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Assessing residual hydropower potential of the La Plata Basin accounting for future user demands

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Abstract

La Plata Basin is shared by five countries (Argentina, Bolivia, Brazil, Paraguay and Uruguay), which are having fast growing economies in South America. These countries need energy for their sustainable development; hence hydropower can play a very important role as a renewable clean source of energy. This paper presents an analysis of the current hydropower production and electricity demand in La Plata Basin (LPB) and makes an analysis of the maximum and residual hydropower potential of the basin for a horizon of 30 yr (i.e. year 2040). Current hydropower production is estimated based on historic available data while future energy production is deduced from the maximum available water in the catchment, whereas electricity demand is assessed by correlating existing electricity demand with the estimated population growth and economic development. The maximum and residual hydropower potential of the basin, were assessed for the mean annual flows of the present hydrological regime (1970–2000) and topographical characteristics of the area.

Computations were performed using an integrated GIS environment called Vapidro-Aste released by the Research on Energy System (Italy). The residual hydropower potential of the basin is computed considering that first the water supply needs for population, industry and agriculture are served and than hydropower energy is produced. The calculated hydropower production is found to be approximately half of the estimated electricity demand, which shows that there is a need to look for other sources of energy in the future.

1 Introduction

Energy produced by hydropower has several advantages over fossil fuels (coal, petroleum, natural gas) and nuclear power (uranium): it is renewable; it has low impact on the environment; it reduces the green house emissions; it implies relatively low maintenance; it is reliable in terms of technology and it is proven over time.

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Hydropower plays a vital role in more than 150 countries over the globe; according to the statistics of the International Journal on Hydropower and Dams, hydropower contributes to at least 90 % of the electricity production in 23 countries and to at least 50 % in 63 countries (IHA/IEA/CHA, 2000). The world's gross theoretical hydropower potential is about 40 000 TWh, of which 14 000 TWh could be used as the technical feasible hydropower potential. At present 7000 TWh are used as economically feasible hydropower potential. Most of the unexploited economically feasible hydropower potential lays in emerging countries or countries in transition (Yuksel, 2010). Even though the contribution of hydropower to the socio-economic development process could be valuable, it is still low when compared with the contribution of overall energy mix of the world. This is estimated as low as 6.15 % of the total energy mix of the world (Dudhani et al., 2006). It is expected that the remaining hydropower potential of the world would not supply the total future electricity demand, but it is needed to harness the remaining hydropower potential to meet the increasing electricity demand as a clean renewable source of energy (Dudhani et al., 2006).

Nowadays, worldwide, many studies are carried out to identify the hydropower potential and to promote hydropower projects in large and small scale basins. Kosnik (2008, 2010) studied the potential for small scale hydropower to contribute to United States of America (USA) renewable energy supplies, and identified several thousands of viable sites for the hydropower production throughout the USA and showed that cost effectiveness is an important factor in developing these sites. It was revealed that the average cost for developing small scale hydropower sites is relatively high; however there are hundreds of sites which can be implemented at the lower side of the cost scale.

Supriyasilp et al. (2009) studied the use of multi-criteria decision making (MCDM) to determine the priority of hydropower projects, over 100 KW, in the Ping River Basin in Thailand. Their assessment of the advantages and disadvantages of 64 projects was based on five criteria: electric generation, engineering and economics, socio-economics, environment, and stake holder involvement. The weights for the criteria

were given by two groups of experts who identified the environment as the most important aspect among the five criteria, followed by socio economics, electricity generation, engineering and economics and stake holder involvement. This study also shows the importance of including non-technical aspects when ranking priorities for the selection of sites for hydropower development.

Ohunakin et al. (2011) evaluated hydropower development with respect to the established policies and energy power sector reform in Nigeria. Authors highlighted the urgency for incorporation of subsidies, feed-in-tariffs, and framework for Price Purchase Agreements (PPA) into the small scale hydropower agreements in order to promote the small hydropower projects and to attract local and foreign investors.

China has the highest gross amount of water resources, and by the end of 2010 reached 852 million kW by 2010, due to the need to supply the increasing energy demand and to minimize the environmental pollution to achieve the sustainable development (Chang et al., 2010).

The study of the current role of the hydropower production, remaining potential and some development plans related to hydropower in various parts of the world reveals that South America is one of the regions which has vast unexploited hydropower potential and there will be major hydropower developments, in the future, in countries such as Brazil (28 600 MW), Bolivia (700 MW), Paraguay and Argentina (200 MW) (Qurios, 2002; Clarke, 2007).

Modern techniques such as Geographic Information System (GIS) and Remote sensing (RS) are widely used nowadays for the assessment of hydropower potential (Conolly et al., 2010). The main reasons for the use of GIS and RS are the freely availability of some GIS software and Digital Elevation Models (DEM), easy extraction of data such as river networks, topographic information, land use, etc, and presentation of outputs in graphical format which can be understood nowadays also by non experts (Gichamo et al., 2012; Hartanto et al., 2011).

Such modern techniques were applied for example in Bangladesh and reported by Mondal and Denich (2010) in their assessment of the potential of different renewable

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sources (solar, hydro, wind power). Dudhani et al. (2006) proposed a method to identify probable sites for small scale hydropower generation in mountain areas of India, based on the use of remote sensing data. The algorithm was developed in Visual Basic platform for the identification and assessment of water resources in plain and mountain areas and was applied for the IRS-ID, LISS III Geo-coded False Color Composite satellite images.

Alterach et al. (2008a,b) developed a GIS integrated tool, the Vapidro-Aste which can be used to determine the hydropower potential maps for Italy for nearly 1500 inter connected sub basins at national scale with known hydrological and physiographic characteristics.

Hydropower generation is not new to LPB. There are more than 30 large hydropower plants, such as: Itaipu (12 600 MW), Ilha Solteira (3444 MW), Salto Santiago (2000 MW), Itumbiara (2200 MW), Sao Simao (1710 MW), Porto Primavera (1814 MW), Ita (1450 MW), Jupia (1411 MW) etc., which provide most of the hydroelectricity for the region. Some of the large hydropower plants such as Itaipu (12 600 MW, Brazil and Paraguay), Salto Grande (1890 MW, Argentina and Uruguay) and Yacyreta (3100 MW, Argentina and Paraguay) were built on bilateral agreements between countries to share the power production (WWAP, 2007).

