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Development of a "Current Energy Mix Scenario" and a "Electricity as Main Energy Source Scenario" for electricity demand up to 2100

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ABSTRACT

In this work, we develop a model to forecast world electricity production up to 2100. We analyze historical data for electricity production, population and GDP per Capita for the period 1900–2008. We show that electricity production follows general trends. First, there is an electricity intensity target of 0,20-0,25 kWh per unit of GDP (US$2012) as economies mature, except in countries traditionally relying heavily on renewable electricity (hydroelectricity), for whom this target ranges between 0,50 to 0,80 kWh per unit GDP. Also, countries that belong to the same region tend to follow the evolution of electricity production and GDP/Capita of a regional "model country". Equations that describe the behavior of these model countries are used to forecast electricity production per capita up to 2100 under a low and a high scenario for the evolution of GDP per Capita. For electricity production two main scenarios were set: "Current Energy Mix Scenario" and "Electricity as Main Energy Source Scenario", with two additional sub scenarios considering slightly different electric intensities. Forecasts up to 2100 yield a demand for electricity production 3.5 to 5 times higher than the current production for the "Current Energy Mix Scenario" and about 9 to 14 times for the "Electricity as Main Energy Source Scenario". Forecasts for the "Current Energy Mix Scenario" matched well with forecasts from IEA/EIA (International Energy Agency/ Energy Information Administration) while the forecasts for the "Electricity as the Main Energy Source Scenario" are much higher than current predictions.

Keywords:

forecast, electricity production, model-country, historical data, logistic function, polynomial regression

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1. Introduction

The target of this work is to forecast the evolution of the electricity production for the long term under two different scenarios. We consider two scenarios for the electricity demand up to 2100. The first scenario "Current Energy Mix" assumes that actual energetic structure and sources remain the same throughout the XXI century, probably by taking advantage from existing reserves of natural gas, coal and non-conventional oils to fill future demand for heat, power generation and transportation fuels and probably also by resorting to liquefaction processes for production of liquid fuels. The "Electricity as main source" scenario assumes a massive shift towards renewable sources, resulting in increasing electricity intensity of the energetic mix because electricity is the most common form of final energy obtained from renewables. Possible triggers that would lead to this radical change include high prices for fossil fuels or increasing environmental pressures.

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The electricity forecast models found in the literature ([9], [1], [3]) are divided in three main timeframes: short-term, medium-term, long-term. For this work the focus was on long-term forecasts which are commonly obtained through trend projections, econometric projections, end-use analysis, combined approaches, system dynamics, and scenario analysis; see Craig *et al.* [9]. There are also extremely complex computer simulations running over multiple variables and developed during decades as is the case of WEPS+ - World Energy Projection System Plus (EIA) [25] and WEM – World Energy Model (IEA) [29].

The model developed here resembles a combined analysis that relies mostly on trend projections and scenario development while resorting to some techniques of system dynamics. The model takes advantage of available historical data for each of the different regions, particularly GDP/Capita, population and electricity production. It tries to identify patterns and relationships between these variables avoiding simple regressions and extrapolation analysis that are far too simplistic and ignore several imponderables.

Current literature addressing the relation between economic growth and electricity consumption is not abundant and is mainly focused on the period between 1970 to 2000 ([2], [6], [18], [20]), revealing that the knowledge about the phenomenon is still scarce and underdeveloped. These studies test the relationship between economic growth and electricity consumption using the Granger causality on an attempt to disclosure whether causality goes from growth to consumption or the opposite way. The revised studies, although focusing mainly on OECD countries, screen a wide range of countries possessing different economic structures and maturity levels. Results do not allow the identification of particular trends because: (1) the directionality of the causality relationship is not the same for all countries, (2) there are contradictory results for some countries over the same timeframe.

This paper is organized as follows. Section 2 presents the methodology, section 3 shows the results and discussion and section 4 concludes.

2. Methodology

2.1. Historical data

Statistical data regarding several world regions corresponds to a wide group of countries for each region [11], [15], [33]. The analysed period are the years from 1900 to 2008 and the collected data are: Electricity production [11], [33]; population [15], [33]; GDP/Capita [15], [33] (GDP - Gross Domestic Product, in terms of PPP – Power Purchase Parity, in United States Dollars of 2012).

The regions are the same adopted by BP World Statistical Review 2011, allowing an easier comparison between different bibliographical sources. The regions considered are: North America, South & Central America, Europe & Eurasia, Africa, Middle East and Asia-Pacific (Fig. 1).

These regions are further subdivided because significant variation of data occurred between countries of the same geographical regions. The region South & Central America is divided into South America (South American continent), Central America (isthmus region between Colombia and Mexico) and Caribbean (islands chains from Venezuela to United States – Florida). The region Europe & Eurasia is divided into Western Europe (all countries west of the eastern borders of Finland, Germany, Austria, Switzerland and Italy plus Former Czechoslovakia), Eastern Europe (remaining countries, excluding Former Soviet Union) and Eurasia (Former Soviet Union countries). Africa divides into North Africa (Maghreb, plus Egypt) and Sub-Saharan Africa. Middle East division is between Oil Exporter Countries and Non-Oil Exporter Countries. Asia-Pacific is divided into Asia (all countries from Asian continent with exception of Former Soviet Union) and Pacific (Australia, New Zealand, Melanesia, Polynesia and Micronesia), as can be seen in Fig. 2

The countries selected to support the study are the ones with data available (1) from 1900 onwards, or (2) for one or more years between 1900 and 1920 (particularly 1913, year containing a large set of data including the former Russian, Austro-Hungarian, British, French, German, Persian and Turkish Empires). When data begins about 1910–20, the growth rate for the first 10–15 years of available data is used to estimate the figures for the earlier years, always comparing with similar economies in the same region with data available from 1900 onwards. Our own estimates are made as consistent as possible, comparing simultaneously the available data for population, GDP/Capita and electricity production, taking into account the countries and region history, geographies, resources, technological development, and economic history.

A notable exception is sub-Saharan Africa because that region displays a major deficiency of data for the 1900–1950 period. The only countries with available

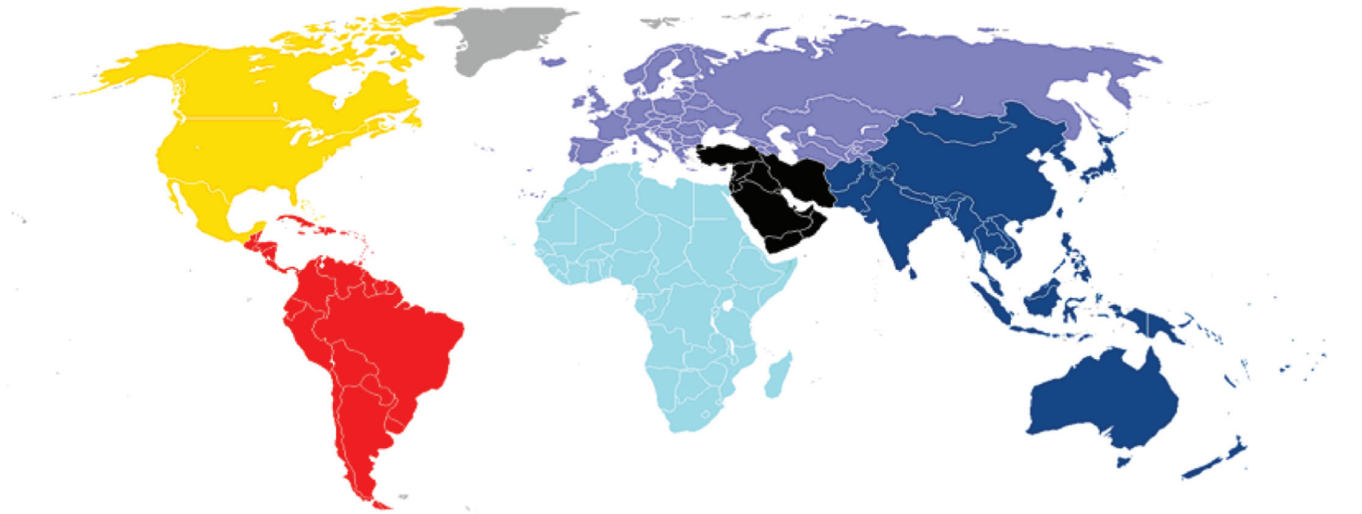

Figure 1: Regions map.

