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Forecasting long-term electricity demand in the residential sector

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Abstract

This work describes a methodology for long-term electricity demand forecast in the residential sector. The methodology has been used in the power market studies of some Brazilian distribution utilities. The methodology is based on decomposition of the total electricity residential consumption in three components: average consumption per consumer unit, electrification rate and number of households. Then, the forecast for the total electricity consumption in residential sector is the product of forecasts for these three components. The prediction for the number of households is based on demographic models while the future trajectory of the electrification rate is defined by the targets for achieving the universal access to electricity. The product of these two components provides a forecast to the number of residential customers. The average consumption per unit consumer depends on the macroeconomic scenarios for GDP, average household income and income distribution. The proposed methodology provides a framework to integrate macroeconomic scenario, demographic projection and assumptions for ownership and efficiency of electric appliances in a long-term demand forecast. In order to illustrate the application of the proposed methodology, this paper presents a ten-year demand forecasts for the residential sector in Brazil.

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Keywords: long-term demand forecast; electricity; residential sector; household

1. Introduction

Long-term electricity demand forecasting plays an important role in the electric power system planning, tariff regulation and energy trading [1]. In the electric power sector the long-term forecast horizon is at least five years ahead. For example, in the Brazilian electricity market, energy trading auctions are realized up to five years before the start of the energy selling. To cope with the uncertainties on demand and mitigate the risks of economic and financial losses the decision making is based on long-term demand forecasts. The electricity distribution tariffs are regulated by the price cap scheme in which at each period of four years the Brazilian Electricity Regulatory Agency (ANEEL) leads periodic tariff review in order to achieve gains of efficiency in

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the electricity distribution sector. The tariff review depends on demand forecasts [2]. In Brazil, the generation and transmission expansion planning studies are carried out by Energy Research Company (EPE in Portuguese). These studies are reviewed in yearly basis in order to consider long-term demand forecasts updated with new data and future perspectives. The more recent planning study available is the Ten Year Plan for Energy Expansion in 2023 [3] which point out a total electricity demand of 689 TWh at the year 2023 with 190 TWh (27.6%) in the residential sector.

Traditionally, the billing system of the electricity distribution utilities classifies the customers in consumption sectors, for example, residential, commercial, industrial and miscellaneous. The sectors evolve at different rates [1], thus the long-term demand forecast must be carried out separately for each sector.

The importance of residential sector in the Brazilian Electric Power System can be recognized by its quantitative size, it concentrates 26% of consumption and 85% of the consumers. In addition, in this sector we find the main public policies such as the target household electrification rate, the program "Light for All", subsidies for consumer units inhabited by low-income families and the actions of the National Electrical Energy Conservation Program (PROCEL) to promote energy efficiency.

The residential electricity consumption in the year t (E_t) can be expressed as the product of the total number of households (H_t), the electrification rate (NC_t / NH_t) and the average consumption per unit consumer (E_t / NC_t), where NC_t is the total residential consumer units.

$$E_t = \frac{E_t}{NC_t} \cdot \frac{NC_t}{H_t} \cdot H_t \tag{1}$$

In this way, the forecast for the electricity demand in the residential sector is based on three forecasts: a prediction for the number of households, a scenario for the electricity consumption per unit consumer and a scenario for the electrification rate.

The scenario for the electrification rate is set by the targets in the Resolution ANEEL No. 223/2003. The prediction for the number of households is determined by demographic models while the scenario for the electricity consumption per unit consumer is based on assumptions for future evolution of the appliance ownership, energy efficiency, household income and income distribution [4].

This paper presents a methodology that integrates the projections described above and their respective input data in order to achieve a long-term electricity demand forecast in the residential sector. Fig. 1 provides a brief view of the proposed methodology.

As illustrated in Fig. 1, the forecast for the number of household from demographic model is based on Census statistics and population pyramid projection for Brazil provided by the Brazilian Institute of Geography and Statistics (IBGE). The main results from demographic model are the forecasts for the total number of households that form the potential number of consumer units in the residential sector. Also in Fig 1, the projections for household income and the income distribution are obtained from macroeconomic scenarios for the GDP growth and household final consumption expenditure as well as the microdata available in the National Household Sample Survey (PNAD-IBGE). The PNAD's microdata also provides statistics about the ownership of household appliances. The macroeconomic model produces forecasts for the average household income as well as the distribution of the households among the income ranges while the microeconomic model produces the forecasts for electricity consumption in the residential sector.

