period, when the CO_2 price exceeds 40 $/tn. Solar PV constitutes in "Symphony" a competitive option for electricity generation for the same reasons as in "Jazz". Regarding hydropower, government support for large-hydro projects triggers a significant expansion of installed capacity: on average about 20 GW of new hydropower is installed in each decade in the region. The remaining renewables, geothermal and biomass, penetrate at almost the same rates as in the "Jazz" scenario. Finally, nuclear capacity expands from 2 GW to 9 GW given stronger government support. However, nuclear is unlikely to be a game changer in the region due to the high capital costs and institutional requirements. It is worth noting that the share of intermittent renewables (solar and wind) in total electricity generation is almost the same in both scenarios, 27% in "Symphony" and 28% in "Jazz" in 2050, which may create challenges in terms of capacity adequacy and grid stability in spite of the high quality of these renewable resources.

Table 7
Final consumption by fuel in PJ.

TFC by fuel in PJ		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
Coal	835	737	890	941	1103	737	445	502	611
Oil	2787	3168	4724	5772	7755	3039	4310	5050	5775
Gas	109	520	847	1303	1578	479	845	1194	1302
Biomass & Biofuels	2259	3628	5203	6640	8580	3632	5170	6498	8157
Non-commercial biomass	9828	6733	4913	3694	2876	6866	5172	4038	3213
Electricity	1214	1828	3053	5843	10120	1789	2902	5416	9271
Heat*	0	218	704	1681	3111	209	664	1513	2878
Solar thermal	0	52	118	214	363	52	118	214	363
Hydrogen	0	44	28	67	151	44	36	87	172
Total	17031	16927	20479	26154	35636	16846	19663	24511	31742

* From district networks and produced on-site.

Table 8
Generation capacity per capita and per unit of GDP between Sub-Saharan Africa and other regions.

Region	Capacity per capita (MW/million population)	Capacity per unit of GDP (MW/billion GDP US2010)
Sub-Saharan Africa	110	80
Central Asia	180	130
Pacific (non-OECD) Asia	260	80
India	170	130
China	760	170
Latin America	550	70
Eastern Europe	970	150

The investment requirements for new power generation capacity and grid expansion are significant in both scenarios (Fig. 9). In "Jazz" around 975 GW of new capacity is added in the period 2011–2050, with a cumulative undiscounted investment cost of $1241 billion,[15] or $31 billion per year. Similarly in "Symphony" around 934 GW of new capacity is added in the period 2011–2050, with a cumulative undiscounted cost of $1393 billion or close to $35 billion per year. The investment needs in both scenarios are larger in the second half of the projection period when electricity demand is significantly higher.

For grid investment, we have assumed in the GMM model that an expansion of transmission and distribution infrastructure is needed for each MW of new centralised capacity (i.e. excluding decentralized options like solar PV).[16] Following this assumption, the calculated investment in grid expansion amounts to $1011 billion in "Jazz" and $967 billion in "Symphony", or, viewed another way, close to another $25 billion annually in both scenarios.

Net imports

Another important element of a sustainable energy system is energy security. In this context, Table 10 presents net imports in terms of quantity and monetary units in the two scenarios. The region is currently a net exporter of fossil fuels and biofuels, since SSA is well endowed with resources and domestic consumption is currently low. In both scenarios, region remains a net exporter of oil and biofuels until 2050, but becomes a net importer of gas after 2040 due to the depletion of cheap local resources and increasing demands.

Population with access to electricity

Fig. 10 presents the rate of electricity access in the different countries in SSA in 2010 (Banerjee et al., 2013). It is estimated that in 2010 around 590 million people lacked access to electricity in the region (IEA, 2013a), due to under-exploited energy resources, underserved demand, high costs of modern energy, high poverty, low urbanisation rates, fragmented energy markets and a low capacity to attract private sector financing. According to IEA statistics (IEA, 2013b, 2012, 2011a, 2010, 2009, 2006, 2004, 2002), the rate of electrification in the region doubled in the period 1990–2010, but a significant part of this increase can be attributed to improvements in data collection.

The positive developments in the main drivers affecting the access of population to electricity, namely the per capita income, urbanisation rate, reduction of poverty, institutional development result in a reduction to the number of people without access to electricity in the longer term. However, none of the scenarios solves the problem completely: in "Jazz" around 266 million will still not have access to electricity in 2050, while in "Symphony" this number is close to 400 million. To put this in a perspective, China realised 80% access in 1990 and the Central & South Asia (including India) is projected in Jazz and Symphony to exceed 80% by 2020 (Frei et al., 2013). The "Symphony" scenario lags 5 years compared to "Jazz" in the progress of the electrification of the population. Fig. 11 presents the historical and projected rate of electrification in SSA region and a comparison of the present study with the electrification rates published in the World Energy Outlook 2014 (IEA, 2014), World Energy Outlook 2013 (IEA, 2013b) and in the Africa's infrastructure outlook to 2040 (PIDA, 2010). It should be noted that the current results for the population with access to electricity are slightly different in "Symphony" scenario compared to the published results from WEC (Frei et al., 2013), because of updates both in the database and in the structure of the econometric model.

The results obtained seem to be in-line with the projections from IEA and PIDA, which is a positive verification of the methodology applied in the present study for estimating the population with access to electricity.

Assessing the energy trilemma

Three key dimensions of energy sustainability identified by WEC (2013) include environmental sustainability, energy security, and energy equity. Below we examine specifically how the two scenarios perform along these dimensions for selected indicators.

Environmental sustainability: CO_2 emissions and energy intensity

The main element of environmental sustainability quantified by GMM is CO_2 emissions, along with derived indicators such as the CO_2 emissions per capita and the CO_2 intensity of the economy. The energy intensity (measured at primary or final energy consumption) also provides an indication of the resource intensity of the economy, although the environmental implications also depend on the sources of energy and the end-use equipment used (see Table 11).

Carbon dioxide emissions in "Jazz" increase by 164%, but only 32% in "Symphony" in the period from 2010 to 2050. Energy intensity (which provides some indication of efficiency) is similar although "Symphony" is slightly less energy intensive for the same income level.

Energy security: diversification in primary supply

Like environmental sustainability, GMM captures only some elements of energy security. Selected indicators of energy security are presented in Table 12, including: a) the Shannon–Wiener[17] and Herfindahl–Hirschmann[18] diversification indexes commonly used in studies on energy security (EU, 2014) and b) the share of net imports in total primary energy supply.

As shown in Table 12, net import dependency is negative since the region is net exporter. Similarly, the diversification indices indicate increasing diversity of supply in both scenarios.[19] The results obtained suggest that both scenarios perform well in terms of energy security, with "Symphony" performing slightly better than "Jazz".

[15] Refers to USD 2010.

[16] This is a basic feature of MARKAL family models, as they do not represent the electricity grid in detail.

