Challenges and gaps for energy planning models in the developing-world context

Abstract

Energy planning models (EPMs) support multi-criteria assessments of the impact of energy policies on the economy and environment. Most EPMs have originated in developed countries and are primarily aimed at reducing greenhouse gas emissions while enhancing energy security. In contrast, most, if not all, developing countries are predominantly concerned with increasing energy access. Here, we review thirty-four widely used EPMs to investigate their applicability to developing countries and find an absence of consideration of the objectives, challenges, and nuances of the developing context. Key deficiencies arise from the lack of deliberation of the low energy demand resulting from lack of access and availability of supply. Other inadequacies include the lack of consideration of socio-economic nuances such as the prevalence of corruption and resulting cost inflation, the methods for adequately addressing the shortcomings in data quality, availability and adequacy, and the effects of climate change. We argue for further research on characterisation and modelling of suppressed demand, climate change impacts, and socio-political feedback in developing countries, and the development of contextual EPMs.

1 Introduction

Continued anthropogenic greenhouse gas (GHG) emissions have led to their unprecedented atmospheric concentrations[1], contributing to and amplifying global climate change[2]. Fossil fuels and land use change (for example, through deforestation and farming) are two primary sources of GHG emissions, of which the emissions from land-use has been nearly constant[3], while the emissions from fossil fuel based energy systems increased by 50% between 2000 and 2013[4]. Current energy and transportation systems can result in substantial GHG discharges[5], with a likely global mean temperature increase between 2.0–4.9 °C, with a median of 3.2 °C by 2100[6]. Even if current GHG concentrations remain constant, the world will experience a few centuries of rising temperature and ocean level[7,8]. Therefore, substantial reductions in global GHG emissions are essential for mitigating climate change.

In addition to the infrastructural elements of national energy systems (i.e. generation, distribution, and transmission), access to grid electricity and purchasing power of the population influence energy end-use and GHG emissions. Figure 1a illustrates that both access to electricity and per capita CO_2 emissions are more significant in high-income countries, compared to low- and middle-income developing countries. Most developed countries can ensure 100% access to electricity, which only a few developing countries can match. In 2010, annual per capita CO_2 emissions ranged from 0.02–15.14 tCO_2 in low and middle-income countries, compared to 1.6–42.63 tCO_2 in high-income ones. In general, there is a positive association between electricity access and GHG emissions. One notable exception is Costa Rica, an upper middle-income country, which had 98% access to electricity but per capita CO_2 emissions of 1.7 tCO_2, well below the average of 2.09 tCO_2 for all low and middle-income countries in 2010. This is because 93.3% of Costa Rica's energy was from renewable resources, of which hydroelectric sources accounted for 75.8% (ref.:[9]).

<Insert Figure 1 about here>

As a result, future energy planning objectives of developed and developing countries are distinctly different. In developed countries, the focus today is on reducing emissions while enhancing energy security, primarily characterised by a shift from fossil fuels towards more renewable resources. However, developing countries are concerned with increasing access to electricity, which is considered a prerequisite for development and economic empowerment, as reflected by the inclusion of energy as a goal in the Sustainable Development Goals[10]. The current CO_2 emissions per capita of developing countries are low, often much below the global average (Figure 1c). Hence, emission reduction is not always on the agenda for developing countries, even at a cursory level, except for a few large countries such as China and India[11].

Energy planning models (EPMs) play an essential role in the development of the energy sector at global, national and regional levels by enabling informed decision-making. EPMs are especially crucial as significant investments in innovative energy research and planning are required for decarbonisation[12]. The development of EPMs started in the late 1950's and early 1960s[13] but intensified after the oil crisis of the 1970s in light of the realization of the effects of exogenous political events on global and national energy supply[14]. It was necessary, then, to critically assess the interrelationships between the sources of energy supply and demand, as well as to identify pathways for long-term development of the energy sector[15]. The drive for global sustainability in the 1990s -- spurred in particular by the Rio Earth Summit in 1992 and the 1995 report of the Intergovernmental Panel on Climate Change (IPCC)[16]--brought forward the issue of GHG emissions and their impact on the environment. As a result, further models were developed for projecting climate change and investigating the environmental impact and its mitigation. However, given that some two-thirds of global GHG emissions come from the electricity, heat, and transportation sectors[4], the integration of the environmental aspects of energy demand and supply within EPMs became necessary, providing a comprehensive picture of the interrelationships between energy, environment, and climate change.

Over the past four decades, a substantial number of EPMs have been developed by researchers and organizations in different countries, with various objectives and scopes. EPMs range from the holistic

– modelling the partial or whole energy system of a country, region or the world – to the more sectoral – providing projections of the energy needs of, for example, transportation or industry. Given that the IEA estimates the growth in energy demand over the next 23 years will be higher in developing Asian countries than the rest of the world[17] and future emissions from growth regions will be critical in the current 1.5°C temperature discourse[1], it is essential to understand how EPMs reflect the challenges being faced by decision-makers in different parts of the world.

Previous work has reviewed EPMs of different types. Suganthi et al.[18] categorised energy demand projection models based on their methods but misclassified bottom-up and top-down approaches. Bhattacharyya et al.[19] analysed available EPMs for application in developing countries but did not present details on relevant socio-economic parameters and their effect on policies. Pfenninger et al.[20] categorised EPMs into four types: energy system optimization; energy system simulation; power system and electricity market and qualitative and mixed methods. They recommended further development and integration of innovative approaches into EPMs to address the complex interactions among disciplines such as social science, ecology, finance, and behavioural psychology. Urban et al.[21] analysed twelve EPMs to investigate their suitability for developing contexts and suggested that critical characteristics of developing countries such as the informal economy and supply shortages were overlooked. The study identified a bias towards industrialised countries in the EPMs, yet specifics were not offered on socio-economic drivers such as political stability (or lack thereof) and corruption in energy markets in developing contexts.

In light of this, there is a lack of evidence-based analysis of contextual variations, model structures, and relevant emerging socio-economic variables for EPMs in the developing world context. To that end, we reviewed thirty-four current, highly used, macro-level EPMs to investigate their applicability and deficiency for energy systems in developing countries. Our focus is on the factors that affect the demand and supply of energy, as well as the rational development of the energy sector in a developing country.

2 Typology and structure of energy planning models

We conducted a systematic survey of published literature on EPMs. Our study focuses on models predominantly used for the planning of energy systems and infrastructures and that are more strategic, as opposed to operational. First, a preliminary study was conducted to gather an overview of the topics related to EPMs that resulted in the identification of two main themes: energy demand and supply; and energy information and emission models. Electronic databases – namely Google Scholar, ScienceDirect, JSTOR, IEEE Xplore, Scopus, Web of Science, and other official websites with energy databanks, specifically United Nations (UN), World Bank, International Monetary Fund (IMF), International Energy Agency (IEA), Energy Information Administration (EIA) –were searched for relevant publications using the keywords listed in Table 1. The keywords were categorised into five-word groups, which were combined using the Boolean operator ‘AND’, e.g. ‘Energy planning model’ AND ‘Forecasting’ AND ‘Input variables’ AND ‘Organization’ AND ‘Global’. Based on the search and the available literature, thirty-four models developed by international organizations or institutions were selected for analysis (Table 2). In addition to the published journal articles and books, manuals of different models were investigated to explore their structure and key components. The reviewed models were categorized based on model objectives to contextualise the subsequent analysis and discussion. Model structures were then analysed to investigate their relevance and deficits in developing contexts. For the categorization by model objective, four categories were used: energy information systems, energy demand-supply, energy-economic and energy emissions models. Table 2 illustrates EPM types, and their inputs, outputs, and underlying methods. Five characteristics of input variables were analysed: qualitative, quantitative, financial, aggregated and disaggregated. Although financial data are typically classed as ‘quantitative’, based on the extensive use of these variables in different models it was deemed worthwhile to include them as a separate characteristic. The underlying methods were categorised into accounting framework, regression, optimization, econiomic, simulation, and equilibrium methods. Output variables were classified into energy, emissions, and cost measures.

<Insert Table 1 about here>

Among the analysed 34 models, quantitative and financial data are utilised in 34 and 32 models respectively. 27 models used disaggregated data as input variables. In the case of the output variables, most of the model’s outputs are energy (30 models), emission (29 models), and cost (28 models). Model outputs are often normalised; e.g. cost/GDP, cost/capita, cost/generation, and emissions/GDP. Reviewed models adopted different underlying methods for estimation and projection. Optimization methods are widely utilised (13 models), followed by simulation (11 models) and economic (10 models) methods. Optimization methods are mostly applied to energy demand and supply, and economic models.

<Insert Table 2 about here>

EPMs have three common components and a basic workflow: input variables underlying estimation/projection methods output variables. Key variations, however, lie in the type, resolution (temporal and spatial), scope and timeframe of the input and output variables. Model objectives and the nature of the data most often determine the choice of estimation/projection methods.

Primary input variables in the studied EPMs are quantitative, financial and disaggregated. EPMs are numerical models and utilise quantitative data for calculation. Qualitative parameters are typically interpreted as ordinal data for modelling purposes. While modelling energy infrastructure in a holistic approach to cover a broader context, the supply, demand and socio-economic sectors require disaggregated data for a better interpretation of the existing systems.

In the case of underlying methods, optimization was utilised in fourteen models because they would create an optimization loop as a way of testing whether the selected output satisfies the defined constraints. In some models, especially energy demand and supply models, the primary objective is to find the least cost solution for the energy market. Optimization methods in such models would render the opportunity to test different policies against the least cost option. However, simulation methods were also utilised in a significant number of models.