The countries in the LPB are highly depended on hydroelectricity (Barros et al., 2008): 76 % of the total installed capacity of power in the countries of LPB, in the year 2000, was provided by hydropower. LPB is endowed with 28 % of world's water resources. This, along with its topographical distribution, contributes to the high hydropower potential that can be utilized for the increasing electricity demand due to growth of population and economic development of the five LPB countries.

However, the present hydropower production is exposed to stream flow variations due to climatic variability in the region. In addition to climatic variability, hydropower production has been limited by potential water withdrawals operated by different users such as agricultural, municipal and industrial sectors. The amount of water withdrawals are increasing with the growing population, urbanization, some factors associated with

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land use changes and changes of cropping pattern, agricultural, industrial and infrastructure development (OSA, 2005).

The Water Assessment Program of the United Nation (WWAP, 2007) favours the development of both renewable (hydropower) and non renewable (petroleum) sources to achieve the goals and strategies for future energy demand. However, it highlights the importance of development of hydropower in LPB as the limited resource availability of non renewable sources.

The Organization of American States (OSA, 2005) has identified that LPB has high hydropower potential due to basin characteristics and discharges. To exploit the remaining hydro potential of the basin, it is necessary to carry out a proper assessment of remaining potential. The advent of modern computation tools, such as geographical information system (GIS), remote sensing and hydrological models, can support us in the first accurate estimation of hydropower potential (Gichamo et al., 2012).

This paper presents an analysis of the current hydropower production and electricity demand in La Plata Basin (LPB) and makes an analysis of the maximum and residual hydropower potential of the basin for a 30 yr horizon (i.e. year 2040). Current hydropower production is estimated based on historic available data while future energy production is deduced from the maximum available water in the catchment, whereas electricity demand is assessed by correlating existing electricity demand with the estimated population growth and economic development. The maximum and residual hydropower potential of the basin, are assessed for the mean annual flows of the present hydrological regime (1970–2000) and topographical characteristics of the area.

2 Theoretical considerations on the assessment of the hydropower potential

Hydropower is an important source of energy, especially in the countries of South American continent, where water available for hydropower production is abundant. Assessment of the hydropower potential, especially of the residual one, is an important tool for a proper plan of the energy use. This study assessed the potential hydropower

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energy production in La Plata Basin, in order to determine the residual hydropower potential in the basin.

In order to assess the potential hydropower an analysis of the past hydrological regime in the catchment, for the last 70 yr, was made. Based on the hydrological regime in the catchment and on the physical characteristics of it, the potential hydropower of the basin was assessed by means of the GIS based tools Vapidro-Aste. Finally, future energy demand in the basin was estimated by regression analysis on the historical data.

VAPIDRO-ASTE is a GIS integrated numerical tool (the software is developed in Visual Basin language and integrated with ARCGIS9) that allows the evaluation of the residual potential hydropower energy and all possible alternatives concerning the sites for hydroelectric plants along the drainage network, taking into account the relationship between the full costs of the hydropower and the benefits from selling the generated power in the national market. The tool takes into account the current water resources exploitation with its geographical location and elevation (with respect to irrigation uses, drinkable water, existing hydropower plants, etc.) and the limitation that this creates regarding the potentiality for energy production. Based upon a user friendly graphical interface the tool is able to split the river into hundreds of cross sections and to calculate the available discharges and potential hydropower production, considering constraints like minimum flow, withdrawals and restitutions scheme.

A brief overview of the equations applied to compute maximum potential and residual hydropower is outlined here, for a comprehensive description of the methods applied by VAPIDRO-ASTE to compute maximum potential and residual hydropower the reader is invited to check Alterach et al. (2008).

The maximum potential hydropower establishes the theoretical top of energy that the study basin can produce assuming that all water resources are used to produce energy, which in real life application does not occur, because of environmental flows, other water uses and economic cost/benefit analysis.

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The potential hydropower in a given point of the river basin, with respect to the basin outlet section, has been computed with the following equation:

$$E_{\text{own_max}_i} = \text{Conv} \cdot g \cdot \eta \cdot (A_i \cdot \rho_i \cdot cd_i)(H_i - H_{\text{closure}}) = \text{Conv} \cdot g \cdot \eta \cdot Q_i \cdot (H_i - H_{\text{closure}}) \quad (1)$$

5 where: Conv is an adimensional conversion factor, to calculate energy in GWh (Conv = 0.00876); g is the gravity constant; η is the overall electrical efficiency, which depends on kind of turbine, generator, transformers and/or electrical transmission, water conductors, etc; Q_i is the basin discharge; H_i is the elevation of the given elementary area i ; and H_{closure} is the elevation at closure point.

10 Thus, the potential of the entire watershed is given as the sum of the contributions of the N elementary areas that create the river basin itself:

$$E_{\text{own_max}} = \text{Conv} \cdot g \cdot \eta \cdot \sum_i^N [(A_i \cdot \rho_i \cdot cd_i)(H_i - H_{\text{closure}})] \quad (2)$$

15 If the river basin is seen as a physical entity, as a first approximation, it can be assumed that each basin has a unique constant precipitation (ρ) and runoff coefficient (cd), uniformly distributed in the elementary areas. This means then that $\rho_i = \rho = \text{constant}$ and $cd_i = cd = \text{constant}$.