[17] The Shannon–Wiener index is often calculated as $H = -\sum_i s_i \cdot \ln(s_i)$, where s_i can be the share of energy carrier i in total primary supply. The minimum value is 0 and the maximum value is attained when all shares are equal.

[18] The Herfindahl–Hirschmann index is calculated as $= \sum_i s_i^2$, where s_i can be the share of energy carrier i in total primary supply; the index ranges from $1/N$ to 1, where N is the total number of energy carriers. The higher the value is the more concentrated the supply.

[19] Note, the Shannon–Wiener index indicates higher diversification of supply with higher values, while the Herfindahl–Hirschmann index implies higher diversification with lower values.

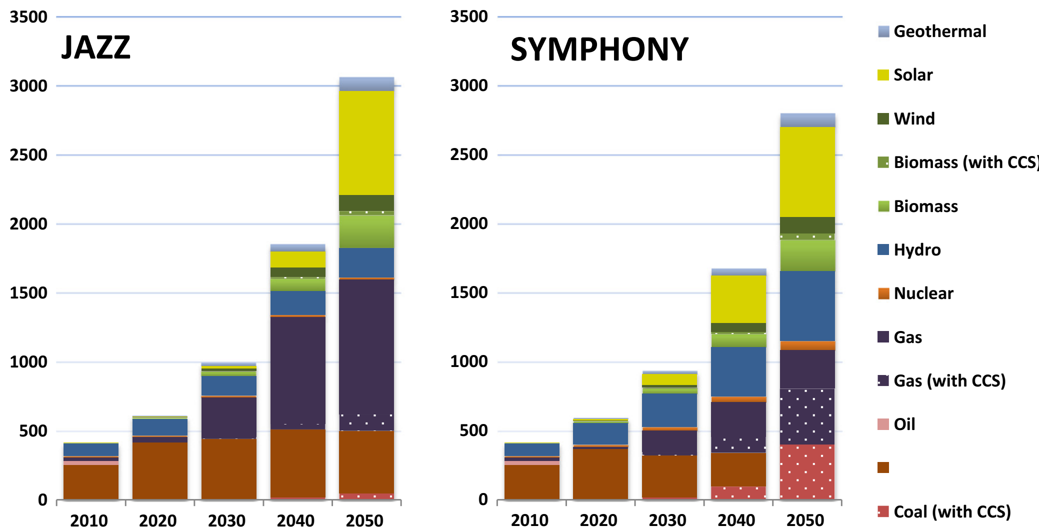

Fig. 8. Electricity generation by fuel type in SSA in both scenarios (in TWh).

Table 9
Key indicators of the power generation in SSA in both scenarios.

Indicators of power generation		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
Efficiency for thermal electricity	34%	35%	38%	42%	45%	35%	36%	37%	41%
Electricity from CCS	0%	0%	2%	4%	6%	0%	5%	13%	30%
Non-fossil fuels in electricity	25%	24%	22%	23%	39%	33%	42%	51%	51%
Nuclear	3%	2%	1%	1%	1%	3%	3%	2%	2%
Renewables	22%	22%	20%	22%	38%	30%	39%	49%	49%

Energy equity: the energy development in SSA

From the analysis with GMM and the reduced-form econometric model described in Section 2.2, indicators can be derived for affordability and access to modern energy carriers. Here we present total energy system cost as % of GDP (as a proxy of the cost of the energy to the economy) and an Energy Development Index[20] using a similar approach to IEA (IEA, 2013b, 2012).[21] The latter can also illustrate the gap to be made up for SSA to reach the levels of energy equity in the rest of the world.

The total energy system cost (net out of taxes and subsidies) increases in both scenarios over the long term, driven by the expansion of the energy supply and demand infrastructure, with “Symphony” being around 20% more expensive than “Jazz” towards the end of the projection period (Fig. 12). The energy system cost, if expressed as percentage of GDP, declines over the projection period from around 20% in 2010 (as calculated by the GMM model) to less than 10% in both scenarios. This reduction is due to the economic growth (as GDP is the denominator of this calculation), the less energy intensive economy because of the energy efficiency developments and the continuation of technology learning in energy supply and demand that reduces the investment and operational costs.

The Energy Development Index is shown in Fig. 13, where Sub-Saharan Africa is compared to the other world regions in the World Energy Council scenarios.[22]

The figure suggests that although the improvement of SSA's score is significant in both scenarios, the gap between SSA and the rest of the world remains quite important. In absolute terms, the performance in “Jazz” is better than in “Symphony”, but both scenarios imply the effort that the SSA has to undertake in order to cover the distance is huge. For instance, the score of SSA's achieved in 2050 has been already achieved by South & Central Asia in 2030.

Sensitivity analyses

In this section we provide some additional insights by examining: a) a normative variant of “Jazz” and “Symphony” scenarios aiming at achieving 100% population electrification rates by 2050 and b) a series of sensitivity analyses on GDP and population assumptions of the two scenarios.

100% population electrification rate in “Jazz” and “Symphony” scenarios in 2050

Both “Jazz” and “Symphony” scenarios fail to attain universal access to electricity in the region by 2050. In this section we assess the additional effort required to achieve this target by examining a normative variant of each scenario aiming at 100% of population with

[20] The energy development deals with the transition to the use of modern fuels, reducing energy poverty and increasing the energy affordability (IEA, 2012).

[21] The index is composed of four indicators: i) per capita energy consumption excluding traditional fuels, as an indicator of overall energy development; ii) per capital electricity consumption in the residential and commercial sector, as an indicator of the reliability and the ability of the consumer to pay for electricity services; iii) the share of modern fuels in total residential and commercial use, as an indicator of the level of access to clean cooking facilities; and iv) the share of the population with access to electricity.

[22] Each one of the four indices was normalised according to the maximum value and then the composite index was calculated by taking the geometric mean (which is preferred to the arithmetic mean since the indices are not independent).

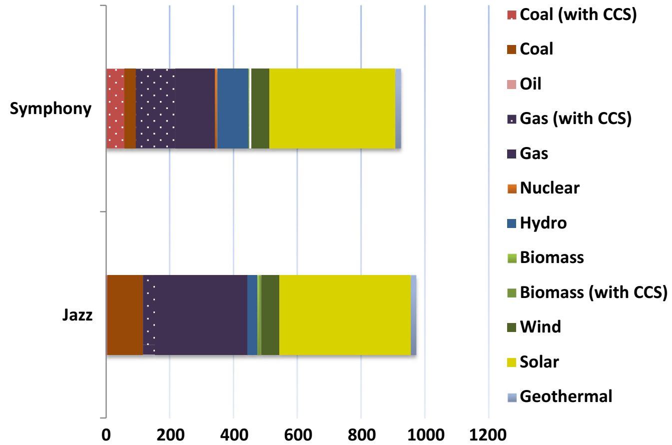

Fig. 9. Cumulative investment in power generation capacity in GW in both scenarios in SSA (2011–2050).

access to electricity by 2050. This target is translated via the econometric model into average electricity consumption per capita in residential/commercial sector of about 945 kWh in "Jazz" and 795 kWh in "Symphony" scenario, which roughly corresponds to an increase of around 250 kWh per capita compared to the base cases in 2050. The new electricity demands are fed into the GMM model to assess the cost-optimal configuration of the energy system of the region in this case.