3 Developing country characteristics not addressed in EPMs

Almost all EPMs were constructed in developed countries (Table 3) and considered their energy systems, economic assumptions, and the extent to which GHG emissions need to be reduced. While CO_2 emissions per capita in high-income countries are decreasing (Figure 1b), they are increasing in the developing upper-middle and middle-income countries, whose primary objective often is to improve access to convenient forms of energy. Despite the fact that some EPMs have been widely adopted for energy system planning in developing countries, they lack consideration of a substantial number of issues affecting developing contexts; e.g. the effects of a lack of innovation, and the varying nature of privatisation, decentralisation and competition in the energy industry[22]. Policy priorities in EPMs need to be more country-specific or regional, because of the differences in objectives due to the common socio-economic vulnerability or conditions, and geographical and climatic characteristics. Indicators relevant to most developing economies include[22]: issues regarding resource management; assessment of energy alternatives; the economic and technical challenges associated with the transformation of the energy infrastructure from a centralised one to an intelligent and decentralised one; and financial vulnerabilities in households. Addressing these in EPMs is necessary to provide higher reliability of estimates.

<Insert Table 3 about here>

In the following sections, the issue of suppressed demand in developing countries is analysed, followed by a discussion of the difference in socio-economic characteristics such as corruption and political stability, as well as their effect on the economy. Subsequent sections explore the impact of data inadequacy on the development of EPMs and the impact of climate change, focusing on the effect of energy planning on land development and food production, as well as the role of extreme weather events. Finally, the impact of poor characterisation of variables on EPMs is discussed.

3.1 Suppressed demand in developing countries

Suppressed demand refers to the incapability of the people or community or nation to meet minimum services levels (MSL) necessary for human development[23], such as clean and safe drinking water and adequate energy for cooking and lighting because of some host barriers[24]. Barriers can be a lack of infrastructure, low technology penetration, and poverty, particularly the high costs of energy services compared to household incomes[25]. Energy infrastructure barriers such as the lack of access to grid electricity can lead to minimal or no use of electrical appliances. The barriers can also interact to produce a situation where the population cannot afford energy for basic needs because of low income and high unit cost. On the other hand, studies show that the reduced unit cost often results in higher demand for energy. For example, the transition from kerosene to electric lighting in developing countries reduced the unit cost of light by more than 90% but augmented the consumption of lighting services (lumens) by a factor of 40[25-27]. In the case of the technology barrier, the penetration of specific technology among the population can be hindered by the higher initial cost. This cost can be compensated by high income and policy incentives (such as tax reduction on the technology or subsidies) by governments.

Emissions from developing countries are much lower than the global average because of suppressed energy demand. Energy consumption of many household needs, such as heating and cooking, and lighting, may not reflect the real demand. The lack of consideration of suppressed demand can result in an inaccurate estimation of baselines for Clean Development Mechanism (CDM) projects[28]. More specifically, CDM rules state that 'the baseline may include a scenario where future anthropogenic emissions by sources are projected to rise above current levels, due to the specific circumstances of the host Party'[29]. However, a UNFCCC report (paragraph 35 of Decision 2/CMP.5[30]) encouraged the CDM Executive Board 'to further explore the possibility of including in baseline and monitoring methodologies, as appropriate, a scenario where future anthropogenic emissions by sources are projected to rise above current levels due to specific circumstances of the host Party'. These guidelines explicitly differentiate energy contexts between developed and developing countries. None of the reviewed EPMs considered the CDM guidelines, which may increase error in future energy planning strategies for developing contexts.

3.2 Difference in socio-economic characteristics

Developed countries have different socioeconomic attributes than those of developing countries. The literature suggests that political instability affects the economic growth of a country[31], especially GDP growth[32]. The rate of change of stability is lower in developed countries that are often characterised by steady GDP growth (Figure 2a-e). However, all developing countries do not necessarily demonstrate a similar association between GDP growth and political stability, which varies substantially (Figure 2f-j). There are also exceptions. Despite the negative progression of political stability, some countries have positive GDP growth (e.g. Japan, Germany, Philippines, and Bangladesh). Developed economies mostly maintain steady progress on the positive side of the political stability scale (that is, they have a political stability score of 0 to 2.5), while the same parameter is on the negative side of the scale in most of the developing countries (that is, the score ranges from 0 to -2.5). In most developed country EPMs, GDP is the only socio-economic parameter for demand projection. Considering GDP growth or GDP volume alone is thus unlikely to represent the nuances of the economic structure of a developing country. More integrative modelling is, therefore, required for predicting future energy demand while accounting for the structural changes in the economy. The increasing share of industry and services in the economic output with a corresponding rise in energy use and emissions in developing countries has the potential to further augment world GHG emissions, despite the decreasing trend for emissions in high-income countries.

<Insert Figure 2 about here>

Along with the stage of economic development, the intensity and distribution of economic activities influence a country's energy consumption. The analysis of GDP per capita against electricity consumption in Figure 3 shows a positive relationship; i.e. electricity consumption increases with the growth in GDP. The coefficients of determination (R^2) in the plots are very high for low and lower-middle-income countries as compared to the upper-middle and high-income countries. In high-income countries, the change in GDP per capita has little influence on electricity consumption. In contrast, an increase in GDP per capita significantly amplifies electricity consumption in low and lower-middle-income countries, as previously reported[33]. This amplification in energy consumption may have resulted from the presence of suppressed demand.

<Insert Figure 3 about here>

The trends in per capita gross national income (GNI) and energy consumption for the period 1960-2013 of eighteen randomly selected countries from four World Bank economic classifications are illustrated in Figure 4. The high and upper-middle-income countries, the relation between GNI per capita and electricity consumption per capita has a logarithmic progression, which denotes that when a country reaches a stable income level, the energy consumption becomes linear in characteristic (Figure 4). In the case of developing contexts with lower middle and low income, the increase in GNI boosts up the electricity consumption exponentially (Figure 4), because GNI/capita augmentation influences the 'suppressed' demand by allowing more people to access electricity. Moreover, improved buying capacity enables consumers to buy and utilise more electronic products, resulting in exponential electricity consumption growth. After reaching a stable economic stage, the energy consumption growth slows steadily[34], despite the fact that the GDP can keep rising.

<Insert Figure 4 about here>

In developing economies, corruption influences policy decisions, including the procurement of mega projects—often resulting in the selection of higher cost options[35,36], that may benefit the decision maker(s) to the detriment of the environment and economy. For example, post-2009, Bangladesh's increased dependence on volatile international energy markets for oil imports was due to the growth in for-profit, private sector oil-based generation plants operating during off-peak hours that resulted in greater macroeconomic risks[37]. The sub-optimal decision to increase oil-based electricity generation beyond peak generation capacity requirements has been reported as ad-hoc and short-sighted[37].

<Insert Figure 5 about here>

Evidence suggests that reduced corruption can result in a significant increase in GDP; e.g. if Bangladesh can enhance its bureaucratic integrity and efficiency to the level of Uruguay its annual GDP growth would elevate by over half a percentage[35]. Figure 5 compares inflation with the Corruption Perceptions Index (CPI) of different nations. Countries with higher CPI scores are less corrupt and more developed and in most cases, have less inflation. In contrast, countries with higher levels of corruption tend to have higher inflation. The economic inflation rate is associated with the size of the national debt of a country. Energy projects are typically big and require significant investments. Loans from international financial organizations such as the World Bank, Asian Development Bank (ADB) and International Monetary Fund (IMF), and local and international banks, constitute a large proportion of energy investments in developing countries. Corruption has been reported in all life cycle stages of energy projects, but most evidence on its existence and extent are reported for the tendering process,[38] which directly increases the project cost and corresponding loan amount. The terms of these loans are typically longer (e.g. decades) and interest rates are higher, due to the perceived risks of political instability and inflation—resulting in higher repayment cost and increased national debt. The consequences of increased pressures on public finance are the inevitable rise in personal and sometimes business tax rates, further increasing inflation. Another impact of a corruption-related increase in macroeconomic stress is the detrimental effect on social and economic development, as money intended for these sectors is often reallocated for debt repayment[37].

Comparatively low levels of corruption in developed countries have limited effects on energy projects and the economy, the modelling of which is, therefore, low in priority. In contrast, energy project procurement, management and operation in developing countries are evidently corrupted with severe impacts on the economy[39]. Corruption and its effects on micro- and macroeconomic performance in all life cycle stages of energy planning should, therefore, be an integral part of any modelling effort in developing countries.

Among the 34 reviewed EPMs, none of them addressed the implications of corruption on the energy economy. In addition to corruption, none of the reviewed models considered the effect of political instability on the economy, which was found to be prominent in developing contexts. Also, the influence of per capita income change drives energy consumption differently in developing economies than that of developed ones; this aspect was also found to be less elaborately modelled in the reviewed EPMs.

3.3 Data inadequacy

Estimation/projection quality in EPMs depend on data adequacy and accuracy, as historical trends determine the future projection. EPMs are mostly mathematical models in which data inadequacy can result in inaccurate estimation or at least increase the uncertainty of prediction. Also, incomplete data records hinder the assessment of potential interrelations among the variables, rendering the EPM development process difficult. Data inadequacy is reported to be more pronounced in developing contexts than that of developed ones[40-42], in particular regarding the required level of disaggregation and resolution, as well as the provenance of data. Careful considerations should be given, especially in developing contexts, to the collection of quality-assured data. On the other hand, modelling approaches should be flexible enough to accommodate incomplete historical data up to an acceptable limit while compensating for the possible variations in temporal and spatial resolutions.