The above Eq. (2) can then be expressed, in terms of mean watershed elevation, as:

20
$$E_{\text{own_max}} = \text{Conv} \cdot g \cdot \eta \cdot Q \cdot (H_i - H_{\text{closure}}) \quad (3)$$

The residual annual potential hydropower related to a given watershed ($E_{\text{own_res}}$), without considering upstream flow contributions, can be calculated, accounting for the Minimum Instream Flow ($E_{\text{own_mif}}$) and the actual withdrawals (E_{prel}), as follows:

$$E_{\text{own_res}} = E_{\text{own_mif}} - E_{\text{prel}} \quad (4)$$

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where:

$$E_{\text{own_mif}} = \text{Conv} \times g \times \eta \times (Q - \text{MIF}_{\text{aff}}) \times (H_{\text{mean}} - H_{\text{closure}}) \quad (5)$$

$$E_{\text{prel}} = \text{Conv} \times g \times \eta \times \sum_j^n [q_j \times (h_j - H_{\text{closure}})] \quad (6)$$

5 where MIF_{aff} is the Minimum Instream Flow computed as 10% of the Q; and q_j represents the mean annual withdrawals from the given watershed (+ positive) or the restored flows to the given watershed (– negative) in a particular point “j” and h_j is the elevation over sea level of the “j” sections where the flows are taken or restored.

3 Study area, data collection and analysis

10 3.1 Study area

La Plata Basin (LPB) is the second largest river basin in South America and the fifth largest in the world with a drainage area over 3.1 million km². Five countries – Argentina, Uruguay, Paraguay, Brazil and Bolivia – develop their daily activities within the basin borders (Fig. 1). It has been estimated by Barros et al., (2008) that almost 70% of the total Gross Domestic Product (GDP) of Argentina, Paraguay, Uruguay, Brazil and Bolivia is produced within the basin.

LPB has three main sub basins: Parana, Paraguay and Uruguay basins. The Parana basin is the largest of the three sub basins, in terms of drainage area, and constitutes 48.7% of the overall area of the basin followed by Paraguay and Uruguay with 35.3% and 11.8%, respectively. The Parana River flows 4000 km from its source in Precambrian Brazilian Shield to its mouth in the Pampa Plain, the Paraguay River extends 2670 km southward from its sources in the western hills of the Brazilian shield to its confluence with the Parana River and the Uruguay River flows 1800 km from its source from the Southern Brazil up to the Plata River. The third World Water Assessment

Program of United Nation – WWAP – (WWAP-UNESCO, 2007) estimated that the population living in La Plata basin was over 100 million inhabitants in the early 2000 (WWAP-UNESCO, 2009). This represents more than 50 % of the total population of the five countries sharing.

3.2 Data collection and analysis

In order to determine the maximum and residual potential of the LPB basin, different types of data were considered, such as hydrological data, population and population growth, land use practices, based on nowadays land use and predicted growth of population and economic industrial growth of the region. We do acknowledge that land use and economic growth might not be exactly as we have estimated it, however the method of estimating them based on population growth is the most logical to be used, in case that no other methods are in place to make such estimations.

Natural stream water availability in the LPB basin was determined from stream flow time series data of 38 gauging stations, located throughout the LPB. Daily mean discharge, for a span of 80 yr (1930–2010), was available for analysis (Fig. 2). Standard deviation and Tukey’s boxplot methods were used to check and filter the outliers in the data. Three homogeneity tests (i.e. Buishand Range, Pettitt and Standard Normal Homogeneity) were used as well to test further the homogeneity of data. After the elimination of the outliers in the data, all three homogeneity tests consistently showed that there is a split of stream flow time series, around the year 1970 in most of the stream flow series in LPB (Fig. 3). It is clearly seen that the mean annual flow, of the years prior to 1970, is higher than the mean annual flow of the time series after 1970s (Fig. 4). The explanation for this change in the hydrological regime of the catchment is due to the variation of land use pattern and deforestation after 1950s in LPB (Scheel et al., 2011; Mondal and Denich, 2010; Bartle, 2002; Collichsonn et al., 2001).

Results of homogeneity test, for the stream flow data of a gauge station in the catchment (at the S Osorio ONS gauge station), for the standard homogeneity test is shown

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in Fig. 4. Figure 5 shows the mean annual averages of the two considered interval of time series, 1930–1970 and 1971 and 2010, for the 38 gauging locations in LPB.

This analysis pointed out that only the last 40 yr of data should be used for the study and for prediction of the potential hydropower availability in the basin.

5 Population data in the LPB was gathered from the published census of the LPB countries (ISA, 2010; INDEC, 2011), as well as data for the GDP (FAOSTAT, 2011). Data on land use, in year 2010, was downloaded from the <http://www.fao.org> (FAOSTAT, 2011).

4 Assessment of LPB maximum and residual potential hydropower

10 As mentioned above, the hydropower potential for the nowadays LPB situation was done using the Vapido-Aste tool for today's available data, while the estimation for the year 2040, was done after all water uses were extracted from the available water. This paragraph presents how the water uses for the year 2040 were estimated, and the estimation of hydropower for 2010 and 2040.

15 The main water users in a basin, in general are agricultural, municipal and/or industrial. Growth in water usage for these three categories is driven by the population and its growth.

4.1 LPB Population growth analysis

20 From the census of the years 1980 up to 2010, the population growth of LPB, and its estimation for the year 2040 was analyzed using Exponential (Eq. 7) and Logistic (Eq. 8) growth models:

$$P(t) = P_0 e^{kt} \quad (7)$$

$$P(t) = \frac{kP_0}{(k - bP_0)e^{-kt} + bP_0} \quad (8)$$

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where k and b are coefficients determined from the trends of growth of existing census data, t is time and P_0 is the population at start year of the computation (i.e. 2010).

Population growth models depend on the trend of population growth. According to population growth studies (Carlson, 1913), population growth should be modelled in two ways depending on the number of population at a certain moment in time. The exponential growth model depicts a rapid growth of population whereas the logistic growth of population depicts a saturation of population in time. This is strongly correlated with the resources and change of culture of a country. As population grows, economy is expected to grow, and the living standard will grow. As soon as the living standard grows, the population growth starts to follow the logistic trend. In LPB the census data was available for each country, till year 2010. In order to identify which of the models are applicable for each country, both models were applied to the collected population data. After determining the population growth model of each of the LPB country, the estimation of the expected population in 2040 could be determined.

The growth of population in Argentina, Bolivia, Brazil, Paraguay and Uruguay was computed based on the census available up to the year 2000 and the prediction of the population according to the logistic (L) and exponential (E) growth model, after year 2010, until year 2040.