The additional cumulative investment in power generation capacity in order to attain universal electricity access is around 200 GW in "Jazz" and 253 GW in "Symphony", resulting in a total cumulative investment of around 1175 GW in "Jazz" and 1187 in "Symphony" during the period 2011–2050 (Fig. 14). In "Jazz" gas and solar are the main options to generate the additional electricity required for universal access, while in "Symphony" also hydropower has an important role as well (right hand side of Fig. 14). In both scenarios there are investments in coal-based generation as a mid-term solution, until the completion of large hydropower projects and the expansion of gas infrastructure.

Fig. 15 presents the cumulative undiscounted investment expenditures in billion USD2010 in power generation capacity and grid expansion for the period 2011–2050. To achieve universal access to electricity in the region by 2050, the additional investment expenditure is $634 billion in "Jazz" and $832 billion in "Symphony", resulting in total cumulative undiscounted investment of around $2886 billion in "Jazz" and $3192 billion in "Symphony" both in power generation capacity and T&D grid expansion. This corresponds to an undiscounted annual investment expenditure of slightly above than $72 billion in "Jazz" and $80 billion in "Symphony" during the period 2011–2050.

Thus, the additional effort required to electrify the remaining 16% of the population in "Jazz" scenario requires 21% more capacity and 28% additional investment expenditures during the period 2011–2050. Similarly, in "Symphony" scenario the electrification of the remaining 20% of the population requires 27% more capacity and 35% additional investment expenditures during the same period. This result implies diminishing returns in the electrification of

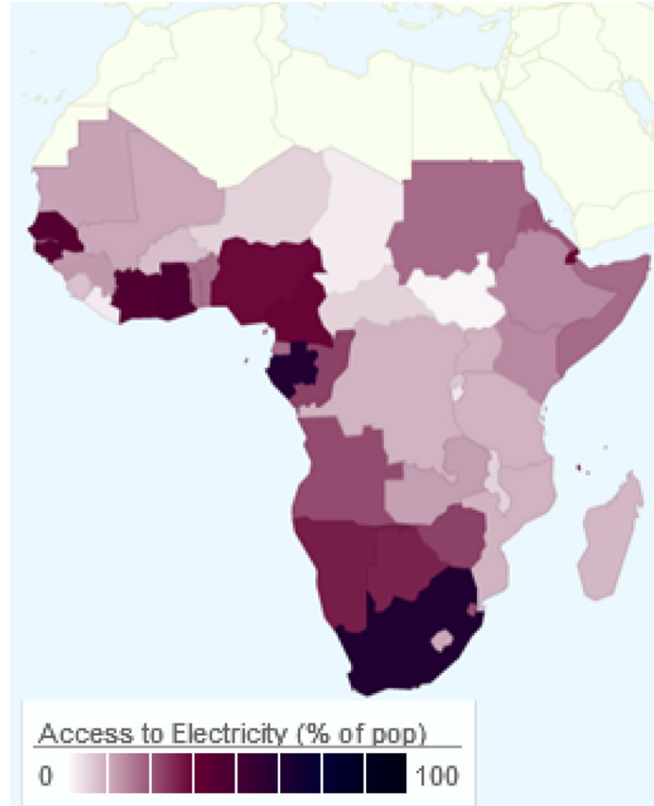

Fig. 10. Percentage of population with access to electricity per country in 2010 (Banerjee et al., 2013).

the population, which is attributed to the fact that the last parts of the population without access to electricity reside in small or dispersed communities or far from national grids.

Sensitivity analyses on GDP and population assumptions

The "Jazz" and "Symphony" scenarios describe two different worlds, with different GDP and population assumptions as well as different energy policies in place and market structures. In order to further enhance the analysis and assess the robustness of the results discussed in the previous sections, we perform a series of sensitivity analyses on GDP and population assumptions of the two scenarios. We examine the following variants (in parenthesis their short names used for reporting the results):

1. The "Jazz" scenario with the GDP growth from "Symphony" ("Jazz_gdp_lo")
2. The "Jazz" scenario with the population growth from "Symphony" ("Jazz_pop_hi")
3. The "Jazz" scenario with both the GDP and population growth from "Symphony" ("Jazz_symp")
4. The "Symphony" scenario with the GDP growth from "Jazz" ("Symp_gdp_hi")

Table 10
Net imports in PJ and billion USD 2010 in the two scenarios.

Net Imports (PJ)		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
Coal	−1969	124	234	465	757	134	351	571	930
Oil	−9231	−12595	−3079	−4726	−6004	−12926	−4193	−7515	−13571
Gas	−1034	−973	−315	586	1290	−923	−292	682	1569
Biofuels	−317	−457	−346	−537	−874	−603	−694	−1070	−1743
Total net imports (PJ)	−12551	−13901	−3507	−4212	−4831	−14318	−4828	−7332	−12816

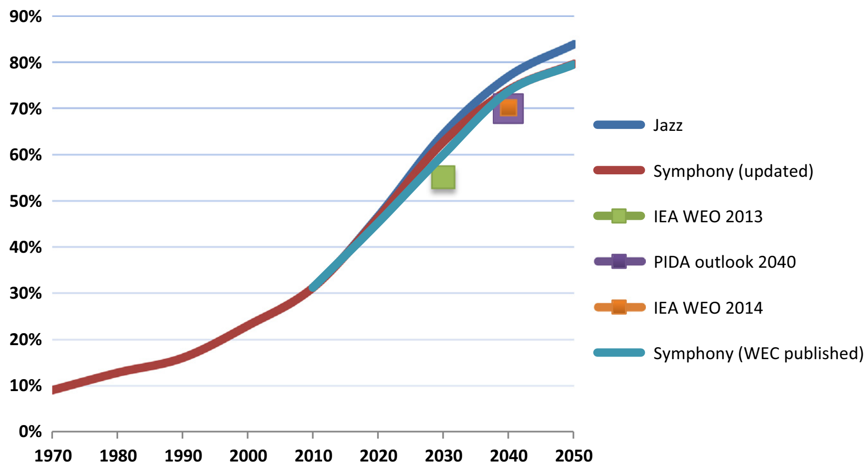

Fig. 11. Historical and projected electrification rate of the population in Sub-Saharan Africa in “Jazz” and “Symphony” and comparison with other studies.

Table 11
Summary of indicators related to sustainability in SSA in both scenarios.