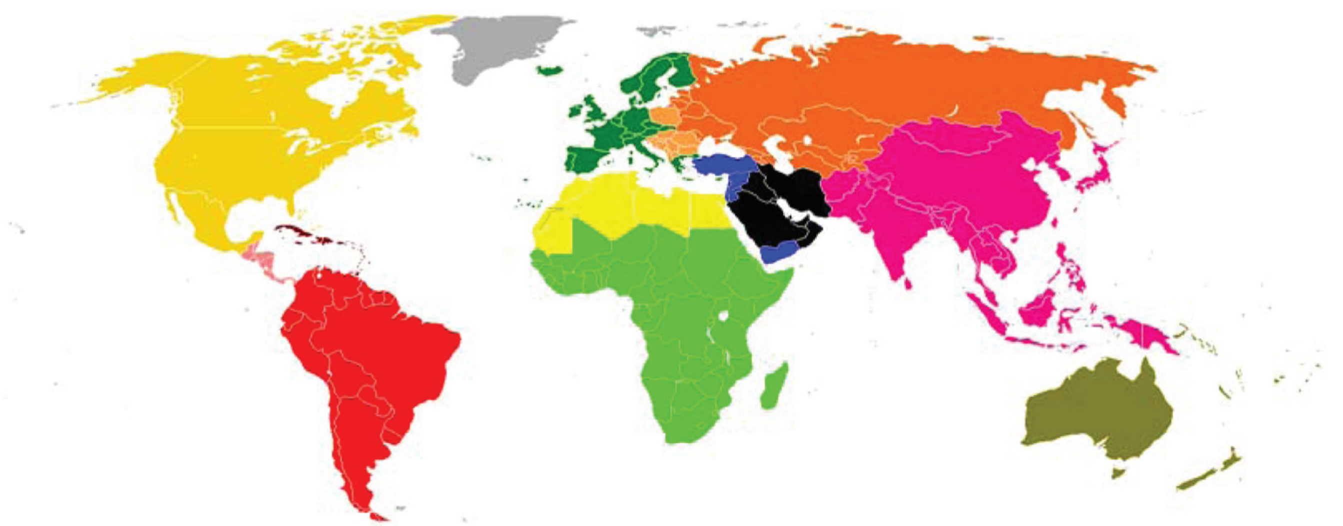

Figure 2: Sub regions map.

data are Ghana and South Africa, and solely for the year 1913. So a estimation is made for the countries of that region using the logistic curve with the data available since 1950 and extrapolating the curve for 1900–1950. The yielded results seem somewhat reasonable (when comparing with the available data) and that is supported by a later development, aiming at a more exact estimation of GDP/Capita for that region and period, resorting to a careful look of each country history since mid-XIX century, regarding for socio-economic development, resource exploitation and foreign influence and intervention. For this development the logistic curve was not used. The divergence in the results yielded by the two methods lay inside an interval of 10-40% and predominantly between 10–20%.

GDP/Capita is not accounted in nominal terms, but instead in PPP/Capita (Purchase Power Parity), allowing for a direct comparison on the same basis throughout the years. The data from [15] is already in PPP/Capita in 1990 Geary-Khamis dollars (international dollars of 1990), which is similar to US$1990. An update to take into account the inflation for US dollar from 1990 to 2012 was made to those figures to obtain current values (depreciation of US dollar during this 22 years period is about 76%, introducing an undesirable bias for the correct understanding of the real monetary value).

From the collected data an analysis is made for kWh/capita and kWh/GDP. These variables link economic progress and electricity consumption, and characterize the consumption pattern and electric efficiency of an economy (kWh/GDP). We compare the evolution of these variables as a function of GDP/Capita for different countries. The most important result is that inside a region the behaviour of the average country is very similar to the past behaviour of "leading countries" for the same GDP/Capita. "Leading countries" from now on will be referred as model countries. For example in Fig. 3 we can see China and India following the past behaviour of Japan.

The model countries for each region are presented in Fig. 4 and summarized in Table 1

2.2. GDP/Capita growth model

To forecast GDP/Capita for the period 2008-2100 we use the logistic function on historical data and assuming limits to GDP/Capita growth:

$$N = N_* \left[1 + \left(\frac{N_*}{N_0} - 1 \right) e^{-at} \right]^{-1} \tag{1}$$

Where N is GDP/Capita, N_* - carrying capacity (limit for year 2100), N_0 – initial value for N (year 1900), a – growth coefficient, t - time (years). We get approximations for parameters a and N_0 applying the finite difference method to the historical data of model countries, following with the least squares method [5]. The resulting equations are applied to obtain forecasts for these countries.

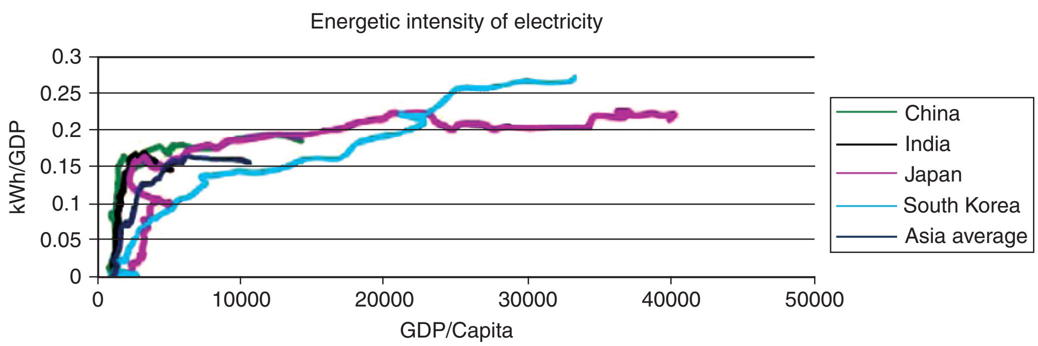

Figure 3: Comparison of electricity intensity for some Asian countries (GDP in US$2012).

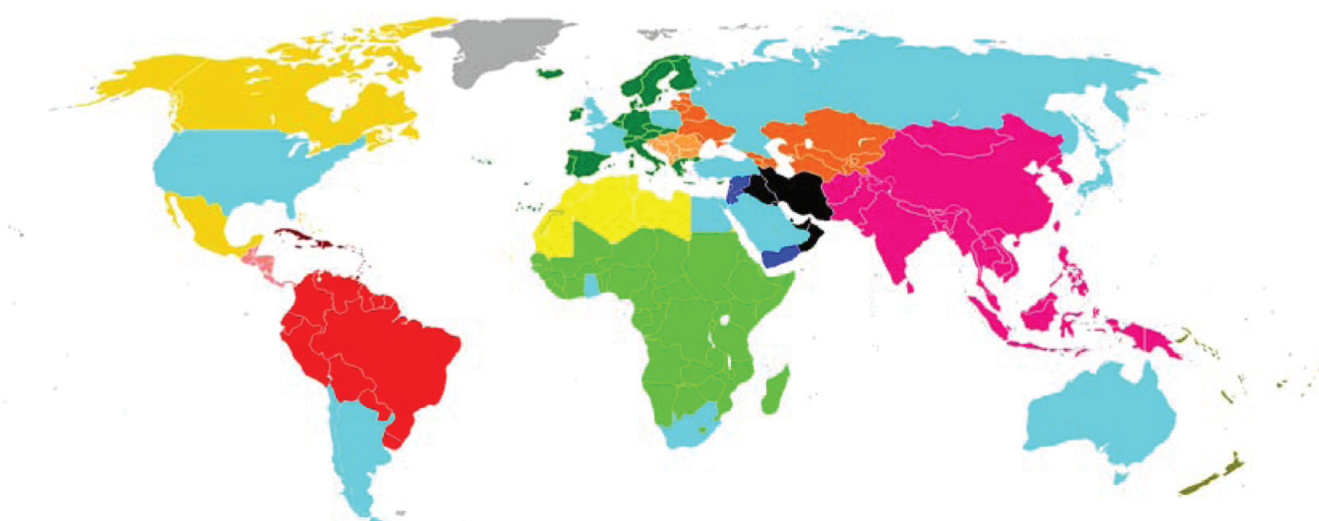

Figure 4: Model Countries Map (light blue).

Table 1: Model Countries for each sub-region.

Sub-Region	Model Countries
North America	United States of America
South & Central America	Argentina and Chile (average)
Western Europe	United Kingdom and France (average)
Eastern Europe	Poland
Eurasia	Russia
North Africa	Egypt
Sub-Saharan Africa	Ghana and South Africa (combination)
Middle East Oil exporter countries	Saudi Arabia
Middle East non-Oil exporter countries	Turkey
Asia	Japan
Pacific	Australia

The logistic function is chosen because 1) it describes well growth phenomena, e.g., technology diffusion applied to energy and power, and population growth with restrictions, 2) the observation of historical data for GDP/Capita, particularly for the most developed economies, strongly suggests the kind of behaviour modelled by that type of function, which is not surprising since GDP/Capita is a direct result of resources and technology diffusion intermingled with population growth.