3.4 Climate change impact

Climate change is projected to disproportionately impact some developing countries (e.g. Bangladesh, Philippines, Malawi and India) not only because of their development status and perceived shortcomings in adaptation capacity but also because of their inherent geographical and social vulnerabilities. Moreover, the global energy system is transitioning away from centralised generation and management to a more distributed, intermittent renewable energy and land-based system, where land and infrastructure resilience to natural hazards is becoming increasingly important, even for energy planning[43]. The impacts of climate change on the broader economy and environment require the consideration of region- and country-specific parameters for resilience, adaptation, mitigation, and development in EPMs. None of the EPMs reviewed considers the impacts of climate change. Even energy emissions models consider only energy related emissions and may also consider their future evolution from decarbonisation perspectives.

3.4.1 Energy vs land vs food

Land-based economic sectors are particularly vulnerable to sea level rise, as well as natural disasters such as floods, tsunamis, and landslides due to increased precipitation, all of whose occurrence is projected to increase. Developing countries are particularly vulnerable to these impacts because of their tropical and sub-tropical locations and geomorphology[44]. For projected sea level rises of 45 and 100 cm, up to 15,600 and 30,000 km^2 of land area respectively will be permanently flooded in Bangladesh[45], corresponding to up to about one-fifth of the country's total land area. The production of rice, the staple food, will decrease from 236 to 96 kg/capita-year if the sea level rises by 32 cm by 2050 and 30 kg/capita-year if the rise is 88 cm by 2100[46]. In the case of Maldives, the entire island country would drown if the sea level rises, as the highest point is only 2.4m higher than the sea level. Moreover, energy infrastructure in several countries is vulnerable to sea level rise[47,48], as they are situated near the water resource such as river and sea for cooling purpose[49]. Direct impacts of climate change on energy systems are thus related to energy infrastructure resilience and energy production when vulnerable lands are used for energy crops.

As a matter of course, and in line with the theoretical discourse on stages of economic growth, the least developed and developing countries aim to become developing and developed respectively—representing a gradual shift in focus from agricultural towards more industrialised societies[50].

Industrial development is often manifested in the transformation of agrarian lands into industries and energy infrastructures in the populated countries with severe shortages of buildable land—which affect food production. The situation is exacerbated when a significant share of arable land is allocated to energy crop production, leading to a conflict between the goals of energy and food securities—both of which are critical issues for developing countries with relatively large population and modest land mass, such as Bangladesh. Of the 34 studied models, only BD2050 considered the effects of energy sector development (e.g. land-based bioenergy) on food production[51]. Before BD2050's launch in 2015, the International Atomic Energy Agency's (IAEA) Wien Automatic System Planning package (WASP) was predominantly used for energy planning. WASP is essentially an optimum solution finder for the supply-side expansion and is mostly unsuitable for modelling land-based interactions. The increasing interactions between food, land and energy, therefore, need to be modelled and assessed holistically for informed decision-making.

3.4.2 Effects of extreme weather events

Extreme weather events are typically rare, yet climate change will make some of these events more likely to occur and more likely to be severe[52]. Slow-onset events such as heatwaves and unexpected low temperatures have a direct effect on comfort related energy demand[53], in addition to the resulting increased mortality, especially among the elderly, children and the infirm. While effects such as these are common to both the developing and developed countries, the amplitude and duration of extreme events, as well as the inability to cope with their sudden onset are often more pronounced in tropical and sub-tropical developing countries; e.g. heatwaves in India and Pakistan in 2015[54]. Air conditioning accounts for 28% of electricity consumption in the hottest months in Delhi, India[55]. Although India started its first energy efficiency rating for air conditioning and labelling programme in 2006[56], aimed at reducing annual electricity demand by 27 TWh by 2020[57], a heatwave can escalate that demand[58]. Climate change impacts are seldom considered in EPMs likely because they originate in developed countries that have been shown to be less vulnerable than developing countries where climate change can cause immense damages[59]. None of the reviewed EPMs considered the climate change impact. BD2050 only explored the implication of energy policies on food security. That does not necessarily explore the impact of climate change in Bangladesh. Energy demand projection and infrastructure resilience should, therefore, consider the probability of extreme weather events, especially in EPMs for developing countries.

3.5 Effects of poor characterisation

Poor characterisation of the energy system and its underlying socio-economic parameters can lead to inappropriate modelling of future energy and emissions scenarios in both developed and developing countries (Table 4). Inaccurate projections affect energy system planning and infrastructure development, especially in the long term. Furthermore, energy dynamics in developing countries are complicated because of the prevalence and different distribution of the following socio-economic and political parameters: political stability, energy use characteristics of the extremely poor, the pervasiveness of small unregistered businesses, the presence of large informal sectors, corruption, and subsidies. Moreover, most of these aspects have seldom been addressed in a reasonable level of detail in the literature. The gap in knowledge is exacerbated by the limited availability of modelling expertise in developing countries. Complexities such as these make the energy models in developing countries more vulnerable to poor characterization than that of the developed ones.

<Insert Table 4 about here>

4 Implications and considerations for EPMs

Although developing countries have lower per-capita GHG emissions than those of developed countries, there is a marked increasing trend in emissions since 1990 1990. The rate of change is often higher than previously projected. For example, despite the energy system being mostly based on renewable energy (93.3% of the total in 2010), per capita, CO_2 emissions in Costa Rica increased by 78.6% between 1990 and 2011 (ref.:[9]). Similarly, higher emissions growth rates can be found for United Nations Framework Convention on Climate Change (UNFCCC) non-Annex countries that did not have an emissions reduction target[9]. In contrast, most developed countries demonstrate a decreasing trend. CO_2 emissions from the middle-income nations already surpassed that of the high-income countries as illustrated in Figure 1d. Upper-middle-income nations are also about to exceed the emissions from high-income countries. Although India and China dominate in emissions growth at present, Brazil, India, Indonesia, China and South Africa are projected to eclipse global GHG emissions in 2050[60]. According to the 2017 IEA World Energy Outlook[17], China will start to decrease CO_2 emissions from 2030 but will still emit 2.8 times more in 2040 than in 2000. On the other hand, CO_2 emissions from advanced economies started to decline in 2014, and by 2040, they will emit 0.3 times less than in 2000. However, CO_2 emissions from the rest of the world will keep increasing gradually, and will collectively emit 2.4 times more CO_2 by 2040 than in 2000.

The current discourse on economic development is that along with Brazil, Russia, India, China and South Africa (BRICS), eleven further countries, known by the numeronym N-11— Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, Turkey, South Korea and Vietnam – have a high potential of becoming among the world's largest economies in the 21st century[61]. Projections of energy demand growth in smaller economies but with more significant populations have primarily been inaccurate. For example, the 2010 Power Sector Master Plan (PSMP) projected that primary energy demand in Bangladesh in 2030 would be 616 TWh[62], which was later revised up in 2015 Plan to 860 TWh in the ‘business as usual’ (BaU) scenario—a 40% increase in the projected amount within five years[63]. The updated projected demand can be ascribed to flawed assumptions of the probability of demand growth and the lack of the consideration of suppressed demand. Policies based on inaccurate projections are unlikely to be efficient and sustainable.

The consideration of the identified deficiencies in developing contexts and their treatment in energy planning models need to be context specific, both regarding integration with existing models and for the development of new ones. In cases where empirical relationships between deficient parameters and outcome variables are well established and accepted by the stakeholders, the decision on integration versus new EPM development will depend on the complexity of integration with the existing model and the potential for contribution in policy development and energy planning. On the other hand, not all deficiencies need to be accounted for in all model types. Table 5 provides an applicability matrix of the identified variables against model typologies.

<Insert Table 5 about here>

A summary of potential considerations for the identified deficiencies for the development of or integration into future country/region specific localised EPMs follows.

Suppressed demand. Detailed relationships between the constituent variables of energy demand – such as the elasticity between income threshold and buying capacity and grid connectivity – need to be addressed in EPMs for developing contexts.

Dynamics between political stability and economic growth. Not all developing countries share similar political stability. If there exists an evident correlation between economic growth and political stability, it should ideally be explicitly modelled in the EPM. Where the relationship is not conclusive, further research needs to be conducted, even for implicit or proxy considerations.

Influence of corruption on the energy economy. The treatment of corruption in models should be context specific. Multiplier based modelling will be time and cost effective if a significant relationship exists between corruption and outcome indicators. In cases where the relationship is not apparent or cannot be mathematically formulated, conveniently, underlying causes can be investigated further.

Data gathering, validation and sharing. A structured data gathering and sharing system can contribute to the enhanced accuracy of the EPMs, as well as the effectiveness of the resulting policies.

Climate change impacts on energy infrastructure and systems. Depending on the country-specific impacts of climate change on energy systems and infrastructure, its degree of incorporation in EPMs can be varied. If the projected climate change has a significant effect on future energy infrastructure and systems, it should be modelled explicitly, especially for land-based variables such as land use, distributed energy generation, food production and bioenergy. In most cases, the explicit modelling of climate change impacts would require further investigations on the interactions between related variables.

5 Outlook

Distinct differences exist between the evolution of energy systems in developing and developed countries, as a response to varying social, technical, economic and environmental stimuli. Developed countries primarily aim to reduce climate-affecting GHG emissions while enhancing energy security. In contrast, developing countries are predominantly concerned with increasing access to conventional forms of energy through infrastructure expansion, which is often seen as a prerequisite for economic and social development. Despite the differences in overall policy goals, EPMs play a central role in energy sector development and transformation in both developing and developed countries. Current EPMs were mostly created in developed countries, often with the assumptions and biases of the country and region in which they were developed. Recognising the importance of EPMs in shaping the energy future, our analysis of 34 EPMs revealed several important shortcomings for the developing context.