Indicators		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
CO_2 emissions (Mtn CO_2)	661	814	1106	1505	1749	737	834	927	871
CO_2 captured (Mtn of CO_2)	0	0	12	38	107	1	28	122	469
Final consumption per capita (GJ)	20	16	16	18	22	15	15	15	16
CO_2 per capita (kgr of CO_2/year)	771	761	863	1018	1061	677	616	563	444
Primary energy intensity (MJ/$)	19.76	13.18	9.03	5.97	4.16	13.10	8.85	5.87	4.28
Final energy intensity (MJ/$)	14.68	9.40	6.32	4.08	2.97	9.53	6.36	4.15	2.93
CO_2 intensity (kg CO_2/$)	0.57	0.45	0.34	0.23	0.15	0.42	0.27	0.16	0.08

5. The “Symphony” scenario with the population growth from “Jazz” (“Symp_pop_lo”)
6. The “Symphony” scenario with both the GDP and population growth from “Jazz” (“Symp_jazz”).

Fig. 16 presents the final energy consumption by fuel in each variant in 2030 and 2050. The results obtained are quite robust among the different variants and the general conclusions of the previous sections regarding the trends in the final energy consumption are still valid. One additional insight obtained from the analysis of the variants is that for the same level of income the electrification of the demand in a “Jazz”-like world is lesser than in a “Symphony”-like world. This is mainly attributed to the fact that electricity supports efficiency and helps in reducing the emissions in the demand side, both of which are policies implemented in “Symphony” and not in “Jazz”. Thus, the highest electrification rate of the final demand is achieved at the “Symp_jazz” variant, which is the “Symphony” scenario with the highest income per capita (at the levels attained in “Jazz”), while the lowest electrification of the final demand is observed in the “Jazz_symp” variant, which is the “Jazz” scenario with the lowest income per capita (at the levels attained in “Symphony”).

Fig. 17 shows the electricity production mix in each variant in 2030 and 2050. The results suggest that the general conclusions about the role of the individual technologies in supplying electricity to the region, which were drawn from the base “Jazz” and “Symphony” scenarios and presented in the previous sections, are still valid in the variants too.

Fig. 18 presents the electrification rate of population in each variant. The analysis shows that for the same level of income a “Symphony”-like world achieves higher population electrification rates than a “Jazz”-like world. This is attributed to the reluctance of utilities in a highly liberalised electricity market environment assumed in the “Jazz” scenario to serve areas with low population densities, low electricity demand levels with peaky profiles and low income levels (Goldemberg, 2000). This effect is captured by the econometrically estimated equation for electricity access. Thus, the “Symp_jazz” variant shows the highest electrification rates of population with around 236 million people without access to electricity in 2050, while the “Jazz_symp” displays the lowest electrification with 447 million people without access to electricity in 2050. The rest of the variants, including the base cases of “Symphony” and “Jazz” are between these two numbers. These results strengthen the general conclusion drawn from the analysis of the base “Jazz” and “Symphony” scenarios that universal

Table 12
Indicators to quantify energy security in SSA in two scenarios.

		Jazz				Symphony			
	2010	2020	2030	2040	2050	2020	2030	2040	2050
Net import dependency (%)	−55%	−59%	−12%	−11%	−10%	−62%	−18%	−21%	−28%
Shannon–Wiener index	1.07	1.24	1.41	1.52	1.60	1.23	1.42	1.56	1.62
Herfindahl–Hirschmann index	0.45	0.37	0.29	0.25	0.23	0.38	0.31	0.27	0.25

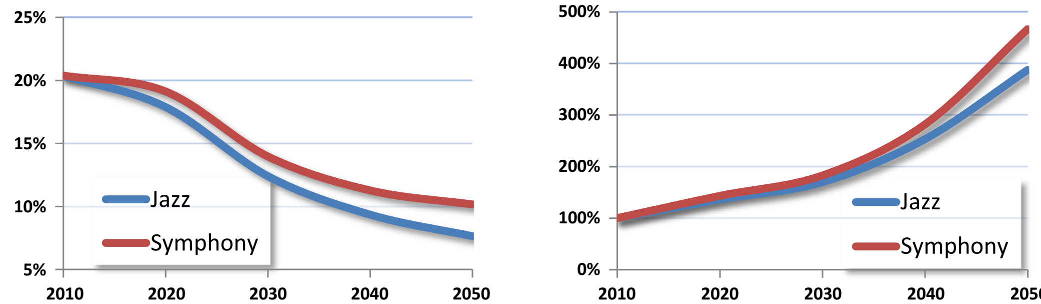

Fig. 12. Undiscounted total energy system cost (net out of CO2 taxes and other subsidies) as percentage of GDP (left) and indexed to 2010 energy system cost (right).

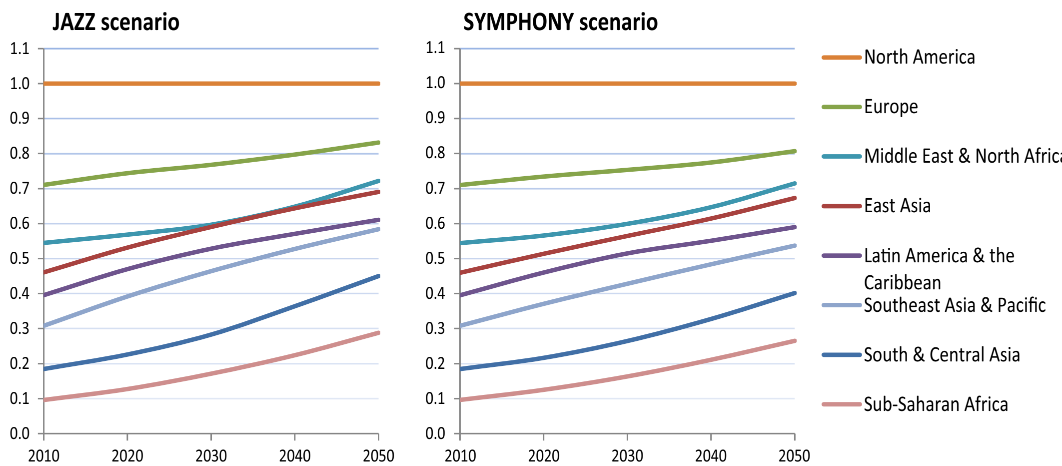

Fig. 13. Measuring the progress towards energy development (the best region has a value of 1).

electricity access cannot be achieved without additional effort in a "Jazz"-like or in a "Symphony"-like world.

Conclusions

Sub-Saharan Africa has enormous development potential over the long term, and a rapid expansion of the energy sector will be critical for increased prosperity and higher living standards. A key challenge for the region will be to shape the policy mix in such a way to ensure access to affordable energy, while improving environmental sustainability and maintaining energy security. For this purpose we analysed two scenarios describing alternative configurations of the economy and the energy system. The scenarios were developed by the Paul Scherrer Institute and the World Energy Council.