2.3. Electricity production forecast for model countries

We obtain equations to forecast kWh/Capita as a function of GDP/Capita for each model country using historical data and adjusting for 2100 by the following procedure:

- Estimation of upper and lower foreseeable figures for GDP/Capita of the model countries, taking into account: today's GDP/Capita, historical evolution, economic structure, regional and worldwide commercial relationships, natural resources, technological capabilities, economy maturity.
- Computation of GDP/Capita up to 2100 using the logistic function.
- Estimation of target values for the variable kWh/GDP (US$2012) based on trends and variability in the historical data:

– Current Energy Mix Scenario: lower limit 0.20 and higher limit 0.25

– Electricity as Main Energy Source Scenario: lower limit 0.50 and higher limit 0.80

- Computation of kWh/Capita in 2100 with the forecast values of GDP/Capita and kWh/GDP in 2100 (multiplying kWh/GDP by GDP/Capita).
- Trend line fitting, selecting the type of curve that yields the best fit to the points from 1900 to 2008 (kWh/Capita vs. GDP/Capita). For "Current energy mix" scenario those are mostly of the polynomial type, from 3rd to 5th order, and some of the logarithmic type. For "Electricity as main source" scenario, the best fits are obtained through power curves, intersecting the graphic origin.
- Extraction of equations kWh/Capita = f(GDP/Capita) from curves to use as "behaviour laws" for the model countries.

2.4. Electricity production forecast for "followers"

We made a forecast for all countries considered in our study assuming the "followers" theory (for the other countries inside that region). For each non-model country the following methodology is used:

- Matching the values of GDP/Capita of the follower with the forecast for the model country for that region, typically somewhere between the years 1995–2008.
- All values of GDP/capita for the model country, after the matching, are considered as a forecast for the follower.
- All values of forecast that (if) surpass year 2100 are not accounted for.
- When the available forecast values are not enough to fill until 2100, the last value is used to fill all the remaining figures, to get a complete series until 2100 (this happens when the GDP/Capita in 2008 is already high and close to the model country).
- The equation kWh/Capita = f(GDP/Capita) of the respective model country is used to obtain a forecast for the evolution of kWh/GDP for the follower.

2.5. Forecasts for electricity production until 2100

Forecasts for kWh/Capita are made for each country in each region for the several scenarios considered, two main scenarios plus four sub scenarios: "Current Energy

Mix Scenario" containing an upper and lower GDP/Capita forecast each of them with two electricity intensity targets (0.20 and 0.25 kWh/GDP), yielding four sub scenarios. The same for the "Electricity as Main Energy Source Scenario", but in this case, electricity intensity targets are 0.50 and 0.80 kWh/GDP. To make forecasts for world total electricity production the population figures until 2100 are obtained from the United Nations for the 2011-2100 period [31], assuming the medium fertility scenario.

3. Results and discussion

3.1. Historical data review

The kWh/GDP (Fig. 5) consistently approaches the value of 0.20 kWh/GDP (US$2012) for the most developed economies, even in those situations when countries or regions had, in the past, already largely surpassed that value, but meanwhile took a convergent path. Exceptions are the countries whose economies rely mostly on oil or gas exports, or the ones possessing very immature economies, these countries display two extreme behaviours when observed in terms of the kWh/GDP indicator:

- Very low kWh/GDP figures (oil exporters).
- Very high kWh/GDP figures (immature economies).

That kind of divergences appear mostly for: Middle East Oil Exporters and Eastern Europe, Eurasia and Africa (both regions), respectively. The most extreme behaviour is shown by Bolivia and Mongolia (for Mongolia see Fig. 9) in contrast with the regions they belong to. Countries that are strongly dependent on hydroelectricity, particularly Norway, Sweden and Finland, also show high kWh/GDP electricity intensity values ranging between 0.50 and 0.80 kWh/GDP (US$2012).

Countries displaying extreme deviations are the ones whose economies, incomes and human development standards are near the opposite extremes of socio-economic development.

The highest intensities appear in generally low demand and very impoverished countries (immature economies), thus causing the observed anomaly. The opposite is observed for middle-high to very high income economies relying mainly on the extraction of very high prized mineral resources, most notably oil, yielding a very low figure for energy intensity caused by a major monetary influx and a relatively low demand for electricity because the GDP/Capita is extremely high, and the major electricity consumer sectors are small or inexistent, especially for general industries. That pattern progresses into a steeply rise as the "oil economies" mature and supports a growing consumption of electricity mostly for appliances in domestic and service sectors.

The kWh/Capita indicator (Fig. 6) generally evolves linearly with GDP/Capita for historical data, but expectancy is that in the future this indicator will be

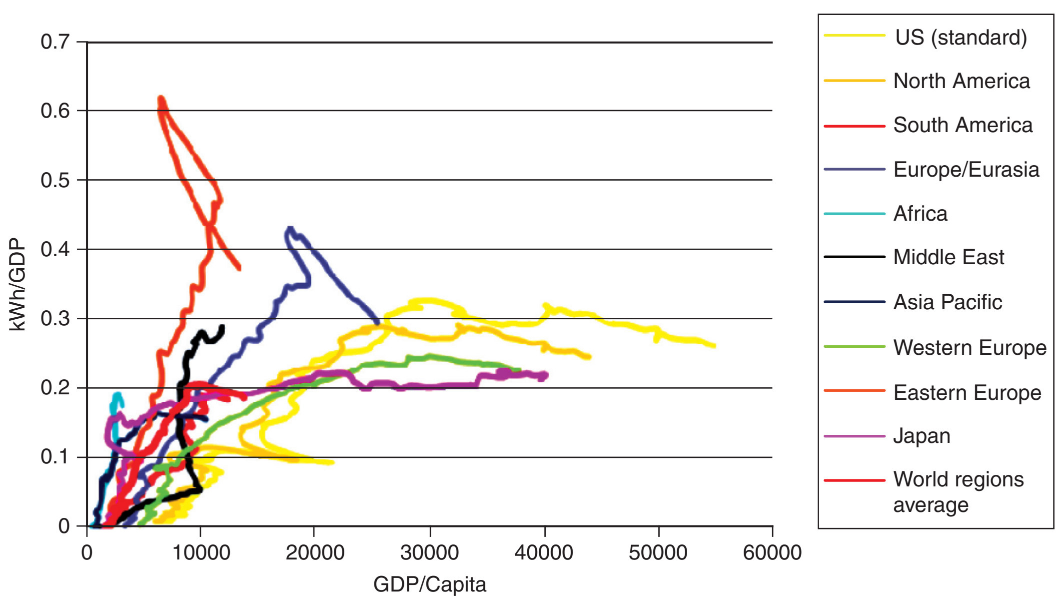

Figure 5: Regional Electricity Intensity from 1900 to 2008 (GDP in US$2012).

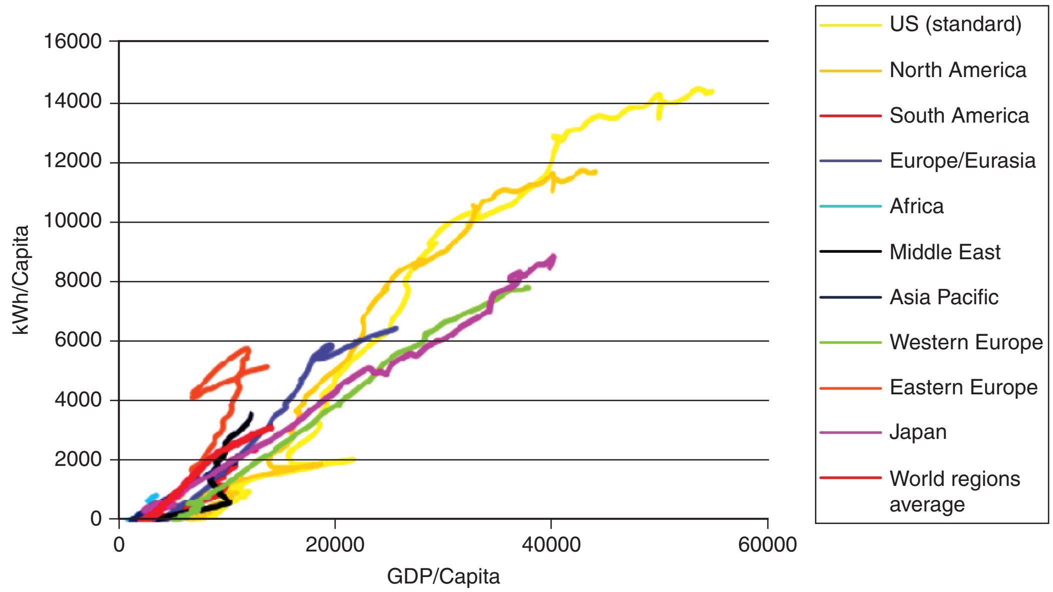

Figure 6: Regional Electricity consumption per capita from 1900 to 2008 (GDP in US$2012).