A key finding from our Review is the lack of consideration in the analysed EPMs of the unique socioeconomic characteristics in developing countries such as suppressed demand, corruption, and political instability. Disregarding suppressed energy demand can potentially underestimate total demand, rendering future planning inaccurate and ineffective, especially for long-horizon planning such as 2050 pathways. Corruption is a complex socio-economic factor and can increase capital and operation costs of energy projects and infrastructure in some developing countries, affecting sustainability. Also, the economy is sometimes linked with political instability which, on its own can affect energy infrastructure resilience.

Apart from the developing context-specific socio-economic deficiencies in the current EPMs, climate change impact on land availability and food production is likely to alter the dynamics of energy-food-emissions interactions, especially in the highly populated developing countries. Increasing penetration of distributed energy resources and bioenergy goals require that EPMs should now consider land-based interactions between energy, food, and environment for future planning and development.

Country-specific trends in GHG emissions are also evolving. Collectively, middle- and upper-income countries now emit more than that of the high-income countries since 2007. Emissions are increasing at a much faster rate in developing economies than previously projected. EPMs can play an essential role in setting the emerging economies towards a low-carbon pathway while enhancing access to energy. Most reviewed EPMs were initially intended for their country/region of origin in the developed world, embedding the contexts in which they were designed. Their later use in developing countries demonstrated their potential for informed decision-making on energy systems planning. However, the identified shortcomings in this review suggest that the formulation of localised EPMs are essential not only for the countries concerned but also for a low-carbon pathway for the world.

References

1 Pachauri, R. K. *et al. Climate change 2014: synthesis Report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. (IPCC, 2014).

2 Raupach, M. R. *et al.* Global and regional drivers of accelerating CO_2 emissions. *Proceedings of the National Academy of Sciences* **104**, 10288-10293 (2007).

3 Le Quéré, C. *et al.* Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* **2**, 831-836 (2009).

4 IEA. CO_2 Emissions from Fuel Combustion Highlights. (2015).

5 IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2014).

6 Raftery, A. E., Zimmer, A., Frierson, D. M. W., Startz, R. & Liu, P. Less than 2 °C warming by 2100 unlikely. *Nature Climate Change* **7**, 637-641, doi:10.1038/nclimate3352 (2017).

7 Ramanathan, V. & Feng, Y. On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *Proceedings of the National Academy of Sciences* **105**, 14245-14250 (2008).

8 Clark, P. U. *et al.* Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature climate change* **6**, 360-369 (2016).

9 WB. *DataBank*, <http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators> (2017).

10 IEA. Energy access outlook 2017: From poverty to prosperity. (International Energy Agency (IEA), 2017).

11 CAT. *Rating countries*, <http://climateactiontracker.org/countries> (2014).

12 Amorim, F. *et al.* Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. *Energy* **69**, 104-112 (2014).

13 Sterner, T. *International energy economics*. (Springer Science & Business Media, 2012).

14 Barsky, R. & Kilian, L. Oil and the Macroeconomy since the 1970s. (National Bureau of Economic Research, 2004).

15 Craig, P. P., Gadgil, A. & Koomey, J. G. What can history teach us? A retrospective examination of long-term energy forecasts for the United States. *Annual Review of Energy and the Environment* **27**, 83-118 (2002).

16 IPCC. IPCC second assessment. *A Synthesis Report. Geneva: WMO* **1** (1995).

17 IEA. *World Outlook Energy 2017*. (International Energy Agency, 2017).

18 Suganthi, L. & Samuel, A. A. Energy models for demand forecasting—A review. *Renewable and Sustainable Energy Reviews* **16**, 1223-1240, doi:http://dx.doi.org/10.1016/j.rser.2011.08.014 (2012).

19 Bhattacharyya, S. C. & Timilsina, G. R. A review of energy system models. *International Journal of Energy Sector Management* **4**, 494-518 (2010).

20 Pfenninger, S., Hawkes, A. & Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews* **33**, 74-86 (2014).

21 Urban, F., Benders, R. M. J. & Moll, H. C. Modelling energy systems for developing countries. *Energy Policy* **35**, 3473-3482, doi:http://dx.doi.org/10.1016/j.enpol.2006.12.025 (2007).

22 Pandey, R. Energy policy modelling: agenda for developing countries. *Energy Policy* **30**, 97-106, doi:http://dx.doi.org/10.1016/S0301-4215(01)00062-3 (2002).

23 UNFCCC/CCNUCC. Guidelines on the consideration of suppressed demand in CDM Methodologies. version 02.0. (2012).

24 Gavaldão, M., Battye, W., Grapeloup, M. & François, Y. Suppressed Demand and the Carbon Markets: Does development have to become dirty before it qualifies to become clean?. Looking into Passive Solar Houses (PSH). *Field Actions Science Reports. The Journal of Field Actions* (2013).

25 Spalding-Fecher, R. Suppressed demand in the clean development mechanism: Conceptual and practical issues. *Journal of Energy in Southern Africa* **26**, 2-10 (2015).

26 Barnes, D., Domdom, A., Peskin, V. & Peskin, H. Rural Electrification and Development in the Philippines: Measuring the Social and Economic Benefits. *Washington, International Bank for Reconstruction and Development/World Bank* (2002).

27 IEG. The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits. (World Bank, 2008).

28 UNFCCC. *Clean Development Mechanism (CDM)* <http://cdm.unfccc.int/index.html> (2017).

29 UNFCCC. Modalities and procedures for a clean development mechanism as defined in Article 12 of the Kyoto Protocol. (2001).

30 UNFCCC. Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its fifth session, held in Copenhagen from 7 to 19 December 2009. (2010).

31 Alesina, A., Özler, S., Roubini, N. & Swagel, P. Political instability and economic growth. *Journal of Economic Growth* **1**, 189-211 (1996).

32 Aisen, A. & Veiga, F. J. How does political instability affect economic growth? *European Journal of Political Economy* **29**, 151-167, doi:http://dx.doi.org/10.1016/j.ejpoleco.2012.11.001 (2013).

33 Debnath, K. B., Mourshed, M. & Chew, S. P. K. Modelling and Forecasting Energy Demand in Rural Households of Bangladesh. *Energy Procedia* **75**, 2731-2737, doi:http://dx.doi.org/10.1016/j.egypro.2015.07.480 (2015).

34 Medlock, K. B. & Soligo, R. Economic Development and End-Use Energy Demand. *The Energy Journal* **22**, 77-105 (2001).

35 Mauro, P. Corruption and Growth. *The Quarterly Journal of Economics* **110**, 681-712, doi:10.2307/2946696 (1995).

36 Aladwani, A. M. Corruption as a source of e-Government projects failure in developing countries: A theoretical exposition. *International Journal of Information Management* **36**, 105-112, doi:10.1016/j.ijinfomgt.2015.10.005 (2016).

37 Mourshed, M. Pitfalls of oil-based expansion of electricity generation in a developing context. *Energy Strategy Reviews* **1**, 205-210, doi:http://dx.doi.org/10.1016/j.esr.2012.08.001 (2013).

38 Wells, J. Corruption in the construction of public infrastructure: Critical issues in project preparation. 30 (U4 Anti-Corruption Resource Centre, CMI, Bergen, Norway, 2015).

39 Lovei, L. & McKechnie, A. The Costs of Corruption for the Poor–The Energy Sector. *Public Policy for the Private Sector* **207**, 1-8 (2000).

40 Nye, J. S. Corruption and Political Development: A Cost-Benefit Analysis. *The American Political Science Review* **61**, 417-427, doi:10.2307/1953254 (1967).

41 Vera, I. & Langlois, L. Energy indicators for sustainable development. *Energy* **32**, 875-882, doi:http://dx.doi.org/10.1016/j.energy.2006.08.006 (2007).

42 Geng, Y. *et al.* Recent trend of industrial emissions in developing countries. *Applied Energy* **166**, 187-190, doi:10.1016/j.apenergy.2016.02.060 (2016).

43 McLellan, B., Zhang, Q., Farzaneh, H., Utama, N. A. & Ishihara, K. N. Resilience, Sustainability and Risk Management: A Focus on Energy. *Challenges* **3**, 153-182, doi:10.3390/challe3020153 (2012).

44 Alcántara-Ayala, I. Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology* **47**, 107-124, doi:http://dx.doi.org/10.1016/S0169-555X(02)00083-1 (2002).

45 Butzengeiger, S. & Horstmann, B. *Sea Level Rise in Bangladesh and the Netherlands: One Phenomenon, Many Consequences*. (Germanwatch, 2004).

46 Workshop on climate change impact modeling: report and presentations. (Climate Change Cell, Department of Environment, Bangladesh, 2006).

47 Khan, I., Alam, F. & Alam, Q. The global climate change and its effect on power generation in Bangladesh. *Energy Policy* **61**, 1460-1470 (2013).

48 Wadey, M. P., Roberts, H. & Harris, J. Impacts of climate change on built structures (onshore and coastal).

49 Greenpeace. The impacts of climate change on nuclear power stations sites: a review of four proposed new-build sites on the UK coastline. (2007).

50 Archibugi, D. *Technology, globalisation and economic performance*. (Cambridge University Press, 1997).

51 BD2050. *Bangladesh 2050 Energy and Emissions Pathways*, <http://calc.bd2050.org/> (2015).

52 EPA. *Understanding the Link Between Climate Change and Extreme Weather*, <https://www.epa.gov/climate-change-science/understanding-link-between-climate-change-and-extreme-weather> (2016).