The analysis was conducted using the GMM model, which assesses the developments in the energy system, linked with a reduced-form econometric model that projects urbanisation, poverty, institutional development and electricity access. The latter was specifically developed in the context of this study and its methodology is generic enough to be applied also to other developing regions and countries or to be

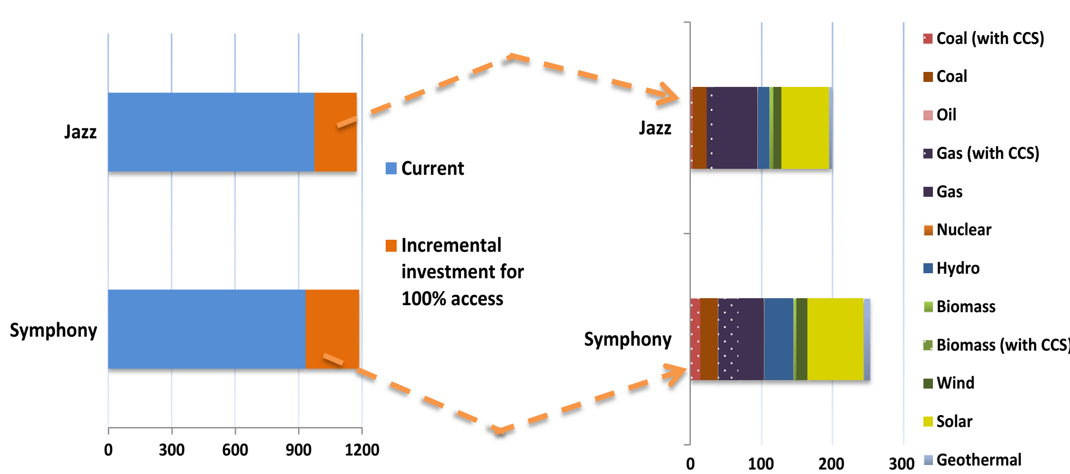

Fig. 14. Incremental investment requirements in power generation capacity to achieve 100% electricity access (in GW).

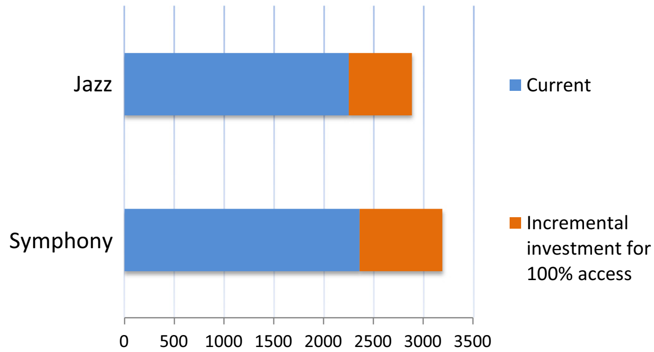

Fig. 15. Cumulative undiscounted investment requirements (2011–2050) both in electricity capacity and grid expansion to achieve 100% electricity access by 2050 (in billion USD2010).

used with other than GMM large scale energy systems models. This contributes to the current literature on operations research tools and methodologies for long-term projections of population with access to electricity. As a partial validation, the results on electricity access were seen to be in line with the results published by IEA and PIDA programme (IEA, 2014; 2013b; PIDA, 2010) for the least common horizon (2035–2040). In terms of the developments in the whole energy system, the results also seem to be in line with the IEA World Energy Outlook 2014 (IEA, 2014), IEA World Energy Outlook 2013 (IEA, 2013b) and the EIA International Energy Outlook (EIA, 2013). The recent World Energy Outlook (WEO) from IEA (IEA, 2014) includes Sub-Saharan Africa as a separate region, which facilitates a direct comparison between our study and WEO 2014. The "Jazz" scenario lies between the IEA "Current Policy" and IEA "New Policy" scenarios, while "Symphony" stands between "New Policy" and "450 Scenario". Differences between the IEA and the present study are attributed to the different economic and demographic assumptions and to the different energy policies in place and market structures. A direct comparison of our analysis with the EIA International Energy Outlook, the IEA WEO 2013 and the PIDA outlook, is not possible as these studies report the whole African region, including both Sub-Saharan Africa and the more developed North Africa. By including North Africa in our analysis, it can be argued that "Jazz" still lies between IEA "Current Policy" and "New Policy" scenarios, while "Symphony" still stands between IEA "New Policy" and "450 Scenario". Similarly it can be argued that "Jazz" is between the "Reference" and "High Macro" scenarios of the EIA international energy outlook, while "Symphony" is between the "Reference" and the "Low Macro" scenarios in terms of final energy consumption, but comparison for "Symphony" is quite difficult since the EIA scenarios do not assume a stringent climate policy in Africa.

The current analysis suggests that enormous investment in power infrastructure is required in the next decades to power the growth of SSA. The annual investment expenditure for the period 2011–2050 exceeds $55 billion ($56 billion in "Jazz" and $59 billion in "Symphony"), of which around $25 billion is for the expansion of the electricity T&D grid and the rest for new electricity generation capacity. Key options to supply energy in SSA are biomass, solar, gas and hydro. Nuclear is unlikely to be a game changer in the region due to the lack of institutional capacity and the high requirements for human and financial capital. The assessment of the scenarios along the axes of the energy trilemma suggests that: a) energy security is similar under the two development pathways, given the region's rich fossil and renewable resources, b) the environmental sustainability is not ensured unless there is a political will in place towards low-carbon economy and c) energy equity is likely to remain a challenge beyond 2050, without additional, effective and sustained efforts to ensure full access to modern energy carriers. Moreover, the region is likely to remain well behind the rest of the world in terms of energy development. We estimate that the incremental investment expenditure in power capacity and grid expansion, which is required to attain universal electricity access in the region by 2050, is between $16 billion (in "Jazz") and $21 billion (in "Symphony"). We have also assessed the robustness of the above conclusions by conduction a series of sensitivity analyses on the GDP and population assumptions of the two scenarios.

The above imply that in order to achieve sustainability through a low-carbon future and at the same time realise energy equity through affordable energy, the governments of SSA need not only to address the design and implementation of suitable energy policies, but also to create an investment climate to mobilise domestic and foreign capital and innovation. The political momentum in SSA is building and the region has the opportunity to push long-term private investment and innovation to a trajectory towards producing and using energy more efficiently. In this context, the two scenarios analysed can facilitate in the exploration of the different development pathways of the energy system in SSA and shed light on the policy mixes to meet the goals of the energy trilemma.