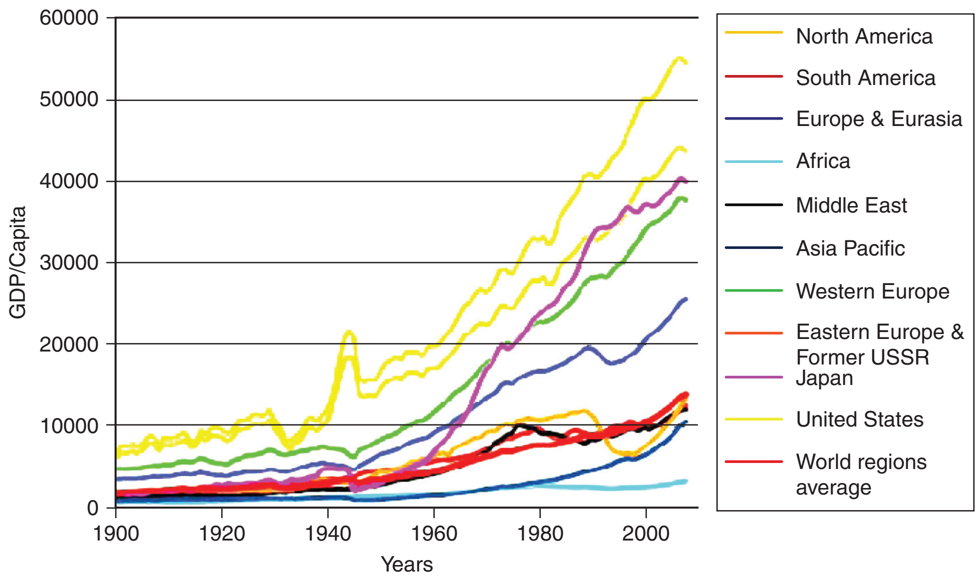

Figure 7: GDP/Capita from 1900–2008 (GDP in US$2012).

better described by the logistic curve as GDP/Capita grows. This kind of behaviour is already apparent for the United States of America where three stages of the electricity production can be identified (Fig. 8):

– Initial: Early deployment of technology, minor markets and infrastructure (US until 15.000$/Capita)
– Expansion: Fast technology adoption, heavy demand in short time (US until 30.000$/Capita)
– Maturity: Growth stabilization, widespread infrastructure, universal access.

Two particular trends characterize the behaviour of kWh/GDP and kWh/capita as a function of GDP/capita:

– Countries that belong to the same region/sub region follow similar evolution curves, usually not overlapping, but remaining near the average curve.

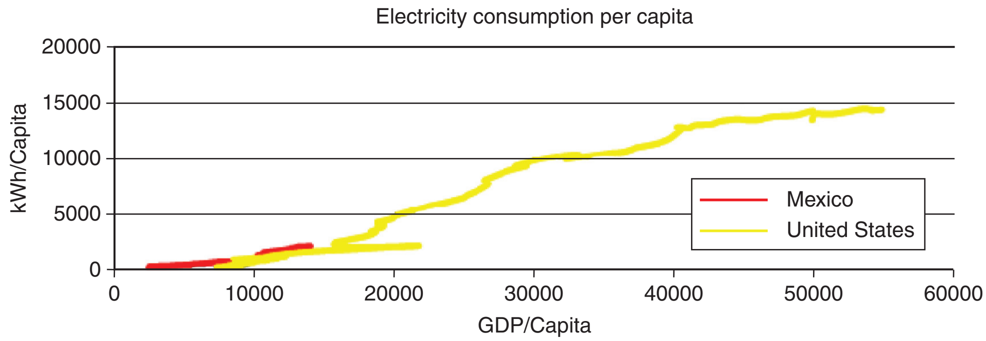

Figure 8: Evolution stages: United States (all) and Mexico (1st and early 2nd) – variation in US for 10-20 k$/Cap is due to the Great depression plus World War II (GDP in US$2012).

– One or two countries inside each region tend to lead the remaining ones, which follow the leaders, sometimes even overlapping the model country curves instead of just keeping near to the average curve (see Japan followed by China and then India in Fig. 9 and Fig. 10).

3.2. GDP/Capita growth model

To estimate GDP/Capita for model countries, we use the logistic function which has been successfully used for several growth forecasts. In this particular case, when the logistic function is applied without a predetermined upper limit, extreme divergence occurs, since the behaviour is heavily influenced by the historical evolution and so diverts markedly from the expected values, reaching stability (maturity) well above (or below) reasonable figures. To avoid this divergence we set the growth limits for 2100 (see Table 2 in next section), which is suggested in [5] for similar situations. Examples are shown in Fig. 11, Fig. 12, Fig. 13 and Fig. 14.

Forecasts for the model country that do not match with data of the country being studied are considered as a forecast for the latter. For example the Japanese forecast matches Chinese historical data at about 14.000$ (red stars in Fig. 15 and Fig. 16). So all figures for the Japanese forecast from 14.000$ onwards (both scenarios) are taken as a forecast for China starting in 2008.

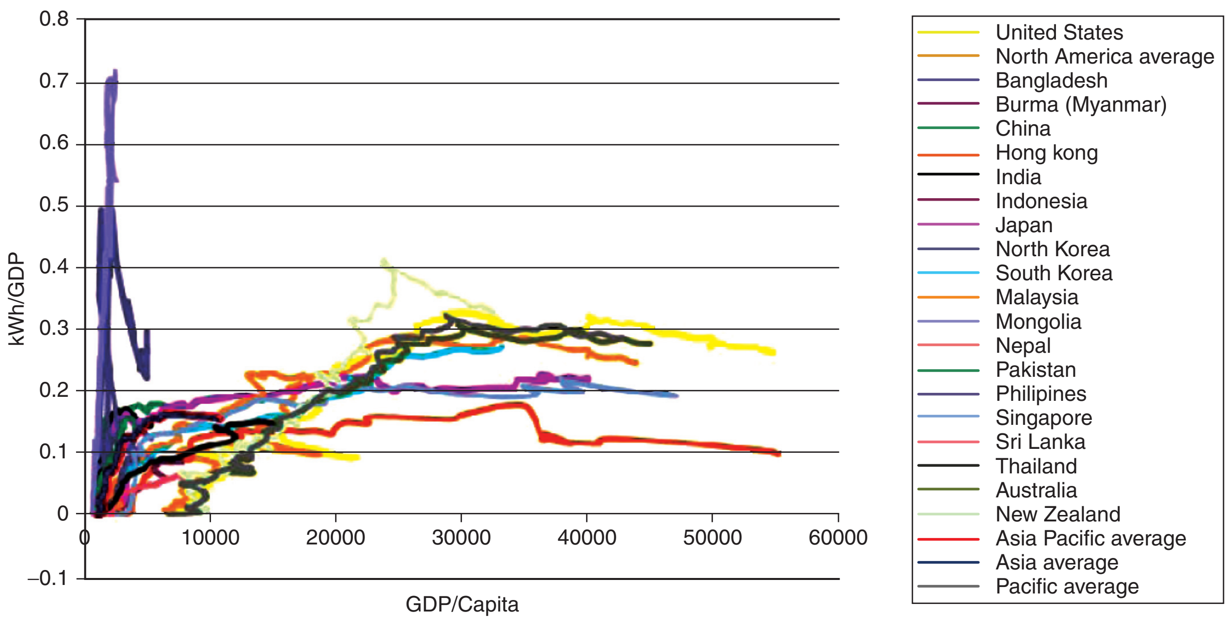

Figure 9: Asia-Pacific electric intensity in 1900–2008 (GDP in US$2012).