53 Ravanelli, N. M. & Jay, O. Electric fan use in heat waves: Turn on or turn off? *Temperature* **3**, 358-360 (2016).

54 Herring, S. C., A. Hoell, M. P. Hoerling, J. P. Kossin, C. J. Schreck III, and P. A. Stott,. Explaining Extreme Events of 2015 from a Climate Perspective. *Bulletin of the American Meteorological Society* **97** (2016).

55 Johansson, T. B., Patwardhan, A. P., Nakićenović, N. & Gomez-Echeverri, L. *Global energy assessment: toward a sustainable future*. (Cambridge University Press, 2012).

56 Conti, J. *et al.* International Energy Outlook 2016 With Projections to 2040. Report No. DOE/EIA--0484(2016) United States 10.2172/1296780 Available at www.eia.gov/forecasts/ieo DOEEIA English, (USDOE Energy Information Administration (EIA), Washington, DC (United States). Office of Energy Analysis, 2016).

57 McNeil, M. A. & Iyer, M. Techno-economic analysis of Indian draft standard levels for room air conditioners. (Lawrence Berkeley National Laboratory, 2008).

58 Miller, N. L., Hayhoe, K., Jin, J. & Auffhammer, M. Climate, Extreme Heat, and Electricity Demand in California. *Journal of Applied Meteorology and Climatology* **47**, 1834-1844, doi:10.1175/2007jamc1480.1 (2008).

59 Yohe, G. W. *et al.* Global distributions of vulnerability to climate change. *Integrated Assessment* **6** (2006).

60 Marchal, V. *et al.* OECD environmental outlook to 2050. *Organization for Economic Co-operation and Development (OECD)* (2011).

61 Lawson, S., Heacock, D. & Stupnytska, A. Beyond the BRICS: A look at the "Next 11". *BRICS and Beyond*, 131-164 (2007).

62 JICA & TEPCO. The study for master plan on coal power development in the People 's Republic of Bangladesh, Power System Master Plan 2010 (Energy and Mineral Resources, Ministry of Power, People's Republic of Bangladesh, 2011).

63 JICA, TEPSCO & TEPCO. People's republic of Bangladesh: Survey on power system master plan 2015 (Draft Final Report). (Energy and Mineral Resources, Ministry of Power, People's Republic of Bangladesh, 2016).

64 Kaufmann, D. & Kraay, A. *The Worldwide Governance Indicators, 2014 Update*, <http://info.worldbank.org/governance/wgi/index.aspx#home> (2014).

65 *World Data Bank*, <http://databank.worldbank.org/> (2014).

66 TI. Corruption Perceptions Index 2014. (Transparency International, 2014).

67 LBST. An Introduction into the Life-Cycle Analysis Calculation Tool. (2008).

68 Strubegger, M. CO2DB Software- Carbon Dioxide (Technology) Database Users Manual. (International Institute for Applied Systems Analysis, 2003).

69 EIA. Model Documentation Report: Macroeconomic Activity Module (MAM) of the National Energy Modeling System. (2014).

70 Manne, A. S. & Wene, C.-O. MARKAL-MACRO: A linked model for energy-economy analysis. (Brookhaven National Lab., Upton, NY, USA, 1992).

71 Van Beeck, N. *Classification of energy models*. (Tilburg University, Faculty of Economics and Business Administration, 1999).

72 Remme, U. & Blesl, M. Documentation of the TIMES-MACRO model. *Energy Technology Systems Analysis Programme (ETSAP)* (2006).

73 IAEA. Case studies to assess and compare different energy sources in sustainable energy and electricity supply strategies. (International Atomic Energy Agency, 2003).

74 Martinsen, D., Krey, V., Markewitz, P. & Vögele, S. *IAEE Proceedings 2004* (International Association for Energy Economics, 2004).

75 Sahir, M. H. & Qureshi, A. H. in *6th WSEAS International Conference on Simulation, Modeling and Optimization.* 227-233 (World Scientific and Engineering Academy and Society, 2006).

76 Heaps, C. G. *Long-range Energy Alternatives Planning (LEAP) system. [Software version 2014.0.1.29]*, < www.energycommunity.org> (2012).

77 Takase, K. & Suzuki, T. The Japanese energy sector: Current situation, and future paths. *Energy Policy* **39**, 6731-6744, doi:http://dx.doi.org/10.1016/j.enpol.2010.01.036 (2011).

78 Cai, W. *et al.* Comparison of CO_2 emission scenarios and mitigation opportunities in China's five sectors in 2020. *Energy Policy* **36**, 1181-1194, doi:http://dx.doi.org/10.1016/j.enpol.2007.11.030 (2008).

79 Kitous, A. POLES Model- Prospective Outlook on Long-term Energy Systems. (2006).

80 Messner, S., Golodnikov, A. & Gritsevskii, A. A stochastic version of the dynamic linear programming model MESSAGE III. *Energy* **21**, 775-784, doi:http://dx.doi.org/10.1016/0360-5442(96)00025-4 (1996).

81 IAEA. *Wien Automatic System Planning (WASP) Package*. (International Atomic Energy Agency, 2001).

82 Loulou, R., Goldstein, G. & Noble, K. Documentation for the MARKAL Family of Models. *Energy Technology Systems Analysis Programme*, 65-73 (2004).

83 Loulou, R., Remme, U., Kanudia, A., Lehtila, A. & Goldstein, G. Documentation for the TIMES Model Part II. *Energy Technology Systems Analysis Programme (ETSAP)* (2005).

84 MacKenzie, G. A. Energy models for Denmark MEDEE 3: Application of the long term energy demand model to Denmark: (Part III). (1982).

85 IAEA. *Model for Analysis of Energy Demand (MAED-2)*. (International Atomic Energy Agency, 2006).

86 EIA. The National Energy Modeling System: An Overview 2009. (2009).

87 DECC. *The UK 2050 calculator*, <http://2050-calculator-tool.decc.gov.uk/> (2013).

88 Schlenzig, C. & Steidle, T. MESAP–A Co-operative Modelling System for Sustainable Local Energy and Environmental Planning. (2001).

89 Schlenzig, C. Energy planning and environmental management with the information and decision support system MESAP. *International Journal of Global Energy Issues* **12**, 81-91 (1999).

90 Van Den Broek, M., Van Oostvoorn, F., Van Harmelen, T. & Van Arkel, W. The EC Energy and Environment Model EFOM-ENV Specified in GAMS. (1992).

91 Stehfest, E., van Vuuren, D., Bouwman, L. & Kram, T. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model description and policy applications. (2014).

92 Mikiko Kainuma, Yuzuru Matsuoka & Morita, T. The AIM/ENDUSE Model and Case Studies in Japan. (1999).

93 Sankovski, A., Barbour, W. & Pepper, W. Quantification of the IS99 Emission Scenario Storylines Using the Atmospheric Stabilization Framework. *Technological Forecasting and Social Change* **63**, 263-287, doi:http://dx.doi.org/10.1016/S0040-1625(99)00100-6 (2000).

94 Burniaux, J.-M., Martin, J. P., Nicoletti, G. & Martins, J. O. GREEN a Multi-Sector, Multi-Region General Equilibrium Model for Quantifying the Costs of Curbing CO_2 Emissions. (1992).

95 Weyant, J. P. Costs of reducing global carbon emissions. *The Journal of Economic Perspectives*, 27-46 (1993).

96 Dean, A. & Hoeller, P. *Costs of reducing CO_2 emissions: evidence from six global models*. (Organisation for Economic Co-operation and Development, 1992).

97 Brenkert, A. L., Sands, R. D., Kim, S. H. & Pitcher, H. M. *Model Documentation: Second Generation Model*. (2004).

98 IAEA. *Planning & Economic Studies Section (PESS): Capacity Building for Sustainable Energy Development*, <https://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.html> (2014).

99 SEI. *LEAP: Long-range Energy Alternatives Planning system*, <https://www.sei-international.org/leap> (2017).

100 CEERD. *Tools and models*, <http://www.ceerd.net/tools-and-models/> (2017).

101 Enerdata. POLES: Prospective Outlook on Long-term Energy Systems. (2012).

102 Munasinghe, M. & Meier, P. *Energy policy analysis and modelling*. (Cambridge University Press, 1993).

103 Giannakidis, G., Labriet, M., Gallachóir, B. Ó. & Tosato, G. Informing energy and climate policies using energy systems models. *Springer International Publishing, Switzerland. doi* **10**, 978-973 (2015).

104 Voß, A., Schlenzig, C. & Reuter, A. MESAP-III: a tool for energy planning and environmental management: history and new developments; STE-Seminar, KFA Jülich, 6. September 1994. (1994).

105 DECC. *Completed calculators*, <http://www.2050.org.uk/calculators> (2014).

106 DECC. *How to build a 2050 calculator*. (2014).

Figures

Figure 1: National CO_2 emissions characteristics. (a) CO_2 emissions vs access to electricity in high and low-income countries in 2010. Access to electricity in low and middle-income countries ranges from 3.5–100% of the population. In contrast, the figure is 72.6–100% in high-income countries. (b) CO_2 emissions per capita for the period 1992-2011. (c) CO_2 emissions per capita in selected developed and developing countries for the period 1972-2011. (d) CO_2 emissions in countries by income group from 1960 to 2011. The income group classification used here is that from the World Bank list of economies (July 2015): low income, $1,045 or less; lower middle income, $1,046–4,125; upper middle income, $4,126–12,735; and high income, $12,736 or more. Data is taken from ref. [9].