Beyond these broad findings, it is of course critical to emphasize that SSA is a diverse region and different sub-challenges and solutions apply in different countries. For instance in some countries the most effective actions are local and small scale, while in others national or regional initiatives are essential. This heterogeneity is

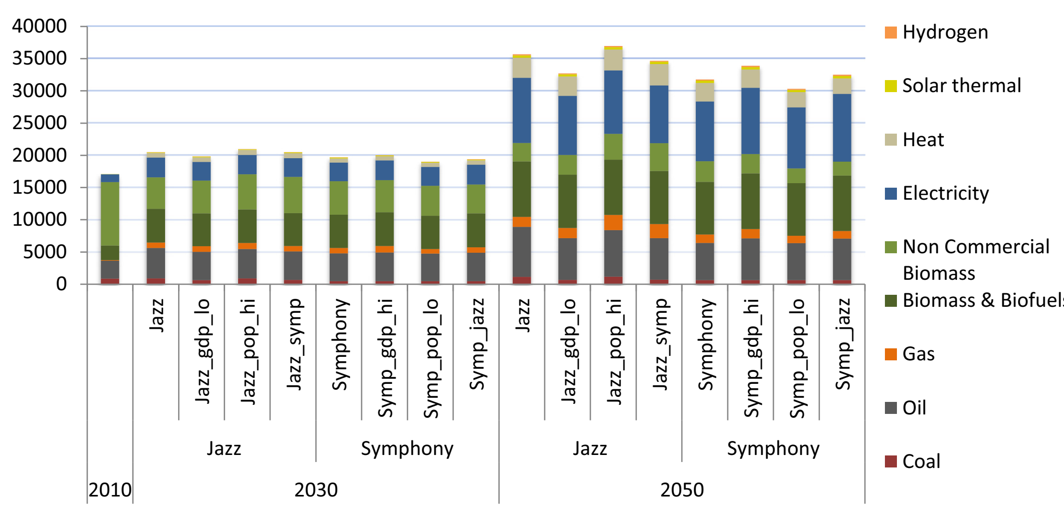

Fig. 16. Final energy consumption by fuel in each variant (in PJ).

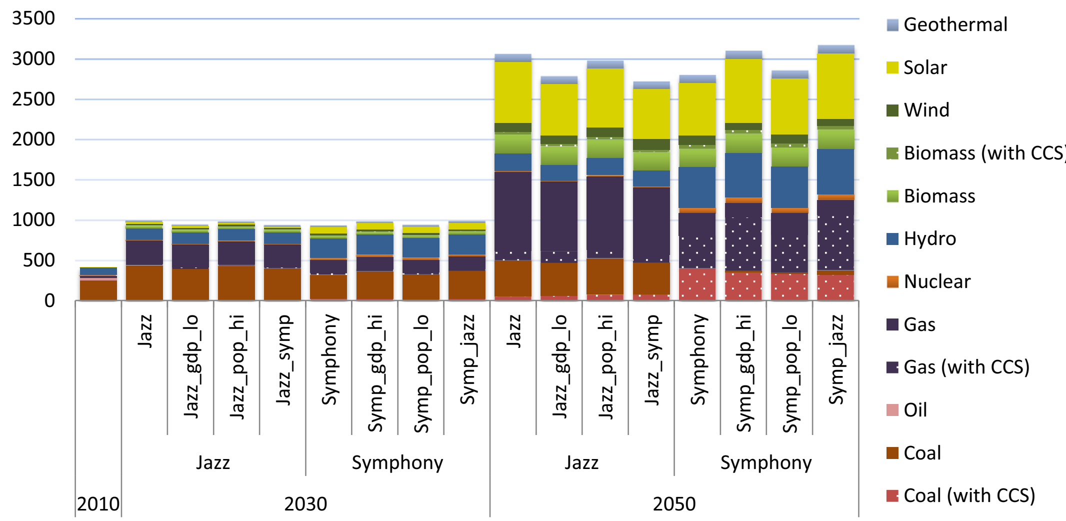

Fig. 17. Electricity production by fuel type in each variant (in TWh).

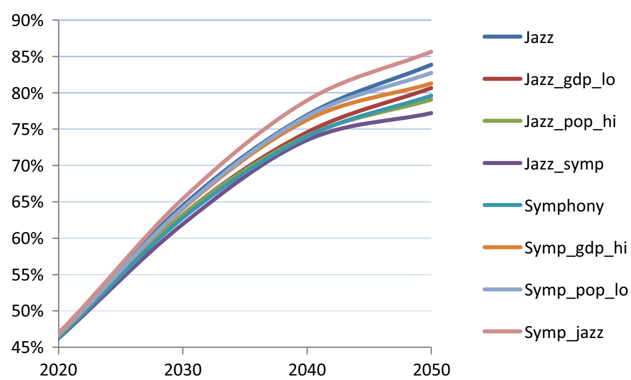

Fig. 18. Percentage of population with access to electricity in each variant.

not directly addressed in our analysis and a future enhancement, in collaboration with WEC's extensive network of stakeholders and partners, is to provide additional insights by dividing the modelling of the region into four or five main energy pools and developing additional scenarios specifically for each pool. In a similar approach, the econometric model can be designed to operate at more detailed levels (regional or country), in order to capture more accurately the impacts of the socioeconomic drivers on electricity access. Yet, the major challenges in the energy systems of the Sub-Saharan African countries are not radically different among them. The results obtained in this work constitute a "what-if" analysis that helps in identifying the major opportunities and challenges for the region (such as investment choices and financial effort required) in a global context of unprecedented uncertainty regarding international prices and patterns of energy trade, global competition for investment capital, technical progress and international interactions in environmental aspects. Sensitivity analyses of key scenario drivers can further enhance the findings of this study and assess the robustness of its main assumptions. Thus, additional variants of the two scenarios can consider constraints on the development of CC(U)S or hydro, CO_2 targets (or other targets along the axes of the Energy Trilemma), etc. These additional sensitivity analyses are being scheduled to be implemented in collaboration with the World Energy Council.

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Appendix A. Description of the reduced-form econometric model for estimating electricity access

The summary statistics of the variables considered in the model are presented in Table A.1. The data were collected for Sub-Saharan Africa as a whole region and the sample is the period 1970 to 2010.

Table A.1
Summary statistics of the historical time series for the dependent and independent variables in the estimation.

	Income per capita (000 USD2005 PPP per capita)	Urbanisation (% of total population)	Poverty (% of total population living with less than \$2 USD2005 PPP per day)	Institutional development (average CPIA for SSA from 1 to 6)	Electricity per capita (kWh per capita in residential/commercial sectors)	Electrification of demand (% of electricity in final consumption of residential/commercial sectors)	Electricity access (% of population with access to electricity — IEA definition)
Mean	1.656	0.297	74.792	3.173	157.857	0.041	0.194
Median	1.612	0.300	74.757	3.175	153.887	0.041	0.186
Maximum	2.013	0.362	78.120	3.205	203.231	0.051	0.312
Minimum	1.466	0.229	70.355	3.154	102.408	0.026	0.118

(continued on next page)

Table A.1 (*continued*)

	Income per capita (000 USD2005 PPP per capita)	Urbanisation (% of total population)	Poverty (% of total population living with less than $2 USD2005 PPP per day)	Institutional development (average CPIA for SSA from 1 to 6)	Electricity per capita (kWh per capita in residential/commercial sectors)	Electrification of demand (% of electricity in final consumption of residential/commercial sectors)	Electricity access (% of population with access to electricity — IEA definition)
Std. Dev.	0.145	0.040	2.353	0.016	26.813	0.007	0.059
Skewness	0.988	−0.079	−0.303	0.626	−0.212	−0.444	0.415
Kurtosis	3.123	1.794	1.959	2.747	2.225	2.318	1.958
Jarque–Bera	5.394	2.034	1.994	0.543	1.074	1.725	2.437
Probability	0.067	0.362	0.369	0.762	0.585	0.422	0.296
Sum	54.641	9.800	2468.128	25.384	5209.281	1.357	6.413
Sum Sq. Dev.	0.670	0.051	177.149	0.002	23005.370	0.001	0.110
Observations	33	33	33	33	33	33	33

The correlations among the variables of the model are presented in Table A.2.