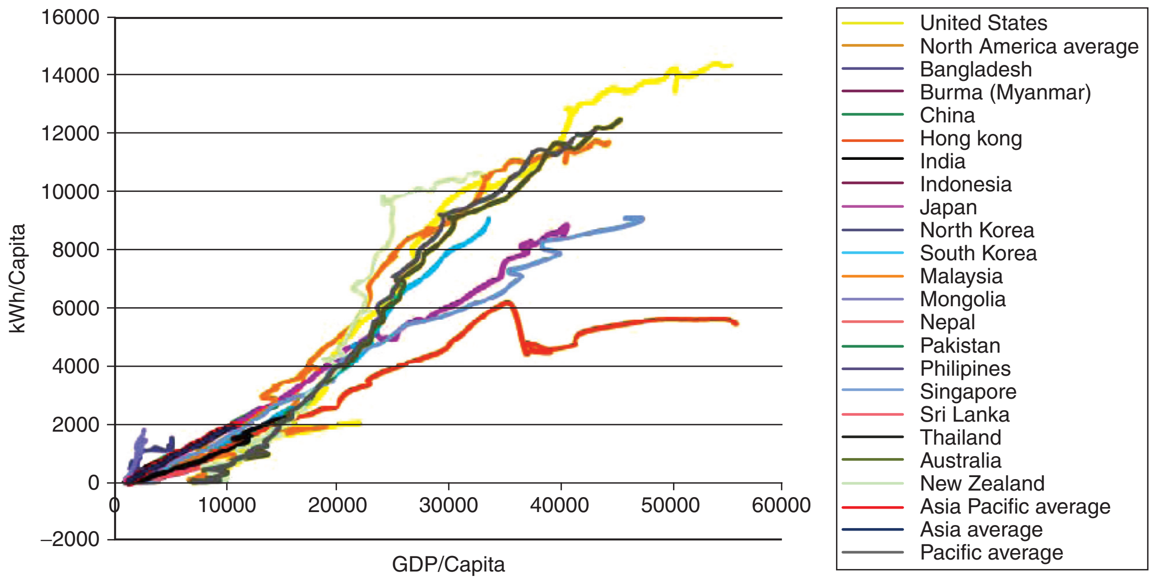

Figure 10: Asia-Pacific Electricity consumption per capita 1900–2008 (GDP in US$2012).

Table 2: GDP/Capita targets for 2100 – Growth sub-scenarios.

GDP/Capita target for 2100 (Current Energy Mix Scenario)		
Region	**Lower(US$2012 /Capita)**	**Upper (US$2012/ Capita)**
North America	50000	60000
South & Central America	30000	40000
Western Europe	40000	50000
Eastern Europe	40000	50000
Eurasia	30000	40000
North Africa	30000	40000
Sub-saharan Africa	20000	40000
Middle East Oil Exporter Countries	20000	40000
Middle East non-Oil Exporter Countries	30000	40000
Asia	50000	60000
Pacific	50000	60000

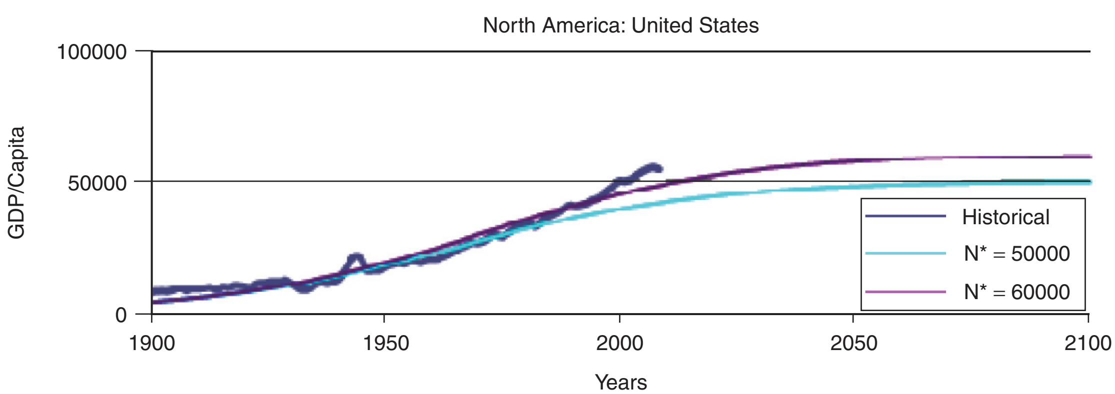

Figure 11: GDP/Capita historical data and forecast - Model Country for North America (GDP in US$2012).

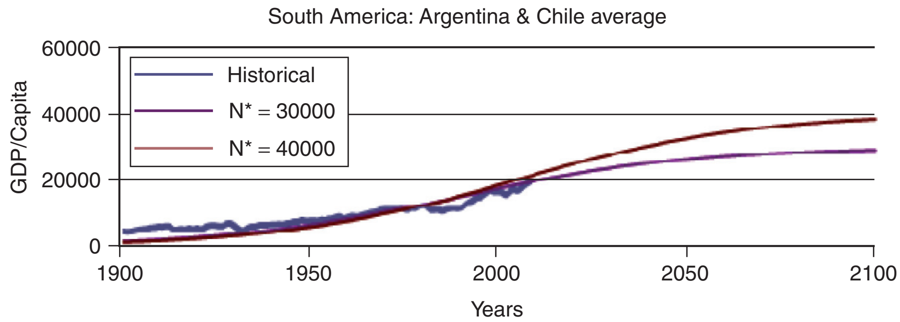

Figure 12: GDP/Capita historical data and forecast - Model Countries for S. Am. (GDP in US$2012).

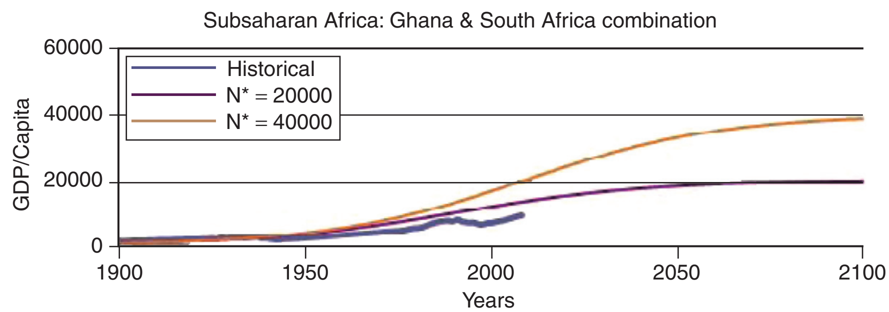

Figure 13: GDP/Capita historical data and forecast - Model Countries for Sub Saharan Africa (GDP in US$2012).

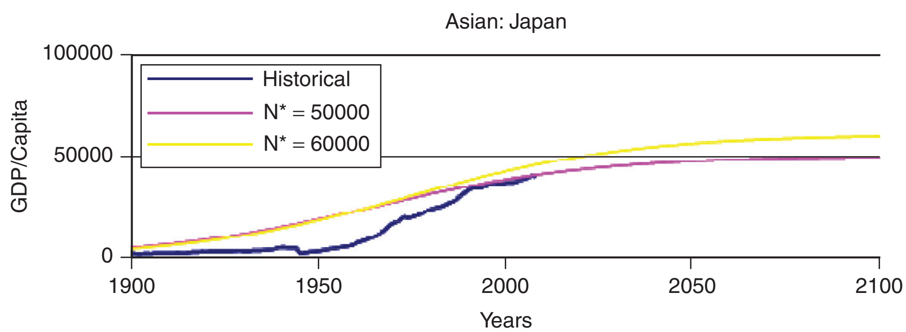

Figure 14: GDP/Capita historical data and forecast - Model Country for Asia (GDP in US$2012).

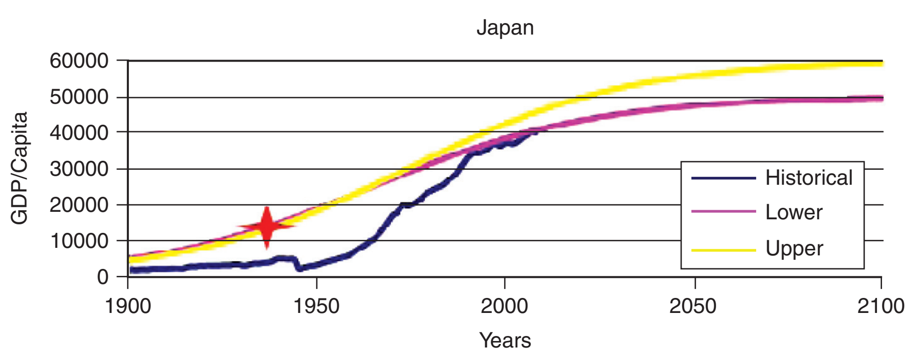

Figure 15: Japan GDP/Capita forecast (star indicates matching between China and Japan, GDP in US$2012).