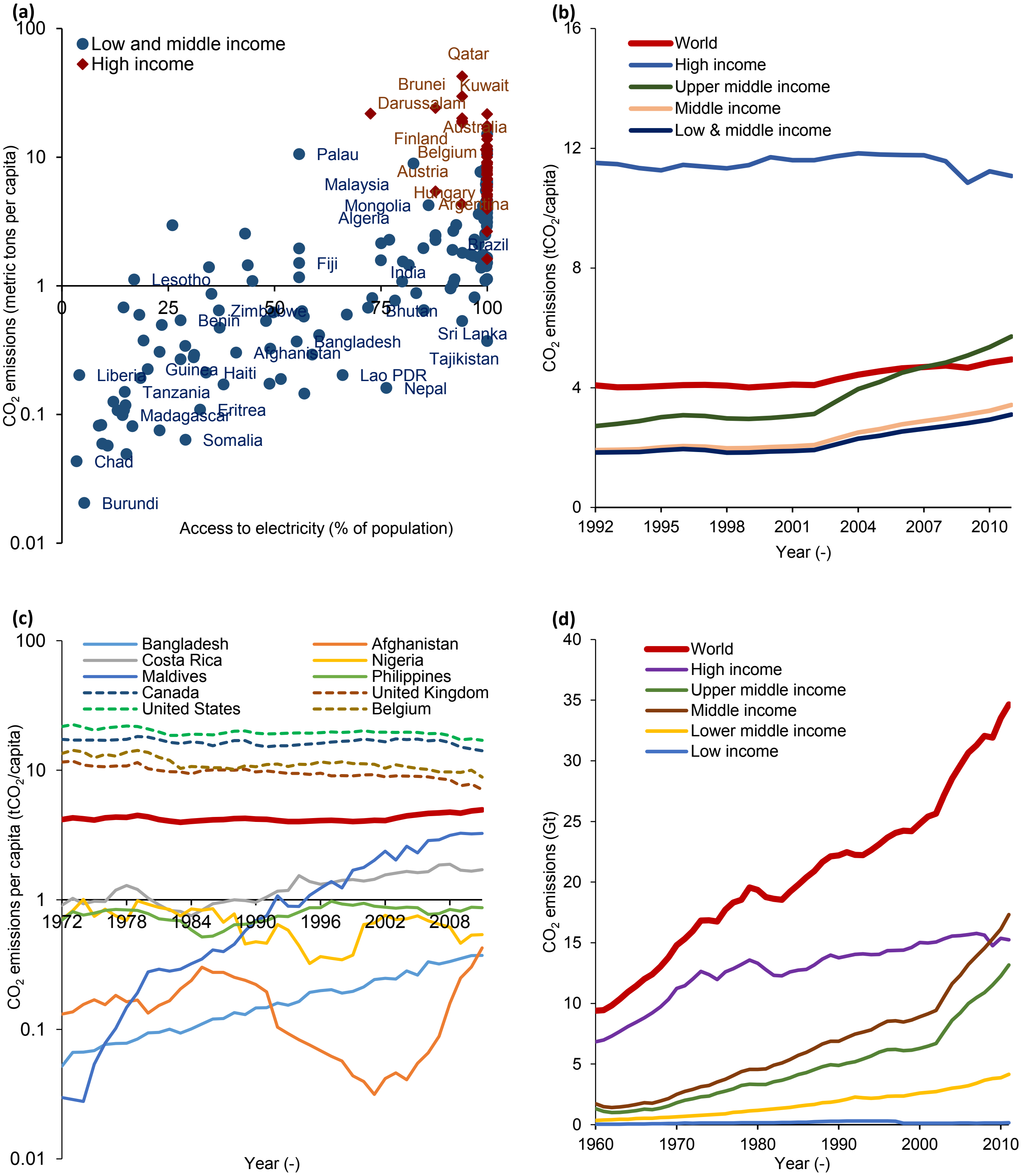


Figure 2: GDP growth vs political stability trends. GDP growth and political stability scores are shown for developed (a-e) and developing (f-j) countries. Straight lines represent the fitted regression line, visually depicting the trend in the data. Data is taken from refs [64,65].

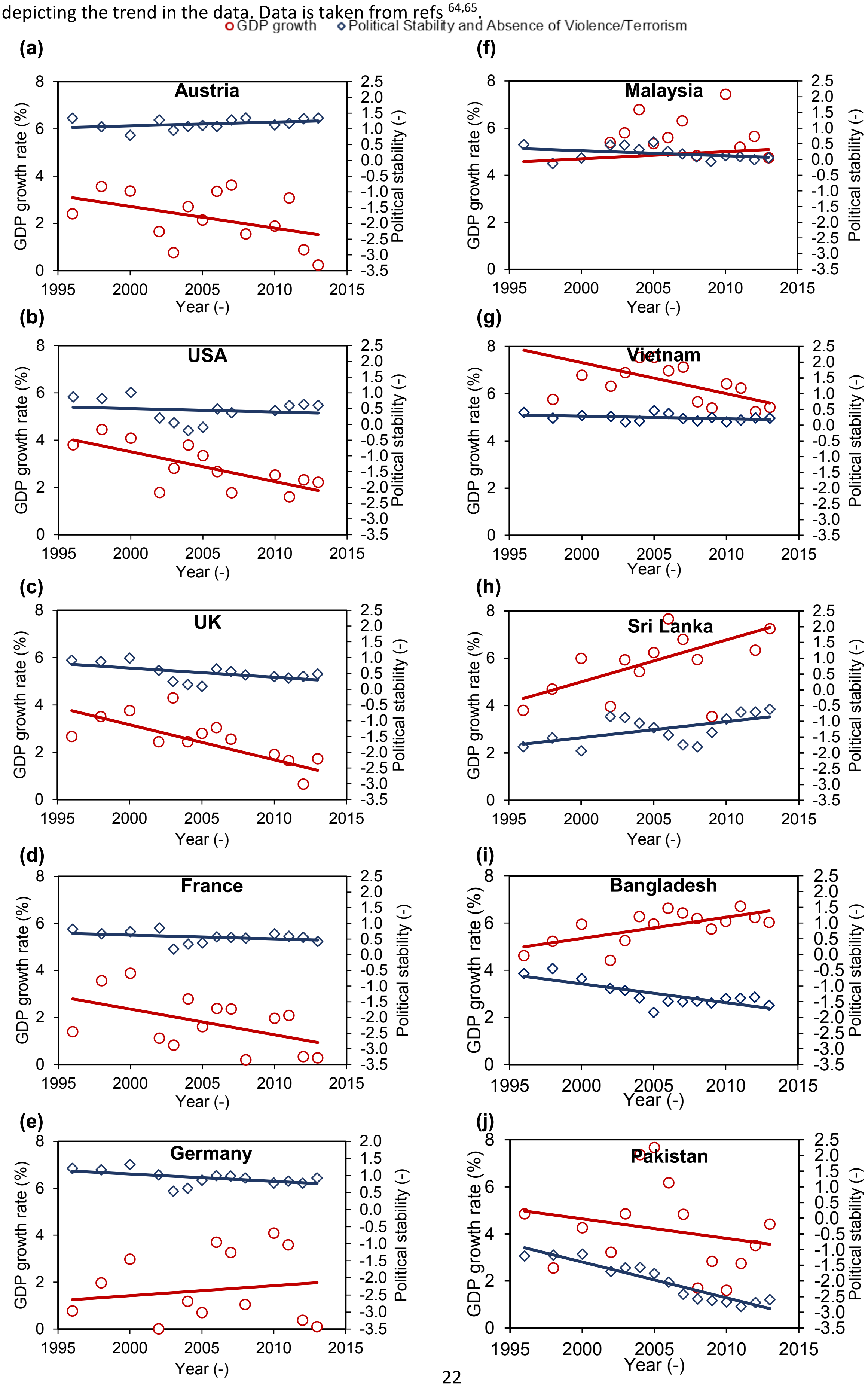


Figure 3: GDP per capita vs electricity consumption from 1995 to 2013. The R^2 values denote the coefficient of determination, which measures how close the data are to the fitted regression lines . Data taken from ref. [9].