This paper is organized in four sections. The proposed methodology is described in section 2 where the three models in Fig 1 are presented: demographic, macroeconomic and microeconomic models. Next, in order to illustrate the proposed methodology, in section 3 we present the forecasts for residential sector in Brazil during the period 2009/2018. Finally, in section 4 we present the main conclusions.

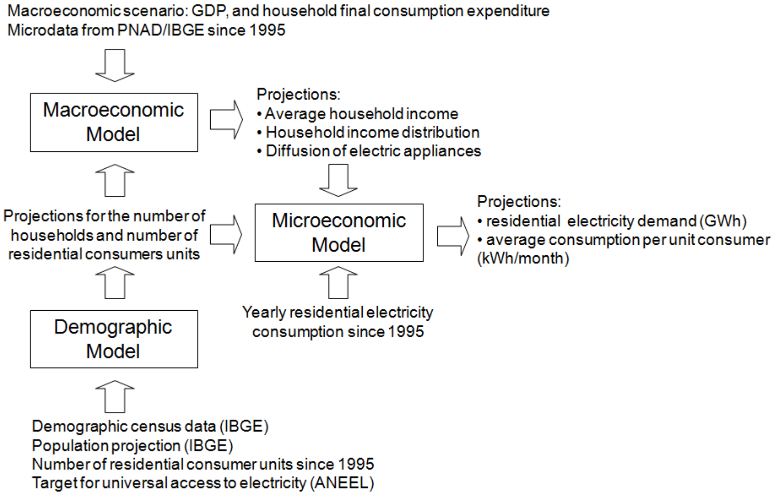

Fig. 1.Long-term demand forecast model

2. Long-term demand forecast methodology

As shown in Fig.1 the proposed methodology has three models: demographic, macroeconomic and microeconomic. Next, we present a brief description of each model.

2.1. Demographic model

The Brazilian age structural transition is in progress. The first effect of the age structural transition on the electricity consumption is increasing the demand per capita in residential sector with the aging population. For example, in the US, at year 2001, the annual residential energy demand per capita was 24.9 MBTUs for people under 25 years of age, 30.4 MBTUs for people between 34 and 44 years, 49.6 MBTUs for people between 65 and 74 years and 54.2 MBTUs for people over 75 years [5].

The second effect of the age structural transition is the reduction of household size. An analysis of results from PNAD reveals that households with up to 3 residents increased their share in total households, while in the same period the households with four or more residents follow a downward trend.

The effects of the demographic transition have different implications for household electricity consumption. The reduction in the average number of residents per household contributes to a lower consumption per consumer unit, contrasting with the increase in consumption due to the aging population and the dissemination of electric appliances.

From the classification of households used in the Brazilian census, we conclude that in the residential sector the potential market is composed by the permanent private households occupied and for occasional use, while the collective and improvised housing units as well as the vacant housing units are not customers served in the residential sector as illustrated in Fig. 2.

The number of occupied housing units is associated with the resident population. In order to forecast the total occupied households taking into account the effects from demographic transition we applied the household headship rate method [6]. This method assumes that the number of households in a population is equal to the number of household heads. Assuming that the number of household heads is identical to the total of occupied housing units, this methodology allows classifying households according to the age and sex of the head of household. Thus, the projection of the number of households is sensitive to the changes in population age structure. Let ${}_nH^s_x(t)$ the total number of households headed by individuals with sex s and age between x and $x + n$ years at the year t. The total number of households at year t, $H(t)$ is the sum of total households headed by men and women across all age groups:

$$H(t) = \sum_{age\ x} \sum_{sex\ s} {}_nH^s_x(t) \tag{2}$$

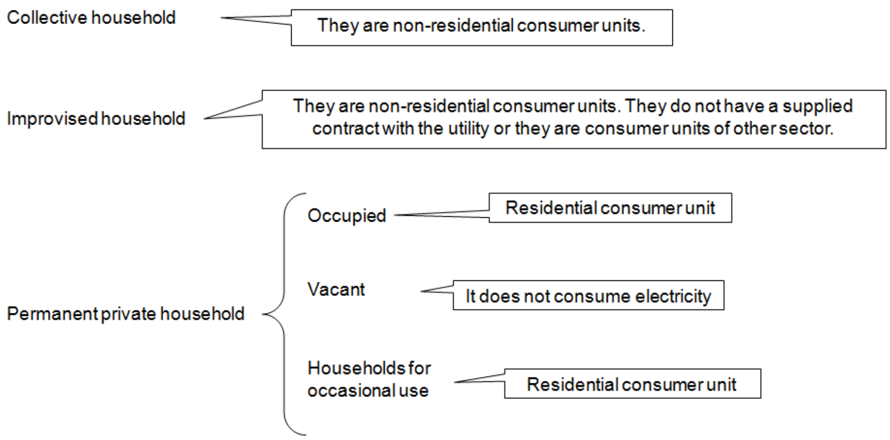

Fig. 2. Classification of the households

The household headship rate is the ratio of the number of household heads by the number of inhabitants, both computed by sex and age group:

$${}_nT^s_x(t) = {}_nH^s_x(t) / {}_nP^s_x(t) \tag{3}$$

where ${}_nP^s_x(t)$ is the population with sex s and age in the interval $[x , x + n)$ years.

Substituting equation (3) in equation (2) gives the forecast equation for the total households as a result of the sum of products between the headship rate forecast and the population forecast in each sex and age group:

$$H(t) = \sum_{age\ x} \sum_{sex\ s} {}_nT^s_x(t) {}_nP^s_x(t) \tag{4}$$

The population forecasts by sex and age group ${}_nP_{sx}(t)$ are from population pyramids provided by IBGE. In turn, the headship rate forecast by sex and age ${}_nT_{sx}(t)$ are computed by the age-period-cohort model – APC model [7], a Poisson regression model where the headship rate is explained by three effects: age, period and birth cohort.

The households for occasional use do not depend on the population structure. The forecast for this type of household is based on the extrapolation of the ratio between the total number of households for occasional use and the total number of households. The projection of the number of residential consumer units holds the following relationship with the projection of the number of households where T_t is the electrification rate at year t:

$$NC_t = T_t \cdot H_t \tag{5}$$

The Resolution ANEEL No. 223/2003 establishes that distribution utilities must achieve the universal access to electricity by the year 2015. Then, from the year 2016 onwards T_t should be equal to 1 and the total number of households will be equal to the total number of residential consumer units.

2.2. Macroeconomic model

The projection of the average household income at year t (AHI_t) is given by the ratio between the household final consumption expenditure ($HFCE$) from the macroeconomic scenario and the projection for the total number of households served in the residential sector (H_t):

$$AHI_t = HFCE_t \;/\; H_t \tag{6}$$

The $HFCE$ is the variable that allows integrate the macroeconomic scenario with the long-term demand forecast for the residential sector.

In order to take into account the effect of the household income distribution on the projection of the electricity consumption per unit consumer, the households were classified into nine income ranges expressed in number of minimum wages:

- without income
- not-declared income
- up to 1 minimum wage
- from 1 up to 2 minimum wage
- from 2 up to 3 minimum wage
- from 3 up to 5 minimum wage
- from 5 up to 10 minimum wage
- from 10 up to 20 minimum wage
- more than 20 minimum wage

The projection of electricity residential consumption by income range requires the modeling of the household income distribution. This modeling is based on annual statistics obtained from PNAD's microdata [8]. Considering the minimum wage at the year of the last available PNAD, the statistics about the household income in the microdata since 1995 were adjusted by a consumer price index (INPC) and then the households were classified in the nine income ranges defined above. Thus, the microdata from PNAD allow construct time series of the average household income as well as the distribution of occupied housing units over income ranges.

The analysis of the time series from PNADs points out the association between the average household income and the share of the income range in the total households. As illustrated in Table 1, the correlations between them indicate that when the average income grows the higher income groups gain housing units and lower income ranges lost them. Based on these results we selected the average income as the main explanatory variable of the household income distribution.