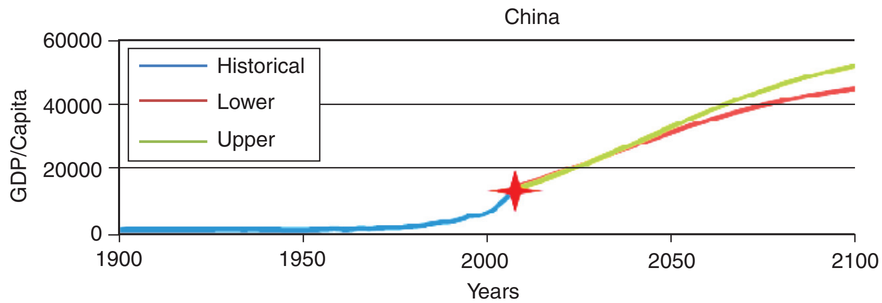

Figure 16: China GDP/Capita forecast (star indicates matching between China and Japan, GDP in US$2012).

These functions (curves) do not allow prediction of economic downturns (crisis) or prosperity outbursts, delivering figures only for medium evolution scenarios. Eventually these forecasts may be adapted to disruptive events by studying the variations introduced by similar historical events and developing functions to characterize and use for simulation on future hypothetical events. A forecast is then performed for the world as can be seen in Fig. 17 .

The assumption that logistic function applied to the evolution of economies was checked by extensive observation of the historical data for the studied countries (about 90), and particularly by a careful look at the most developed economies of each region (like US, Japan, UK, France), with the data widely supporting that assumption, and thus leading to the selection of some of those economies as model-countries.

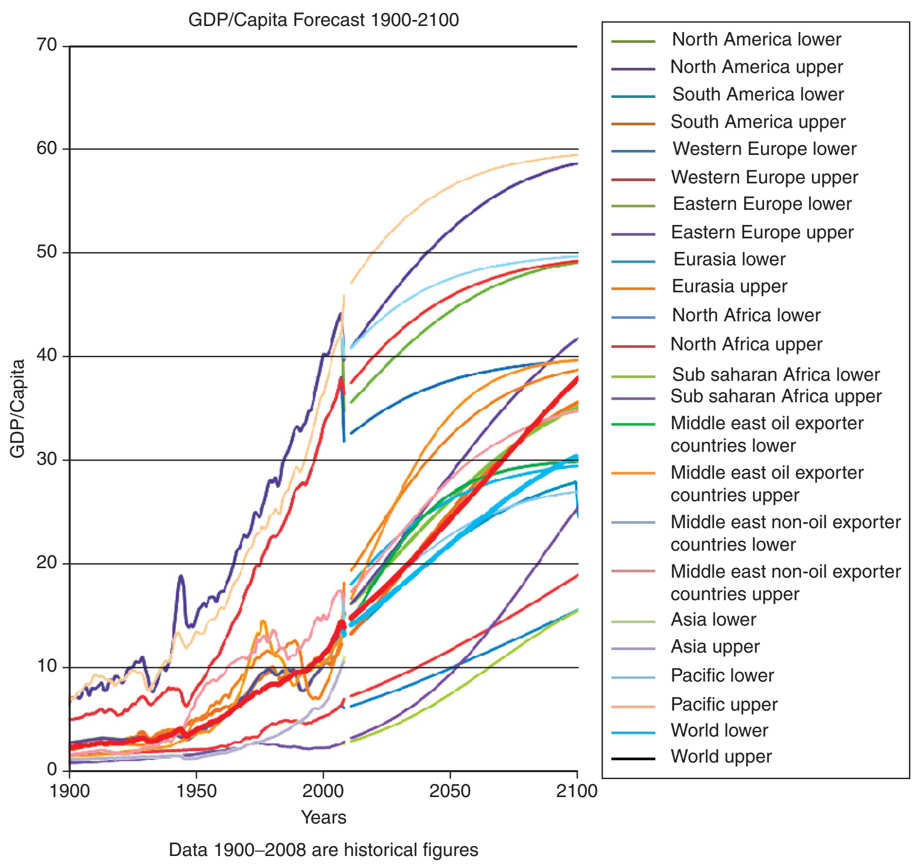

Figure 17: World GDP/Capita Forecast 1900–2100 (GDP in kUS$2012).

3.3. Electricity production forecast model

For "Current energy mix" scenario the limits that are assumed for economic growth (GDP/Capita) and thus for electricity consumption/production evolution (kWh/Capita) are presented in Table 2 and Table 3 below. Fig. 18 and Fig. 19 show the fitting curves used to obtain a "governing law" for the model. A "swarm" of points is created nearby the target regarding kWh/Capita to allow a reasonable curve fitting, then the trend line is drawn and the equation extracted. This equation is the model equation for the electricity production of the model country and is considered as the most reliable prediction curve due to the relative maturity of the electricity market in the model countries. The bottom line is for the lowest electricity intensity of 0.20 kWh/GDP, while the top line is for the highest intensity of 0.25 kWh/GDP. The irregular line behind the trend lines is the historical curve plus the targets at 2100 for the two electric intensities.

Table 3: kWh/Capita targets for 2100 – Energy intensity sub scenarios – two for each growth sub scenario.

Electricity per Capita Production target for 2100 (kWh/Capita)	**Current Energy Mix Scenario**			
	Lower GDP/ Capita		**Upper GDP/Capita**	
Energetic intensity (kWh/US$2012)	0.2	0.25	0.2	0.25
North America	10000	12500	12000	15000
South & Central America	6000	7500	8000	10000
Western Europe	8000	10000	10000	12500
Eastern Europe	8000	10000	10000	12500
Eurasia	6000	7500	8000	10000
North Africa	6000	7500	8000	10000
Sub-saharan Africa	4000	5000	8000	10000
Middle East Oil Exporter Countries	4000	5000	8000	10000
Middle East non-Oil Exp. Countries	6000	7500	8000	10000
Asia	8000	10000	10000	12500
Pacific	10000	12500	12000	15000

In Table 4 and Table 5 are the limits for "Electricity as main source" scenario.

Fig. 20 and Fig. 21 show the procedure as applied above for the "Current Energy Mix" scenario, but now the targets for 2100 are set using electricity intensities of 0.50 and 0.80 kWh/GDP.

Results for the electricity production forecast are shown in Fig. 23 and Fig. 24. We compare these forecasts with those made by EIA (Energy Information Administration/Dep. of Energy) for 2011-2035 period [23], [24]. Forecasts made within the "Current energy mix" scenario match quite well with those made by EIA. For the years 1900-2008, the comparison between historical data and model results shows that model results are significantly above the real figures (in percentage), especially between 1900 and 1950 (not surprisingly). Those were the years in which electricity as a practical technology saw diffusion and became a widespread and fundamental asset for society, representing an era of profound transition in the energy sector with all associated problems and setbacks.

A further comparison with forecasts for 2050 from IEA (International Energy Agency/OECD) [28]

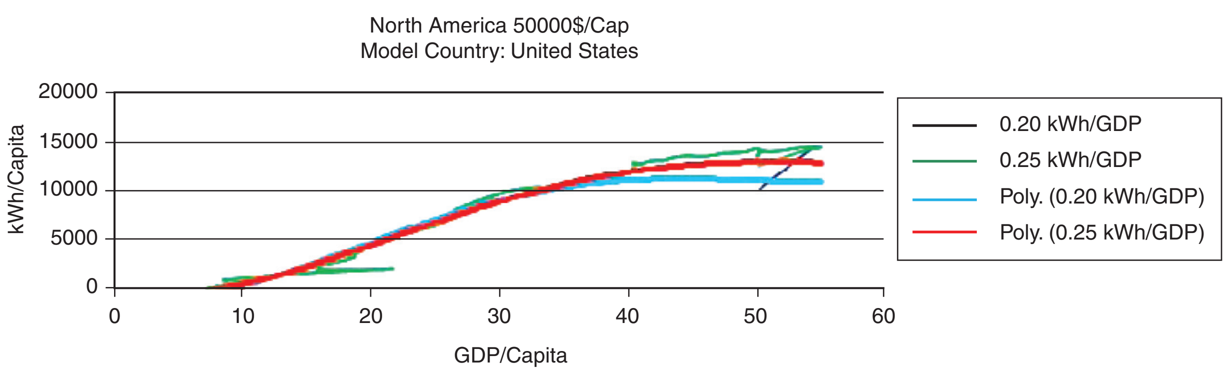

Figure 18: Electricity production historical data and forecast - Model Country for N. Am. (GDP in kUS$2012).