According to these two population growth models, the growth in Brazil follows the exponential growth model up to 2018 and then it will follow the logistic growth model, whereas the population growth in the other four countries follow the logistic growth model.

The LPB countries are not fully contained within the LPB basin, therefore the population models had to be downscaled for the LPB basin. For each country the percentage of population which leaves in the LPB basin was determined and the population of the entire basin was determined.

The exponential growth model was used for Brasil, for the part of the country belonging to the LPB, up to the year 2007, and then due to the number of population in the basin, the logistic one was used to determine the population in the year 2040, whereas

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the population growth in the other four countries, in the LPB area, follows the logistic growth model (Fig. 5). Table 1 shows the prediction for the population in the LPB, per country, every 10 years, from 2010 (collected data from census) till 2040.

4.2 Total water withdrawal from the LPB

4.2.1 Agricultural water withdrawal

Agricultural water withdrawal (AWW) depends on the water requirements for irrigation, which varies depending on the land use. Moreover, the change in land use over the years is very important in order to determine future agricultural water requirements. While analyzing the land use pattern of the last three decades, 1980–2010, it can be noticed that there is a significant change of cultivation of crops and deforestation (Scheel et al., 2011; Barros et al., 2008), which result in variations in the annual water demand for agriculture. For each country of the LPB future water requirements were determined, by analyzing the main crops of the countries, such as rice, sunflower, maize, soybean, sorghum, wheat, cassava and sugarcane (Statistical Yearbook for Latin America and the Caribbean CEPALSTAT 2010). The average water requirement for each crop is given in Table 2, below. Most of the cultivations in LPB are done using rain water; therefore irrigation water requirements will be significantly small when compared with the actual water requirement. CEPALSTAT of year 2009 gives the percentages of rain fed and irrigated area per country in LPB (see Table 3), which forms the basis for computing the necessary water withdrawal from the available water in the basin.

The necessary irrigation water requirements (IWR) for each crop was computed and correlated with the nowadays measured agricultural water withdrawal (AWW). Based on this correlation, the future AWW, for each country in LPB was estimated, as per Eq. (9):

$$AWW = a + \sum_{i=1}^n bIWRC_{i1} + cIWRC_{i2} \quad (9)$$

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where a , b , c are coefficients; $IWRC_{i1}$ is the irrigation water requirement for a certain crop i ; $IWRC_{i2}$ is the crop i water requirement times percentage of the irrigated area; and n is the number of considered crops. Table 4 indicates the total estimated AWW in LPB, by country.

5 4.2.2 Municipal water withdrawal

Municipal water withdrawal (MWW) increases with the population growth. Population growth correlated with the historic MWW is used in order to estimate the future MWW in LPB, by country (Eq. 10):

$$MWW = (a + bPG) \quad (10)$$

10 where a , b are coefficients and PG is the population correlated to the municipal water withdrawal. Table 5 shows the estimated MWW in LPB for each country of the basin.

4.2.3 Industrial water withdrawal

15 Industrial water withdrawal (IWW) depends on factors such as product type, demand for product, rate of production, however when these type of data are not available, population growth and economic development can be used for assessing future IWW. The IWW is expressed by Eq. (11):

$$IWW = (a + bPG + cGDP) \quad (11)$$

where a , b , c are coefficients; PG is population growth and GDP is the Gross Domestic Product. The estimated IWW, for the year 2040 is given in Table 6.

20 4.2.4 Total water withdrawal

The water withdrawals for each subbasin of the LPB were computed based on the percentages of basin area shared by each country, and as a sum of the AWW, MWW and IWW.

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4.3 Electricity demand of LPB on 2040

The electricity demand (ED) of the LPB countries, in the year 2040, is dependent on the population growth and economic development of the region. The consumption of electricity increases with the population growth and also there is a need for more energy (electricity) for the industrial development which contributes to the economic development.

Per Capita Gross Domestic Product (GDP) was used as an indicator to measure the economic development in each LPB country. The existing GDP product variation in each LPB country was analyzed (Fig. 6) and future GDP was estimated based on the present trend.

The relation that gives the ED for year 2040 is:

$$ED = (a + bPG + cGDP) \quad (12)$$

where a , b , c are coefficients, determined from the historical data, PG is the population and GDP is the gross domestic product. The computed ED is plotted in Fig. 7, for all five countries of LPB, up to year 2040.

4.4 Assessment of the needs of hydropower production in LPB

In LPB hydropower is one of the foreseen source for meeting the energy demand (Barros, 2002). Based on the above determined energy demand and analyzing the hydropower production, an estimation of the needs for hydropower production in 2040 has been assessed. The trend of the hydropower production until now (year 2010) and possible needs for hydropower production, based on the nowadays production, in each country is presented in Fig. 9.

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4.5 Determination of hydropower potential of the LPB basin using Vapidro-Aste tool

The maximum available hydropower potential of the LPB basin is determined using the Vapidro Aste 2.0 GIS integrated tool, as presented earlier in the paper. The Vapidro-Aste tool has the advantage that it encapsulates a methodology to assess the maximum and residual hydropower potential in a watershed at two scales: basin wide and reach scale. The basin scale analysis determines the available maximum hydropower potential of a river basin based on the natural available hydrological regime and the topography of the catchment, whereas, the reach scale does the same analysis at sub-basin level.

The residual hydropower potential expresses the hydropower potential of a basin after taking into account all water withdrawals (AWW, MWW, IWW) and the Minimum Instream Flow (MIF) determined from the natural available hydrological data.

In order to perform the analysis of the LPB hydropower using Vapidro Aste the annual mean flow in LPB was taken into consideration. As presented, there is an increased mean annual flow of the streams in LPB after 1970s, therefore, the maximum hydropower potential was computed, using values for the mean annual flows for the last 30 yr (1970–2010).

Two types of Vapidro-Aste models have been developed: first models for estimating the maximum hydropower potential, where no withdrawals were considered, were built; and secondly models for estimating the residual hydropower potential, where all future potential water withdrawals from the basin were considered.