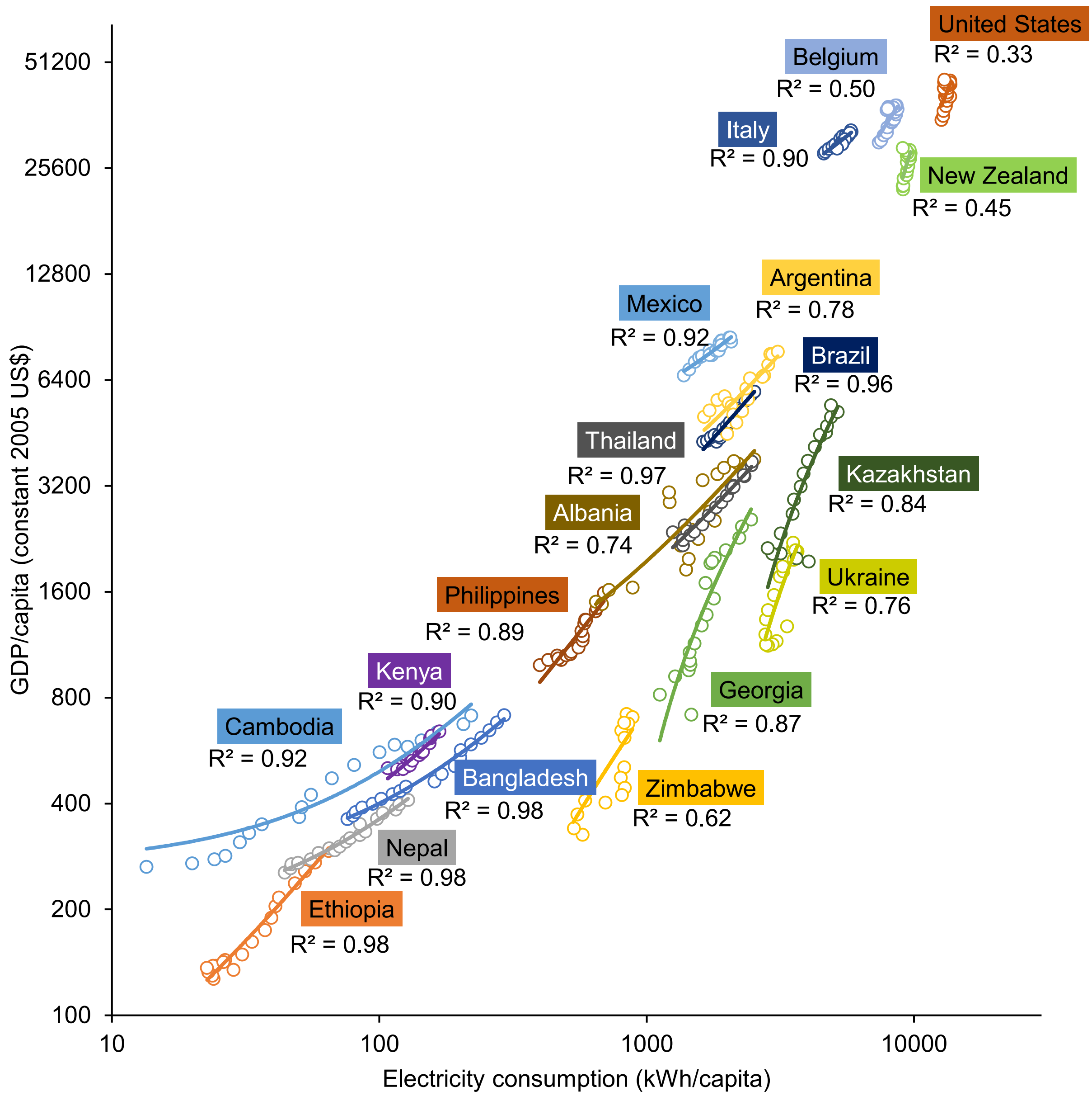


Figure 4: Growth trends across developed and developing countries. (a) Growth in GNI per capita of different countries from 1960 to 2014. (b) Growth trends in electricity consumption of different countries from 1960 to 2014. In panel (b), the trends in the data are visually depicted by fitted regression lines. The y-axis values are on a logarithmic scale, and the dashed and solid lines denote exponential and logarithmic progression of the data, respectively. The income group classification used here is that from the World Bank list of economies (July 2015): low income, \$1,045 or less; lower middle income, \$1,046–4,125; upper middle income, \$4,126–12,735; and high income, \$12,736 or more. Data taken from ref. [9].

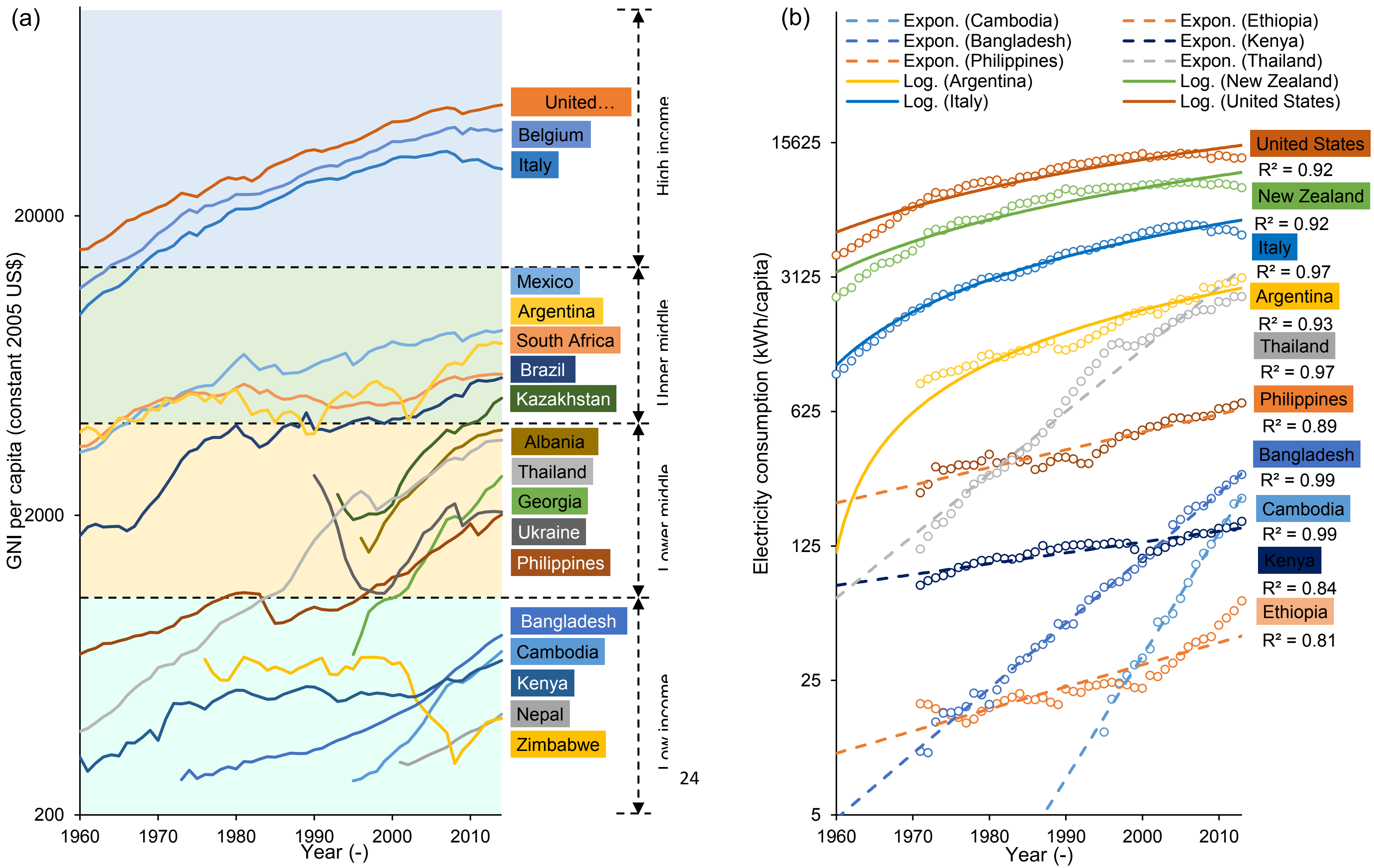
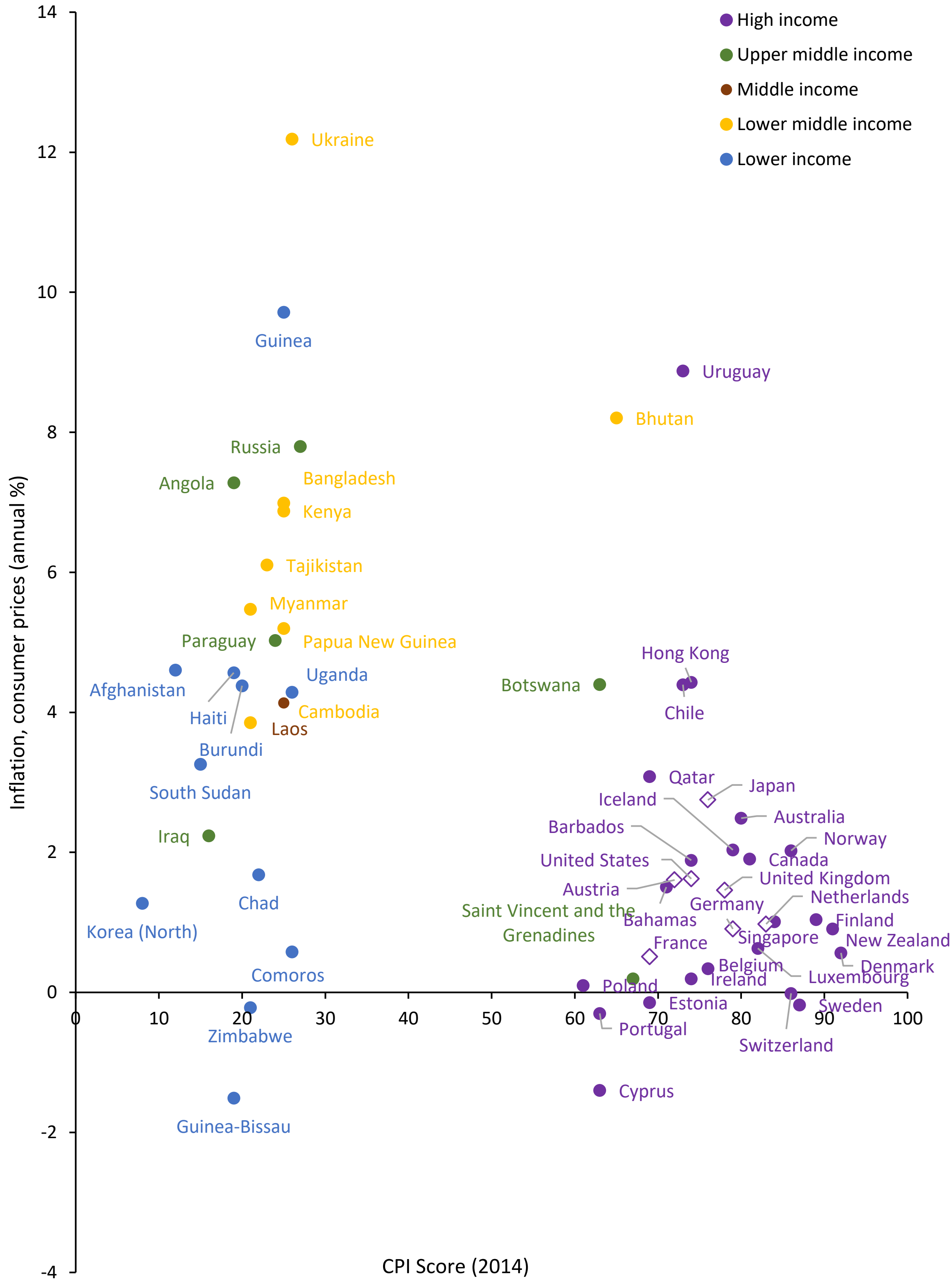


Figure 5: Comparison of corruption perceptions with inflation and consumer prices. Corruption Perceptions Index (CPI) 2014 vs. Inflation (2014) among the top and bottom 35 countries of the CPI list. High-income countries where EPMs have originated are illustrated by hollow purple diamond shapes. For detail, see Table 3. Data taken from refs [9,66].