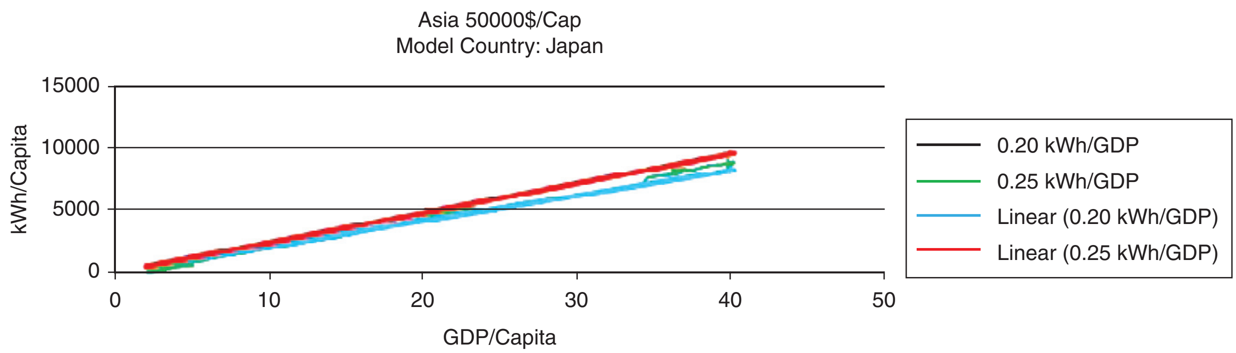

Figure 19: Electricity production historical data and forecast - Model Country for Asia (GDP in kUS$2012).

Table 4: Economic growth (GDP/Capita) target for 2100 – Growth sub scenarios.

GDP/Capita target for 2100 (Electricity as Main Source Scenario)		
Region	**Lower (US$2012/ Capita)**	**Upper (US$2012/ Capita)**
North America	55000	60000
South & Central America	30000	40000
Western Europe	45000	50000
Eastern Europe	40000	50000
Eurasia	30000	40000
North Africa	30000	40000
Sub-saharan Africa	20000	40000
Middle East Oil Exporter Countries	20000	40000
Middle East non-Oil Exporter Countries	30000	40000
Asia	45000	50000
Pacific	55000	60000

Table 5: Electricity production target for 2100 – two energy intensity sub scenarios.

Electricity per Capita Production target for 2100 (kWh/Capita)	**Electricity as Main Source Scenario**			
	Lower GDP/Capita		**Upper GDP/Capita**	
Energetic intensity (kWh/US$2012)	0.5	0.8	0.5	0.8
North America	27500	44000	30000	48000
South & Central America	15000	24000	20000	32000
Western Europe	22500	36000	25000	40000
Eastern Europe	20000	32000	25000	40000
Eurasia	15000	24000	20000	32000
North Africa	15000	24000	20000	32000
Sub-saharan Africa	10000	16000	20000	32000
Middle East Oil Exporter Countries	10000	16000	20000	32000
Middle East non-Oil Exporter Countries	15000	24000	20000	32000
Asia	22500	36000	25000	40000
Pacific	27500	44000	30000	48000

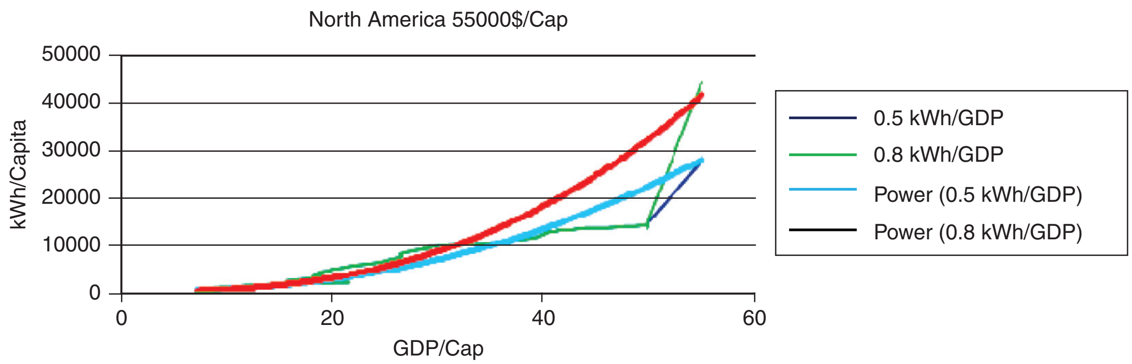

Figure 20: Electricity production historical data and forecast - Model Country for N. Am. (GDP in kUS$2012).

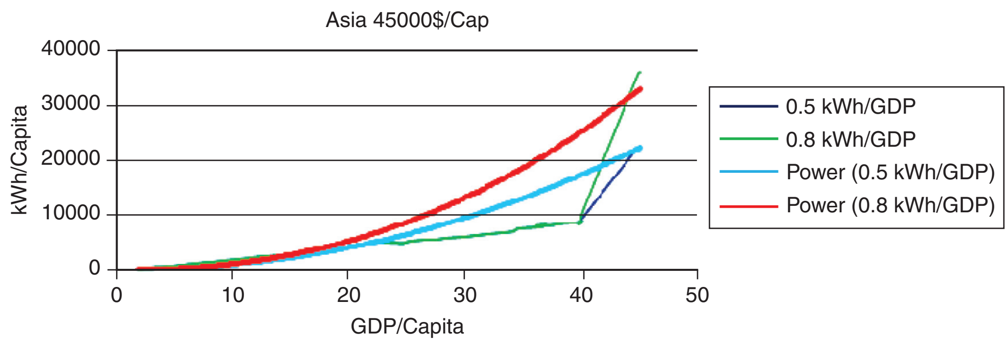

Figure 21: Electricity production historical data and forecast - Model Country for Asia (GDP in kUS$2012).

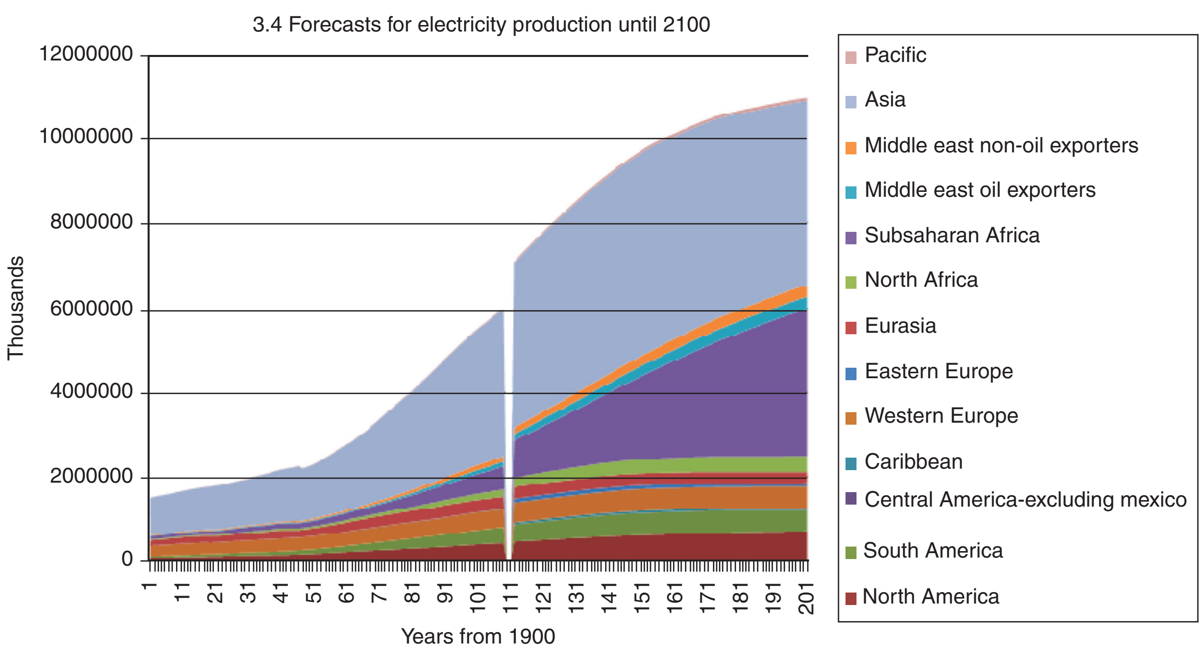

Figure 22: World Population 1900–2008 for studied countries: 6010 million (world total population of 6688 million). UN Forecast 2011–2100 [27], starting in 7083,6 million.