The maximum and residual hydropower potential was computed for 0% and 10% of the hydrological flow as MIF, respectively. The overall efficiency factor for the generation of energy was selected to be 70% and loss coefficient for the transformation of gross head in net head as 0.05. In case of power generation, hydraulic machine efficiency was selected as 80% and transmission coefficient between average seasonal maximum discharge and instant discharge was selected as 1.5.

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The LPB was divided into 66 sub-basins, based on measured stream flow data availability. These 66 sub-basins cover the entire LPB basin taking into account all the main rivers (Parana, Paraguay, Uruguay, Grande, Tiete, Paranapenama, Ivai, Iguacu, Paraniba, Picomayo, Bermejo, Negro) and main tributaries. The flow data which determined this division are located at the gauging stations and forms the outlets of the sub-basins.

The models main assumption is that there are no diversion structures along the river reaches. The model splits the stream into a number of cross sections based on the selected distance between two adjacent cross sections and computes the power and energy available at each cross section. A distance of 50 m was selected for all the models except for the Parana, Paraguay and Uruguay main rivers, where distance was selected to be 250 m.

The Vapidro-Aste program has the option to compute the energy and power for the hydraulic head ranging between 0.5 m and 6 m. The selected 66 sub-basins models calculated power and each cross section considering the back water curve generated by 0.5 m high hydraulic head.

5 Results and discussion

The maximum and residual hydropower potential of the LPB at river reach scale are 354 134 MWh and 307 034 MWh, respectively, whereas at the basin scale, these are 829 202 MWh and 715 602 MWh, respectively.

An analysis of the 2040 hydropower production, electricity demand, and maximum and residual hydropower potential together shows to what extend hydropower can contribute for the energy supply in LPB. Figure 9 shows the results obtained in the present research in comparison with other existing researches in LPB basin. The two studies considered for this comparison are the results coming from the EU-FP6 project CLARIS-LAB (www.claris-eu.org), where upper and lower limits for electricity demand in LPB were determined. The analysis shows that the present hydropower production is

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below the electricity demand of LPB. The gap between residual hydropower potential at basin scale and the hydropower production is the remaining hydropower potential that can be utilized to supply the future electricity demand in LPB. As the electricity demand in LPB in short term is higher than the maximum hydropower potential at basin scale, hydropower cannot supply the total electricity demand in LPB in short term, clearly there is a need for other sources of energy in order to meet the energy demand of the LPB basin.

In case of hydropower production and electricity demand, nowadays (year 2010) hydropower production is 309 503 GWh and the electricity demand is 557 597 GWh, therefore, hydropower contributes 55.5% of the total electricity demand of LPB. By 2040, the estimated hydropower production and estimated electricity demand will be 523 078 and 1 045 054 GWh, respectively, and hydropower will be able to contribute to this demand only with 50.4% of the total electricity demand. There is a clear need to increase the hydropower production or look into other sources of energy to supply the demand.

By country, Paraguay is the only country of the LPB that has more hydropower production than the electricity demand. In the other four countries, electricity demand is higher than the hydropower production, therefore the excess hydropower of Paraguay can be used to supply the electricity demand in other countries, for example Brazil, as it is already the case.

6 Conclusions

There is a worldwide concern to get the maximum use of renewable sources, especially hydropower to supply the increasing energy demand. In this regard, in order to predict the energy demand and availability for the expected future socio-economic developments of the five fast growing countries sharing La Plata basin, we used a GIS-based tool to assess maximum and residual hydropower potential in the basin, taking into account energy losses, due to different water withdrawals.

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In details, this study assessed the nowadays hydropower production and electricity demand generated over the last twenty years in La Plata Basin; estimated the water withdrawals due to industrial, agricultural and municipal uses; estimated the maximum hydropower potential in the basin and computed the residual hydropower potential, accounting for the water withdrawals.

The main outcomes of this study can be summarized in that there is unexploited hydropower potential in LPB and therefore the remaining hydropower potential of the basin can be utilised to supply the electricity demand in LPB.

The present study shows that LPB has more hydropower potential than the estimated maximum and residual hydropower potential, because the study considered just 66 streams of LPB for the assessment of the maximum and residual hydropower potential (at river reach scale), however there are many unaccounted streams for the assessment of hydropower potential of the basin, which can be used for the hydropower generation in a small scale.

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Table 1. Estimated population LPB by country.

Country	Estimated population			
	2010	2020	2030	2040
Argentina	26 197 439	27 436 096	28 289 833	28 863 087
Bolivia	1 782 806	2 008 099	2 261 862	2 547 693
Brazil	84 265 841	94 754 936	105 244 030	115 733 124
Paraguay	7 085 714	9 149 932	11 733 657	14 917 630
Uruguay	2 969 506	2 977 566	2 982 178	2 984 813
Total	122 301 305	136 326 627	150 511 560	165 046 347

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Table 2. Average crop water requirements.

Description	Rice	Sunflower	Maze	Soybean	Sorghum	Wheat	Cassava	Sugarcane
Crop water requirement	900–2500	600–1000	400–600	450–700	250–300	400–450	1400–3000	400–750

Source: CEPALSTAT – Statistical Yearbook 2009.

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Table 3. Percentages of rein fed and irrigated agricultural areas.

Description	Argentina (%)	Bolivia (%)	Brazil (%)	Uruguay (%)	Paraguay (%)
Rain fed	92	90	90	97	60
Irrigated	8	10	10	3	40

Source: CEPALSTAT – Statistical Yearbook 2009.



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Table 4. Estimated agricultural water withdrawal from LPB by country.

Year	Agricultural water withdrawal ($10^9 \text{ m}^3 \text{ yr}^{-1}$)				
	Argentina	Bolivia	Brazil	Paraguay	Uruguay
2010	16.99	0.87	31.24	0.36	3.73
2020	20.86	0.93	36.84	0.37	4.43
2030	24.72	0.98	42.44	0.38	5.13
2040	28.58	1.04	48.04	0.39	5.84

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Table 5. Estimated municipal water withdrawal from LPB by country.