Table 1. Correlations between the average household income and the share of the income range in the total number of households

Up to 1 min.wage	1 - 2 min.wage	2 - 3 min.wage	3 - 5 min.wage	5 - 10 min.wage	10 – 20 min.wage	More than 20 min.wage
-0.69	-0.88	0.08	0.51	0.94	0.94	0.87

The model used to forecast the distribution of households over income range is an ordered logit, an extension of binary logit regression used when the dependent variable has three or more categories [9]. The dependent variable is the accumulated share of households by income group and the independent variables include the average household income (*AHI*) and a set of dummies variables that represent the income range [10]. The ordered logit model provides estimates for the share of income range in the total number of households.

2.3. Microeconomic model

The model assumes that in each income range the households are homogeneous in appliance ownership as well as in consumer habits and spending with electricity. Consumption patterns can be known through sample surveys conducted by electricity utilities, however these studies often are not carried out and the results achieved are not available. The Household Budget Survey (POF/IBGE) provides an estimate for the household spending with electricity, but the estimate is for just one particular year. The best information available on appliance ownership can be found in microdata from PNAD. Despite the PNAD's microdata does not indicate the amount of appliances in a household, we can from them calculate appliance ownership index (*AOI*) for a set appliances [11] such as color TV, black and white TV, refrigerator with 1 and 2 doors, freezers, washing machine, electric lighting, microcomputer and radio:

$$AOI(i,j,t) = \frac{H(i,j,t)}{H(i,t)} \cdot 100\% \tag{7}$$

where $AOI(i,j,t)$ is the ownership index for the appliance j at income range i at year t; $H(i, t)$ is the total number of households in the i-th income range and $H(i, j, t)$ is the number of households in the income range i with the appliance j.

The appliance ownership is a proxy of household income and also a proxy of the average electricity consumption. The relationship between household income, average consumption and the appliance ownership allows building models to establish the average electricity consumption by household income range. Excluding ownership of radios and computers, the global ownership index (*GOI*) for the i-th income range is calculated from the geometric mean of the ownership index of the appliances accounted by the PNAD.

$$GOI(i,t) = \left(\prod_{j=1}^{6} AOI(i,j,t) \right)^{1/6} \tag{8}$$

The global ownership index considers the set of all income ranges and it is a good explanatory variable for the average electricity consumption per unit consumer (*AEC*), except for the rationing period at the year 2001. This relationship can be synthesized by the following linear regression model:

$$AEC(t) = \beta_0 + \beta_1 \cdot GOI(t) + \beta_2 \cdot D(t) + \varepsilon_t \tag{9}$$

where ε_t denotes the random error and $D(t)$ is a dummy variable equal to 1 for year $t \geq 2001$.

Assuming that the coefficients β_0, β_1 and β_2 are the same for all income ranges, the average consumption per unit consumer at i-th income range at year t $AEC(i, t)$ can be estimated by the following equation:

$$AEC(i,t) = \hat{\beta}_0 + \hat{\beta}_1 \cdot GOI(i,t) + \hat{\beta}_2 \cdot D(t) \tag{10}$$

The scenario for global ownership index $GOI(i, t)$ in (10) can be obtained by trend extrapolation from its past estimates (equation 8) and its value is limited to 100%. Then, the forecast for the consumption per residential unit consumer is given by:

$$AEC(t) = \sum_{i=1}^{9} NC(i,t) \cdot AEC(i,t) \Big/ \sum_{i=1}^{9} NC(i,t) \quad (11)$$

In (11), $NC(i, t)$ is the total number of residential consumer units in the i-th income range at year t. Finally, the forecast for the total electricity residential consumption is given by:

$$\hat{E}(t) = AEC(t) \cdot \sum_{i=1}^{9} NC(i,t) = AEC(t) \cdot NC(t) \quad (12)$$

3. Computational experiment

In order to illustrate the proposed methodology we present the long term electricity demand forecasts for the residential sector used in the power market study of a Brazilian distribution utility. The forecasts are based on the Census data (IBGE) from 1970 to 2000, the demographic projection from IBGE, the PNAD's microdata from 1995 to 2008, the target for the electrification rate in Resolution ANEEL No. 223/2003 and the macroeconomic scenario for the Brazilian economy from Institute of Economics - UFRJ at May 2010. Basically, the economic scenario describes the Brazilian economic growth (*GDP*) and the household final consumption expenditure (*HFCE*) ten years ahead.