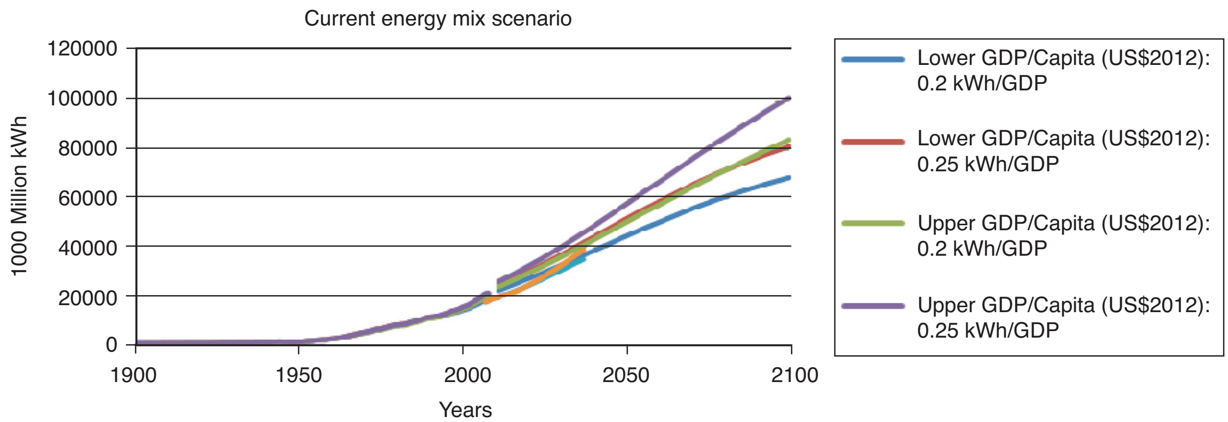

Figure 23: World Electricity Production Forecast 1900–2100.

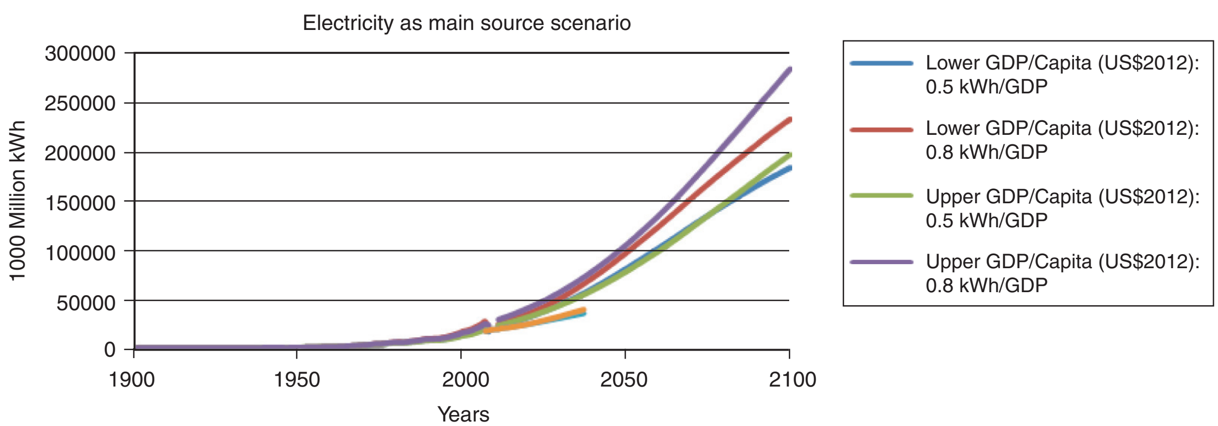

Figure 24: World Electricity Production Forecast 1900–2100.

continues to yield a good match with IEA's baseline scenario forecasting 47.000 million kWh and Current Energy Mix Scenario yielding between 45.000 million kWh (0.2 kWh/GDP) and 52.000 million kWh (0.25 kWh/GDP).

In the "Electricity as main source" scenario, forecasts from the model necessarily move away from the EIA forecasts, and when comparing with historical data, divergence is more significant than in "Current Energy Mix" Scenario. This is because this scenario is a good description of countries with cheap and abundant electricity like the countries with a heavy contribution from hydroelectricity. This scenario moves away sharply from the EIA High Oil price scenario. That is not surprising, because EIA's High Oil Price scenario still relies heavily on an energy infrastructure that is very similar to the current one, probably with some increasing of renewable electricity, but mostly by resorting to fossil electricity (coal and gas) due to the existence of abundant reserves of relatively cheap fuels able to supply today's electrical thermal power plants, most of which will likely remain commissioned until 2035 and even beyond.

4. Conclusions

In this paper, we present the stylized facts that characterize the trends in electric intensity measured as kWh/GDP and kWh/capita. These stylized facts were obtained analysing data from 1900 to 2008 on electricity consumption for several countries in the world comprising currently 90% of the world population. These facts are:

1. For the most developed economies, the kWh/GDP consistently approaches 0.20 kWh/GDP (US$2012); even for countries or regions that, in the past, had already largely surpassed that value, but meanwhile took a convergent path.
2. Countries strongly dependent on hydroelectricity, particularly Norway, Sweden and Finland, show high kWh/GDP electricity intensity values ranging between 0.50 and 0.80 kWh/GDP (US$2012).
3. Oil exporters typically have very low kWh/GDP.
4. Immature economies typically present very high kWh/GDP.
5. The kWh/Capita indicator generally evolves linearly with GDP/Capita.
6. Inside a region the behaviour of countries regarding kWh/GDP and kWh/capita is very similar for the same GDP/Capita. Countries in the same region follow the past behaviour of the "leading country".

The targets (stylized facts 1 and 2) were set based on the historical records. Data shows that 0.20 kWh/US$2012 was the minimum target value attained. It is not probable that a lower target value will be attained in the future because increases in efficiency have rebound effects and the number of electronic appliances is increasing; both effects lead to higher consumption. Also, the record for countries like Japan, with a long time history of energy scarcity and high prices, show that for electric energy intensity a plateau of 0.20 kWh/GDP was reached by 1964 at approximately 10.000 US$2012 GDP/Capita and remained quite stable ever since, despite the spikes of energy costs during late 70's, early 80's and from 2005 onwards.

The kWh/Capita indicator (stylized fact 5) will probably be better described by the logistic curve as GDP/capita grows that is already apparent for the United States of America where the initial, expansion and maturity stages of the electricity production can be identified.

Stylized fact 6 assumes that regions are led by one or two model-countries that set the example for the remaining countries of that region, in the fields of economic development, politics and foreign policy (diplomacy and commerce). The model countries lead regional economies. The economic consequence is a more even distribution of wealth between regions/countries, but which may, or may not, reach the whole population, leading to a change in lifestyles, education and consumption patterns, resulting in some attenuation of GDP/Capita and life quality disparities between different countries of the same region.

These stylized facts are used to develop the "Current Energy Mix" and "Electricity as main source" scenarios. For both cases we considered sub-scenarios with a low and a high GDP/capita in 2100. The evolution of GDP/capita is modelled using the logistic equation parameterized using historical data for the model countries. Population figures until 2100 are obtained from the United Nations for the 2011-2100 period [31], assuming the medium fertility scenario.

Forecasts up to 2100 yield an electricity production 3.5 to 5 times higher than the current production for the "Current Energy Mix Scenario" and about 9 to 14 times for the "Electricity as Main Energy Source Scenario". Forecasts for the "Current Energy Mix Scenario" match well with forecasts from IEA/EIA (International Energy Agency/ Energy Information Administration) while the forecasts for the "Electricity as the Main Energy Source Scenario" are much higher than current predictions suggesting that this scenario is not being taken into account by the Energy Agencies.

These forecasts are made assuming an average behaviour and a quite steady economic and geopolitical environment throughout the XXI century, without taking into account possible major disruptions, like those caused by severe energy shortages, financial meltdowns or large and widespread armed conflicts with commercial supply chain failures. The importance of such non-predictable events can be observed in the behaviour of kWh/capita, kWh/GDP and GDP/Capita data where it is possible to differentiate the effects caused by some of the disruptive events that occurred throughout the XX century, particularly: the Great Depression (1929), the Second World War (1939-45), the strong economic growth (1950-1972) and the fall of Soviet Union (1991-2000).

One of the underlying assumptions in our approach to model electricity consumption is that electricity consumption is a consequence of economic growth for all stages, so the causality is mainly uni-directional and the direction is from economic growth to consumption. At the initial stage the economy is very weak, supporting only a limited electricity market which supplies a small fraction of the general population and also some particular economy sectors such as mining industries and public sector services and infrastructure. Any additional increase in consumption is very dependent on further economic growth. At the expansion stage, the economic progress allows for the creation of an infrastructure and the development of skilled manpower. These conditions precede the installation of a more sophisticated manufacturing sector that then supports a network of service providers increasing the consumption of electricity and contributing to further employment, so increasing the income of the work force. At this stage, wages are not enough to support a large consumption of residential electricity, thus industrial consumption is dominant. At the maturity stage, the industrial electricity consumption is less pronounced than before and meanwhile commercial, and particularly, residential consumption develops significantly. Any reduction in consumption only occurs due to economic restrictions because it implies a loss of comfort for the individual consumer.

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