Year	Municipal water withdrawal ($10^9 \text{ m}^3 \text{ yr}^{-1}$)				
	Argentina	Bolivia	Brazil	Paraguay	Uruguay
2010	3.93	0.05	5.37	0.13	0.08
2020	4.42	0.06	5.98	0.17	0.09
2030	4.91	0.07	6.65	0.22	0.09
2040	5.40	0.09	7.37	0.26	0.10



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Table 6. Estimated Industrial water withdrawal of LPB by country.

Year	Industrial water withdrawal ($10^9 \text{ m}^3 \text{ yr}^{-1}$)				
	Argentina	Bolivia	Brazil	Paraguay	Uruguay
2010	2.30	0.10	8.62	0.05	0.04
2020	2.67	0.14	9.70	0.07	0.05
2030	3.04	0.18	10.67	0.08	0.06
2040	3.41	0.24	11.54	0.09	0.07

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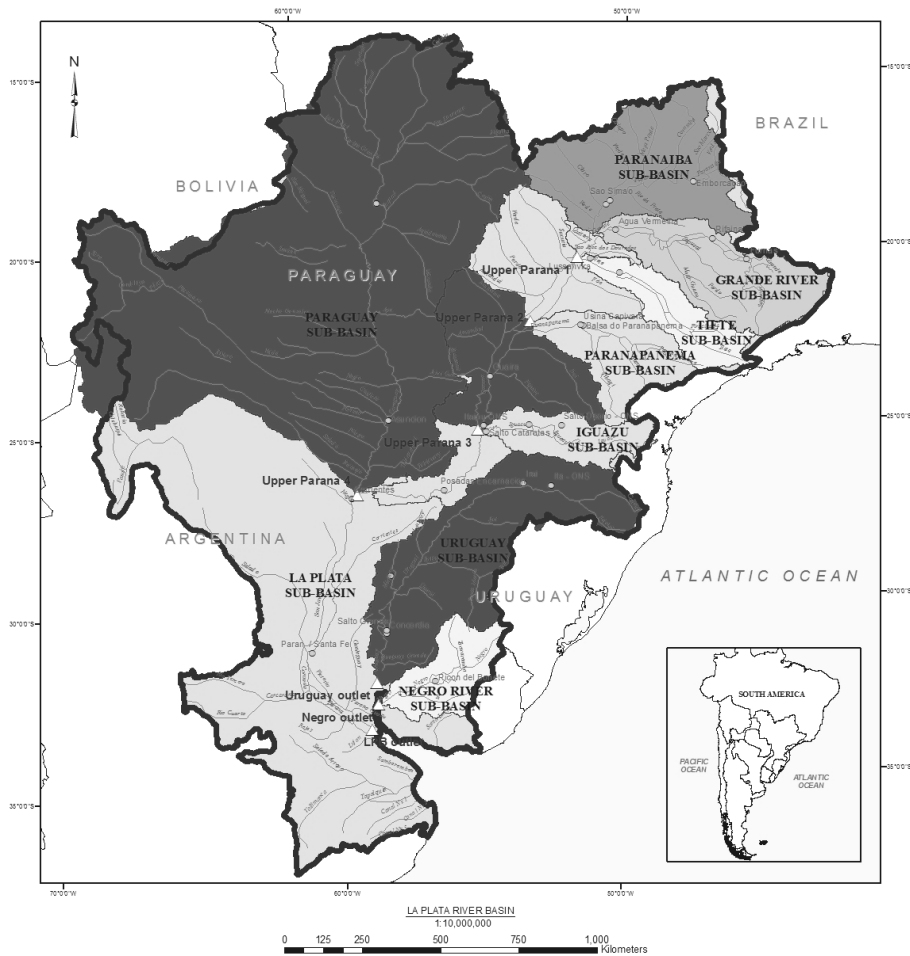


Fig. 1. La Plata Basin.

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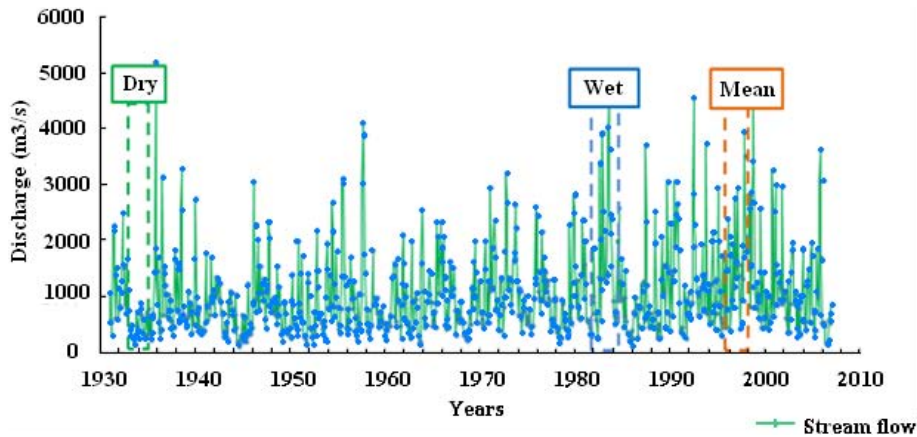


Fig. 2. Hydrological regime in La Plata basin.