Tables

Table 1: Searched keywords and associated groups

Model	Objective	Components	Origin of development	Geographical applicability
Energy planning	Forecasting	Input variables	Organization	Global
Energy information	Projection	Estimation methods	Country	Regional
Energy economic	Demand and Supply; Demand; Supply	Output variables		Country
Energy supply and demand	Economic			
Energy supply	Emission control			
Energy demand				
Emission reduction				

Table 2: Characteristics of existing energy planning models

Model	Input variables*				Method†						Output variables‡			Total	Reference
	Qul	Qua	Fin	Agg	Dagg	RE	OP	EC	SM	EQ	AF	En	Em	Co		
Energy information system															
E3		■	■						■			■	■	■	*6*	[67]
CO2DB		■	■						■				■	■	*5*	[68]
Energy economic model															
MAM		■	■	■				■††						■	*5*	[69]
MARKAL-MACRO		■	■	■	■		■	■‡‡		■		■	■	■	*10*	[70]
MICRO-MELODIE		■	■	■	■		■	■‡‡				■	■	■	*9*	[71]
TIMES- MACRO		■	■	■	■		■	■‡‡				■	■	■	*9*	[72]
Energy demand-supply model															
DECPAC		■	■	■			■		■			■	■	■	*8*	[73]
IKARUS	■	■	■	■	■		■		■			■	■	■	*10*	[74]
ENPEP		■	■	■	■			■‡‡		■**		■	■	■	*9*	[71,75]
LEAP		■	■	■	■			■††	■		■	■	■	■	*10*	[76-78]
POLES		■	■		■			■††		■		■	■		*7*	[79]
MESSAGE-III		■	■		■		■					■		■	*6*	[80]
WASP		■	■		■	■	■					■		■	*7*	[81]
MARKAL		■	■		■		■					■	■	■	*7*	[82]
TIMES		■	■		■		■					■	■	■	*7*	[83]
MEDEE		■	■		■	■					■	■			*6*	[84]
MAED		■			■	■						■			*4*	[85]
NEMS		■	■		■		■					■	■	■	*7*	[86]
ENERPLAN		■						■††	■			■	■		*5*	[71,75]
MESAP		■	■	■	■		■	■††	■		■	■	■		*10*	[71]

Energy emissions model																
UK 2050	■	■	■		■				■			■	■	■	*8*	[87]
BD 2050	■	■	■		■				■			■	■		*7*	[51]
MESAP PlaNet		■	■		■	■			■			■	■	■	*8*	[88,89]
EFOM-ENV		■	■		■	■	■					■	■	■	*8*	[90]
IMAGE		■	■		■	■							■	■	*6*	[91]
AIM		■	■		■	■						■	■	■	*7*	[92]
ASF		■	■						■				■	■	*5*	[93]
GREEN		■	■		■					■		■	■	■	*7*	[94,95]
ERM		■	■		■					■		■	■	■	*7*	[96]
IEA		■	■		■			■[††]				■	■	■	*7*	[96]
CRTM		■	■		■					■		■	■	■	*7*	[95,96]
MR		■	■		■		■					■	■	■	*7*	[96]
WW		■	■		■					■		■	■	■	*7*	[96]
SGM		■	■	■		■						■	■	■	*7*	[97]
Total	*3*	*34*	*32*	*10*	*27*	*8*	*13*	*10*	*11*	*7*	*3*	*30*	*29*	*28*		

* Input types: Qul (qualitative) Qua (quantitative), Fin (financial), Agg (aggregated) and Disag (disaggregated).

† Methods: RE (regression), OP (optimization), EC (economic – econometric, macroeconomic), SM (simulation), EQ (equilibrium) and AF (accounting framework)

‡ Output types: En (energy – demand and/or supply), Em (emissions) and Co (cost).

** Economic equilibrium

†† Econometric

‡‡ Macroeconomic

Table 3: Origin and use of EPMs

Model	Developer	Country of origin	Applied/adopted in developing countries	Number of countries applied/ adopted	Ref.
E3 Database	Ludwig-Bolkow-Systemtechnik GmbH	Germany	N/A		67
CO2DB	International Institute for Applied Systems Analysis (IIASA)	Austria	N/A		68
DECPAC	International Atomic Energy Agency (IAEA)	Austria	N/A		73
IKARUS	Former German Federal Ministry of Education, Science, Research, and Technology (BMFT)	Germany	N/A		74
MAM	U.S. Department of Energy	USA	N/A		69
MARKAL-MACRO	International Energy Agency (IEA)/ ETSAP	France	Yes		70
MICRO-MELODIE	U.S. Department of Energy	USA	N/A		71
TIMES-MACRO	Brookhaven National Laboratory	USA	N/A		72
ENPEP	The Commissariat à l'énergie atomique et aux énergies alternatives (CEA)	France	Yes	60	98
LEAP	The Energy Technology Systems Analysis Program (ETSAP), International Energy Agency (IEA)	France	Yes	190*	99
Mesap PlaNet	International Atomic Energy Agency (IAEA)	Austria	N/A		88
EFOM-ENV	Stockholm Environmental Institute, Boston	USA	Yes	20	100
POLES	It has been developed first by CNRS (France) and now by CNRS / UPMF university, Enerdata, and IPTS (Spain, European Commission research center)	France	Yes	57*	101
MESSAGE-III	International Institute for Applied System Analysis (IIASA)	Austria	Yes		102
WASP	International Atomic Energy Agency (IAEA)	Austria	Yes	100	98
MARKAL	International Energy Agency (IEA)/ ETSAP	France	Yes	70*	102,103
MEDEE	Institut Economics et Juridigue de l'Energie (IEJE), Grenoble	France	Yes		100
MAED	International Atomic Energy Agency (IAEA)	Austria	Yes	40	85
NEMS	U.S. Department of Energy	USA	N/A		86
ENERPLAN	Tokyo Energy Analysis Group	Japan	Yes		102
MESAP	Institutes für Energiewirtschaft und Rationelle Energieanwendung (IER), University of Stuttgart	Germany	Yes		104

UK 2050	Department of Energy & Climate Change (DECC)	UK	Yes	24*†	[105]
IMAGE	PBL Netherlands Environmental Assessment Agency/ Utrecht University	Netherlands	N/A		[91]
AIM	National Institute of Environmental Studies (NIES)	Japan	N/A		[92]
CRTM	Joint Center for Satellite Data Assimilation (JCSDA)	USA	N/A		[96]
SGM	Pacific Northwest National Laboratory (PNNL) and is maintained by the PNNL Joint Global Change Research Institute (JGCRI)	USA	N/A		[97]

*Including all the countries that utilised the specific model

† Several 2050 pathways models have been constructed for the following developing countries: Vietnam, Bangladesh, Thailand, Nigeria, Mexico, Mauritius, Indonesia, India, Colombia, China and Brazil. These models are roughly based on the principles of UK2050 Pathways[106], albeit with some minor country-specific additions. Except BD2050, where electricity consumption is modelled against various scenarios of GDP and population growth, all models lack the consideration of socio-economic parameters. Political instability, corruption, suppressed demand and climate change effects are not modelled in any of these developing country pathways.

Table 4: Effect of poor characterisations of energy systems and economies of developing countries in energy planning models

Model typologies	Effect of poor characterisations
Mathematical procedures	
Regression, economic, simulations and accounting frameworks	Fragmented or inaccurate data and relations in the calculation can prompt incorrect results
Optimisation	The calculated best solution/s may be incorrect, because of the inadequate interpretation of economy and resources framework.
Equilibrium	Overlooking the disequilibrium of business sectors and overestimate business sector impacts that prompt contorted results[21].
Modelling approaches	
Top-down model	The incorrect or incomplete linkage or data in model frameworks results in incorrectly computed outputs
Bottom-up model	This typology of models would be influenced by inappropriate or incomplete relations and information in the frameworks, bringing about incorrect results
Hybrid model	Hybrid models could lead to inconclusive results due to inappropriate interrelations of different parts of the system with economic and scientific data.

Table 5: Applicability of suggested variables in existing EPMs.

Variables	Types of models			
	Energy information systems	Energy demand-supply model	Energy economic model	Energy emissions model
Political stability		√	√	
Corruption			√	
Suppressed demand	√	√	√	√
Climate change impacts		√	√	√