Table A.2
Correlation coefficients between population with electricity access and its drivers considered in the model.

	Income per capita	Urbanisation rate	Poverty rate	Institutional development	Electricity per capita	Electrification of demand
Urbanisation rate	0.85					
Poverty rate	−1.00	−0.85				
Institutional development	0.33	0.32	−0.30			
Electricity per capita	0.76	0.85	−0.73	0.39		
Electrification of demand	0.66	0.79	−0.63	0.37	0.99	
Electricity access	0.88	0.97	−0.87	0.29	0.85	0.79

The estimation method is Ordinary Least Squares (OLS) using time series data for the whole Sub-Saharan Africa region. The short- and long-term effects of the explanatory variables are captured with distributed lag estimation (Box et al., 2008; Pindyck and Rubinfeld, 2000; Romer, 2012). A distributed lag is a relation of the formula:

$$y_t = w_t\delta + \beta_0 x_t + \beta_1 x_{t-1} + \cdots + \beta_k x_{t-k} + \epsilon_t. \tag{A.1}$$

The coefficients β, describing the lag in the effect of x on y, are required to lie on a polynomial of relatively low degree p, reducing both the number of the estimated parameters and the effects of collinearity. A Polynomial Distributed Lag (PDL), or Almon lag, allows the estimation of a model with k lags of x using only p parameters. The coefficients β are of the formula:

$$\beta_j = \gamma_1 + \gamma_2 \cdot j + \gamma_3 \cdot j^2 + \cdots \gamma_{p+1} \cdot j^p \quad \text{for } j = 1, 2, \ldots k. \tag{A.2}$$

Additional constraints may apply to β. A near end constraint restricts the one-period lead effect of x on y to be zero:

$$\beta_{-1} = \gamma_1 + \gamma_2(-1) + \gamma_3(-1)^2 + \cdots \gamma_{p+1}(-1)^p = 0. \tag{A.3}$$

A far end constraint restricts the effect of x on y to die off beyond the number k of specified lags:

$$\beta_{k+1} = \gamma_1 + \gamma_2(k+1) + \gamma_3(k+1)^2 + \cdots \gamma_{p+1}(k+1)^p = 0. \tag{A.4}$$

Both near and the far ends of the lag can be also restricted by introducing both (Eq. (A.3)) and (Eq. (A.4)).
In describing the equations of the econometric model for electricity access, we simplify the representation of a PDL of degree p in variable x using k lags, by writing:

$$y_t = pdl(x_t, p, k, c). \tag{A.5}$$

The parameter c denotes the existence of near-end or far-end constraints: $c = 0$ denotes a PDL without restriction, $c = 1$ implies a near-end restriction, $c = 2$ represents a far-end restriction, and $c = 3$ implies a PDL restricted at both ends.

Poverty was estimated by using the average income per capita as the main explanatory variable, as a modelling framework capturing the various causes of poverty (White and Killick, 2001) is not the main focus of this study:

$$\begin{aligned} &\ln\left(\frac{\text{poverty}_t}{\text{poverty}_{t-1}}\right) = \beta_0 + \beta_1 \cdot pdl\left(\ln\frac{\text{income}_t}{\text{income}_{t-1}}, 10, 1, 2\right) + \\ &\rho\left(\ln\left(\frac{\text{poverty}_{t-1}}{\text{poverty}_{t-2}}\right) - \beta_0 - \beta_1 \cdot pdl\left(\ln\frac{\text{income}_{t-1}}{\text{income}_{t-2}}, 10, 1, 2\right)\right) + \epsilon_t \Rightarrow \\ &\ln\left(\frac{\text{poverty}_t}{\text{poverty}_{t-1}}\right) = \beta_0 + \beta_1 \cdot \textstyle\sum_{k=0}^{10}\gamma_k \cdot \ln\left(\frac{\text{income}_{t-k}}{\text{income}_{t-k-1}}\right) + \rho \cdot \left[\ln\left(\frac{\text{poverty}_{t-1}}{\text{poverty}_{t-2}}\right) - \left(\beta_0 + \beta_1 \cdot \textstyle\sum_{k=0}^{10}\gamma_k \cdot \ln\left(\frac{\text{income}_{t-k-1}}{\text{income}_{t-k-2}}\right)\right)\right] + \epsilon_t \end{aligned} \tag{A.6}$$

where β_i are the estimated coefficients, γ_k are the coefficients of the polynomial distributed lag of degree k, ρ is the auto-correlation correction and ϵ_t is error term of the regression.

The estimation of urbanisation is based on the work presented by Bocquier (2005) and on the theory of mobility transition (Zelinsky, 1983). It is assumed that both rural and urban population can potentially grow according to the natural growth of the total population and the growth is adjusted in order to take into account the income effects that cause the migration from rural to urban areas. The percentage of population migrating from rural to urban settings is turned to be a sigmoid curve reflecting the limited capacity of the rural areas and the historical trend of accelerated migration when the income in rural areas is below a certain threshold. The estimated equation linking the percentage of the rural population rural_migration_t migrating from rural to urban settings with the average per capita income is a sigmoid function transformed to log-linear space. Let R_t, U_t and T_t be the rural, urban and total population in Sub-Saharan Africa in period t, with annual growth rates gU_t, gR_t and gT_t respectively. The urban population increase iU_t due to total population increase and the urban population increase imU_t due to migration from rural areas are then calculated as:

$$iU_t = U_{t-1} \cdot gT_t - U_{t-1} \tag{A.7}$$

$$imU_t = U_t - U_{t-1} - iU_t. \tag{A.8}$$

Similarly the rural population increase iR_t due to natural population increase and the rural population decrease dmR_t due to internal migration are calculated as:

$$iR_t = R_{t-1} \cdot gT_t - R_{t-1} \tag{A.9}$$

$$dmR_t = R_t - R_{t-1} - iR_t = -imU_t. \tag{A.10}$$

The percentage of the rural population rural_migration_t that migrates from the rural area to the urban area is calculated as:

$$m_t = imU_t/(R_{t-1} + iR_t). \tag{A.11}$$

Then the estimated sigmoid function linking the percentage of the rural population rural_migration_t migrating from rural to urban settings with the average per capita income is:

$$\ln\left(\frac{\text{rural}_{\text{migration}_t}}{1-\text{rural}_{\text{migration}_t}}\right) = \beta_0 + \beta_1 \cdot \text{income}_{t-1} + \epsilon_t. \tag{A.12}$$