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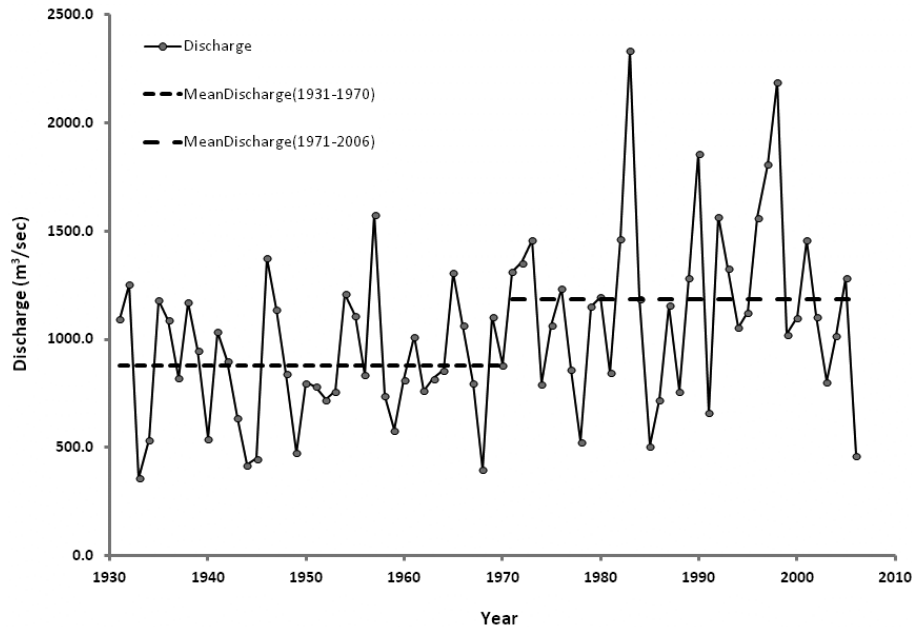


Fig. 3. Standard homogeneity test result for data series from 1931–2006.

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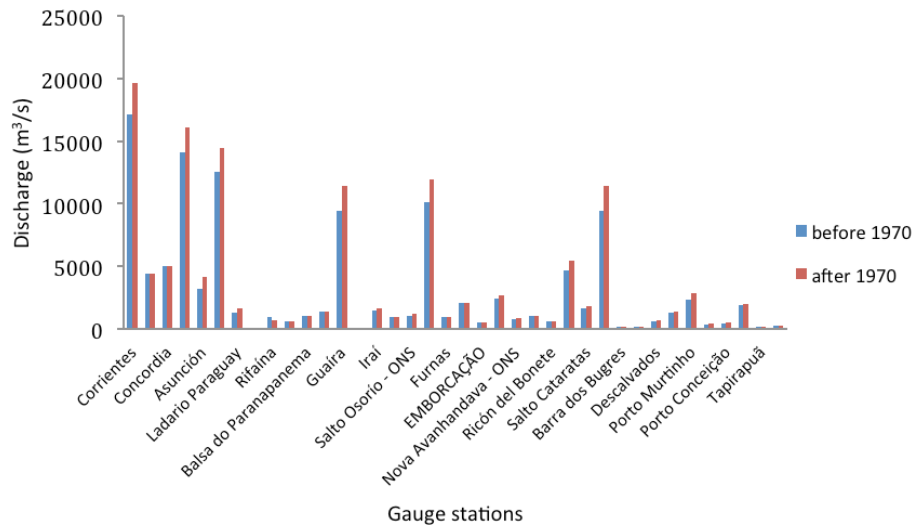


Fig. 4. Mean annual stream flows of the two time series intervals, 1931–1970 and 1970–2006.

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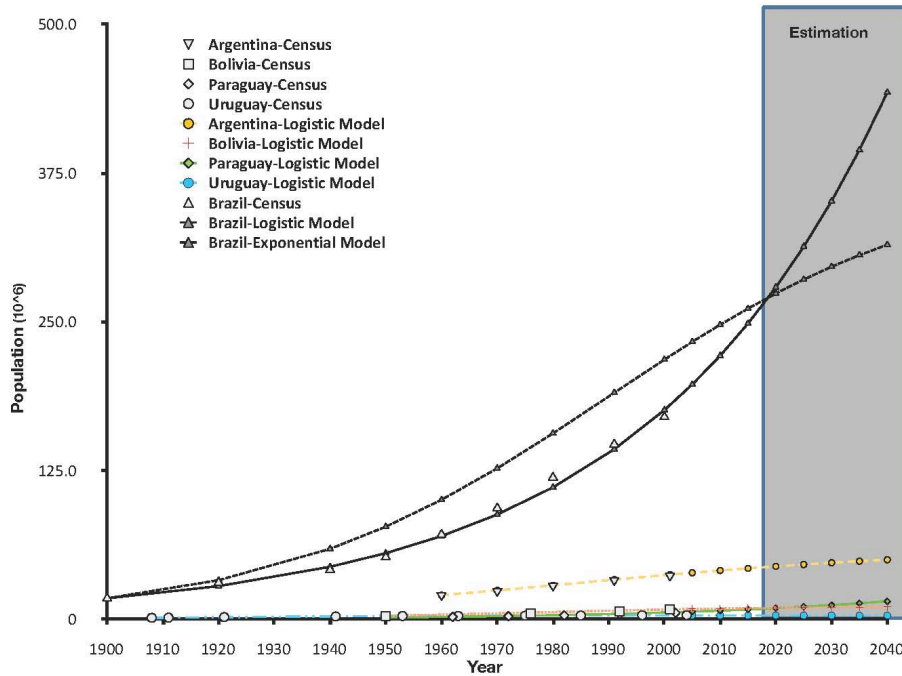


Fig. 5. Growth of population in Argentina, Bolivia, Brazil, Paraguay and Uruguay in LPB.