The World Bank's Country Policy and Institutional Assessment (CPIA) index (WB, 2013) for public sector management and institutions was used as a proxy for the government effectiveness and corruption. The index scale is from 1 = worse to 6 = best. It is estimated as a sigmoid function with a maximum value of 6, using the economic activity as the explanatory variable. The function is log-linear transformed for linear estimation:

$$\ln\left(\frac{\text{CPIA}_t}{6-\text{CPIA}_t}\right) = \beta_0 + \beta_1 \cdot \ln(gdp_{t-1}) + \epsilon_t. \tag{A.13}$$

The equation for the population with access is a sigmoid function transformed into the log-linear space, linking access with the percentage of population living with less than \$2 per day (poverty_t), the electrification rate of residential and commercial demand m_t, the urbanisation rate (urbanisation_t) and the electricity consumption per capita in residential and commercial sectors (ELCCAP_t). The estimated equation is:

$$\begin{aligned}
&\ln\left(\frac{elc_\text{access}_t}{1-elc_\text{access}_t}\right) = \beta_0 + \\
&\beta_1 \cdot pdl(\text{poverty}_{t-1}, 7, 1, 1) + \\
&\beta_2 \cdot pdl(\text{elcdem}_{t-1}, 3, 1, 1) + \\
&\beta_3 \cdot pdl(\text{urbanisation}_{t-2}, 10, 1, 1) + \\
&\beta_4 \cdot pdl(\text{CPIA}_{t-4}, 1, 1, 2) + \\
&\beta_5 \cdot pdl(\text{ELCCAP}_t, 4, 1, 2) + \\
&\rho \cdot \begin{pmatrix} \ln\left(\frac{elc_\text{access}_{t-1}}{1-elc_\text{access}_{t-1}}\right) - \\ \beta_0 - \beta_1 \cdot pdl(\text{poverty}_{t-2}, 7, 1, 1) - \\ \beta_2 \cdot pdl(\text{elcdem}_{t-2}, 3, 1, 1) - \\ \beta_3 \cdot pdl(\text{urbanisation}_{t-3}, 10, 1, 1) - \\ \beta_4 \cdot pdl(\text{CPIA}_{t-5}, 1, 1, 2) - \\ \beta_5 \cdot pdl(\text{ELCCAP}_{t-1}, 4, 1, 2) \end{pmatrix} + \epsilon_t \Rightarrow
\end{aligned} \tag{A.14}$$

$$\begin{aligned}
\ln\left(\frac{elc_\text{access}_t}{1-elc_\text{access}_t}\right) &= \beta_0 + \beta_1 \cdot \sum\nolimits_{k=0}^{7}\gamma_{1k} \cdot \text{poverty}_{t-k-1} + \beta_2 \cdot \sum\nolimits_{k=0}^{3}\gamma_{2k} \cdot \text{elcdem}_{t-k-1} + \beta_3 \cdot \sum\nolimits_{k=0}^{10}\gamma_{3k} \cdot \text{urbanisation}_{t-k-2} + \beta_4 \cdot \sum\nolimits_{k=0}^{1}\gamma_{4k} \\
&\cdot \text{CPIA}_{t-k-2} + \beta_5 \cdot \sum\nolimits_{k=0}^{4}\gamma_{5k} \cdot \text{ELCCAP}_{t-k} + \rho \cdot \left[\ln\left(\frac{elc_\text{access}_{t-1}}{1-elc_\text{access}_{t-1}}\right) - \left(\beta_0 + \beta_1 \cdot \sum\nolimits_{k=0}^{7}\gamma_{1k} \cdot \text{poverty}_{t-k-2} + \beta_2 \cdot \sum\nolimits_{k=0}^{3}\gamma_{2k} \cdot \text{elcdem}_{t-k-2} + \beta_3\right.\right. \\
&\left.\left.\cdot \sum\nolimits_{k=0}^{10}\gamma_{3k} \cdot \text{urbanisation}_{t-k-3} + \beta_4 \cdot \sum\nolimits_{k=0}^{1}\gamma_{4k} \cdot \text{CPIA}_{t-k-3} + \beta_5 \cdot \sum\nolimits_{k=0}^{4}\gamma_{5k} \cdot \text{ELCCAP}_{t-k-1} + \beta_5 \cdot \sum\nolimits_{k=0}^{4}\gamma_{5k} \cdot\right)\right] + \epsilon_t
\end{aligned}$$

Table A.3 presents the output and the statistical significant of the regression and the OLS estimators.

Table A.3
Output of the regressions: estimates with p-values, standard error and quality criteria of the regression.

	β_0	β_1	β_2	β_3	β_4	β_5	ρ	S.E	Adj R^2	Akaike	Schwarz
Poverty								0.004	0.743	−8.072	−7.930
Estimates		−0.038					0.522				
p-Values		0.001					0.008				
Urbanisation								0.008	0.944	−6.620	−6.576
Estimates	−5.493	0.216									
p-Values	0.000	0.000									
Institutional development								0.004	0.718	−7.763	−7.867
Estimates	−0.352	0.063									
p-Values	0.078	0.040									
Electricity access								0.005	0.999	−7.461	−7.118
Estimates	−9.322	−0.001	0.361	0.119	1.277	0.045	0.464				
p-Values	0.001	0.001	0.013	0.000	0.003	0.006	0.044				

The reduced form econometric model described above constitutes an empirical approach to estimate the population with electricity access in Sub-Saharan Africa. Although the model is rather simple compared to other perhaps more sophisticated approaches used by IEA or PIDA, the results obtained are in line with the results obtained in the IEA and PIDA studies. This suggests that the proposed methodology is quite robust. The main advantages of the proposed model are:

- Transparency, since the data used are publicly available and the equations well documented by the literature and the empirical findings
- Applicability to other developing regions and countries, since the structure of the model allows its downscaling to sub-regional or country levels. The major requirement is to substitute the dataset used in this study with the dataset of the region or country at question, which can be obtained from the data sources used also in this work. Then, the next step is to re-estimate the parameters of the econometric Eqs. A.6, A.12, A.13 and A.14, by starting from the formulation presented here and adjust if necessary
- Generic interfaces with large scale energy system models, since the interface is established on GDP, population, electricity consumption per capita and electrification rate of residential demand variables.

In this context, the current work contributes to the literature about tools and methodologies in estimating population with access to electricity in developing regions.

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