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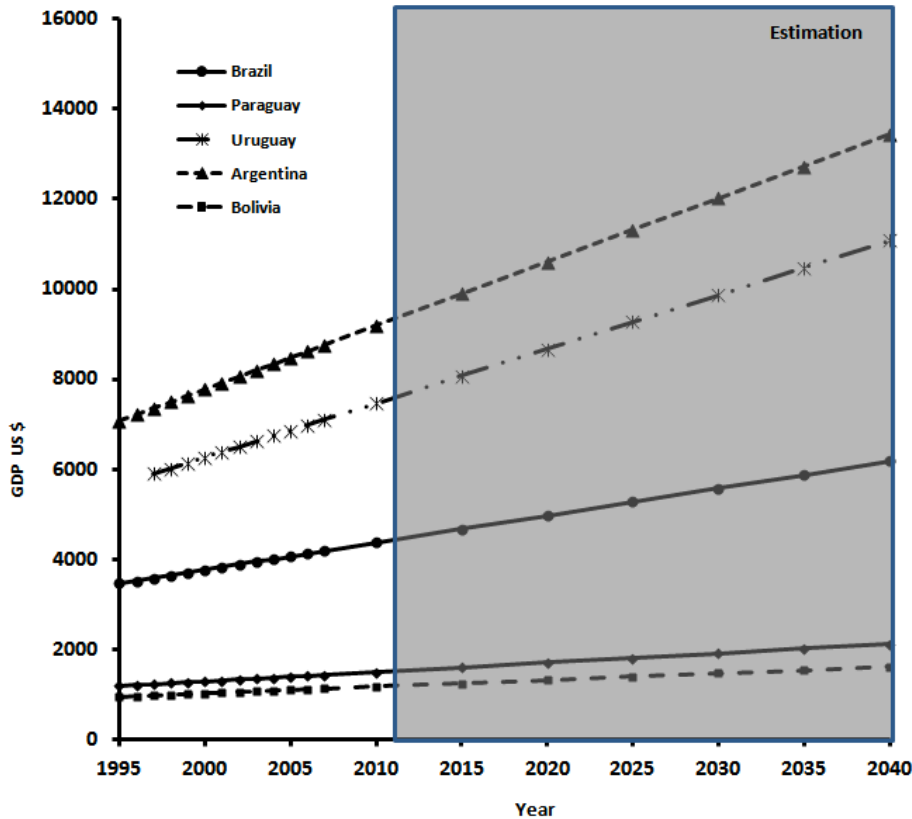


Fig. 6. Variation of per Capita Gross Domestic Product (GDP) in five LPB countries.

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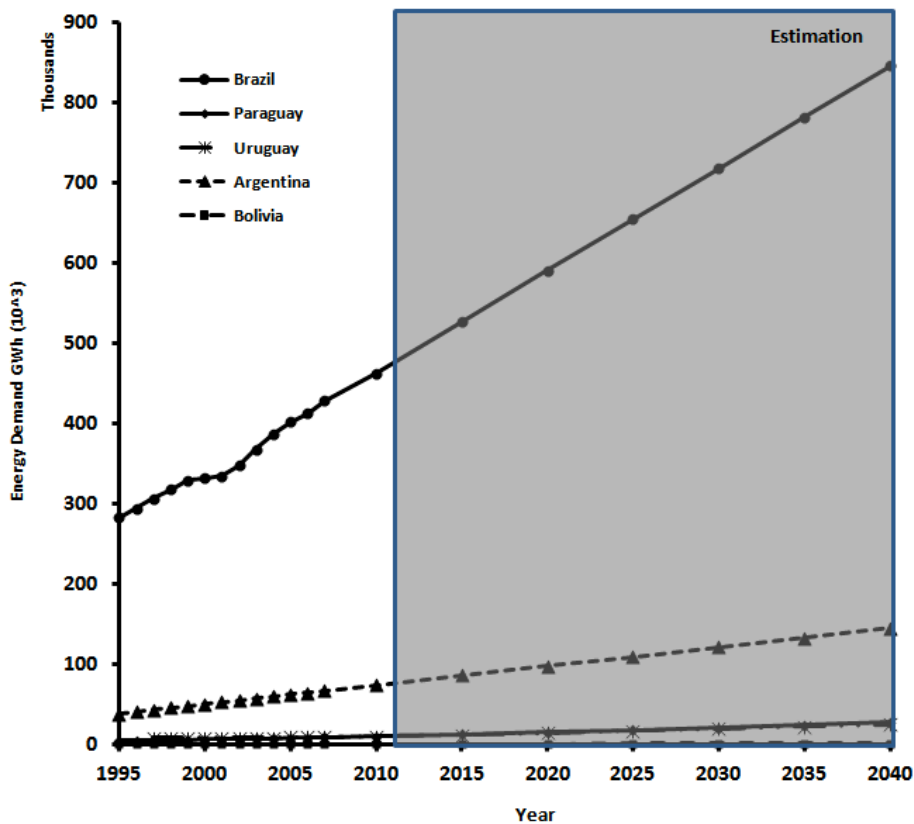


Fig. 7. Actual and estimated electricity demand in five countries in LPB.

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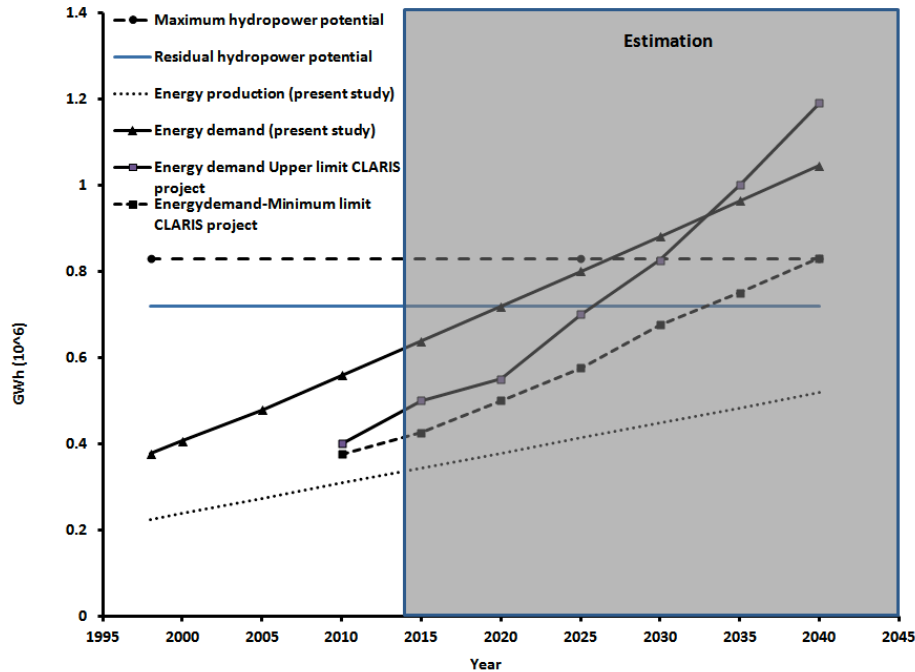


Fig. 8. Potential energy in LPB.

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