Initially, based on Census data and forecast for population pyramid from IBGE we applied the age-period-cohort model (Section 2.1) to predict the total number of households in Brazil in the period 2009-2019. From PNAD's microdata we fitted the ordered logit model described in Section 2.2 in order to forecast the distribution of households by income range. Next, a scenario for the average household income (*AHI*) was generated from the macroeconomic scenario for *GDP* and *HFCE*. Inserting the *AHI*'s scenario in the ordered logit we found the forecast for the distribution of households by income range. After, the forecasts for households were multiplied by the targets for electrification rate (equation 5) in order to obtain the distribution of residential consumers units by income range illustrated in Table 2.

Table 2. Distribution (%) of residential consumer units and scenario for the average household income

Year	Up to 1 min.wage	1 - 2 min.wage	2 - 3 min.wage	3 - 5 min.wage	5 - 10 min.wage	10 – 20 min.wage	More than 20 min.wage	Occasional use	Total of residential consumer units	Average Household Income R$
2009	11.1	17.9	14.3	21.4	16.9	7.0	5.3	6.0	54,904,447	1,961
2010	10.8	17.7	14.5	21.2	17.1	7.2	5.3	6.2	57,501,356	2,015
2011	10.5	17.6	14.7	20.9	17.2	7.4	5.3	6.4	60,406,044	2,068
2012	9.6	16.3	16.6	20.7	17.5	7.7	5.2	6.3	63,147,506	2,135
2013	9.1	16.0	16.1	20.6	18.1	8.1	5.3	6.6	65,957,296	2,229
2014	8.6	15.5	15.5	20.5	18.8	8.8	5.4	7.0	68,830,876	2,345
2015	8.4	16.0	15.1	20.2	18.9	8.9	5.4	7.2	71,767,460	2,387
2016	8.4	15.5	14.8	20.0	19.1	9.1	5.5	7.6	74,114,259	2,431
2017	8.1	15.0	14.6	20.0	19.5	9.5	5.6	7.8	75,835,578	2,480
2018	7.7	14.5	14.4	20.0	19.9	9.8	5.7	7.9	77,547,285	2,531
2019	11.1	17.9	14.3	21.4	16.9	7.0	5.3	6.0	54,904,447	2,588

The equation (8) was applied to the PNAD's microdata (classified by income range) in order to achieve the ownership index (*GOI*) shown in Table 3 for the period 1995-2008. Then, the *GOI* was extrapolated to the forecast horizon (Table 4).

Table 3. Ownership index (%) for the period 1995-2008

Year	Up to 1 min.wage	1 - 2 min.wage	2 - 3 min.wage	3 - 5 min.wage	5 - 10 min.wage	10 – 20 min.wage	More than 20 min.wage	Without income	Not-declared income	GOI
1995	16	31	43	55	69	81	88	27	44	43
...										
2008	31	41	50	60	70	80	86	43	68	56

Table 4. Ownership index (%) for the period 2009-2019

Year	Up to 1 min.wage	1 - 2 min.wage	2 - 3 min.wage	3 - 5 min.wage	5 - 10 min.wage	10 – 20 min.wage	More than 20 min.wage	Without income	Not-declared income	GOI
2009	32	42	51	60	71	81	86	44	69	57
2010	32	43	52	61	71	81	87	44	70	57
...										
2018	39	48	58	68	78	85	91	48	76	63
2019	39	49	58	68	78	85	91	49	77	64

Based on the estimated values of $GOI(t)$ and past values of the consumption per residential consumer unit $AEC(t)$ for the period 1995-2008 we fitted the regression equation (10). Next, the fitted model was applied to GOI's scenario in Table 4 in order to achieve the forecasts for the consumption per residential consumer unit shown in Table 5.

Table 5. Average consumption forecasts by household income range (kWh/month)

Year	Up to 1 min.wage	1 - 2 min.wage	2 - 3 min.wage	3 - 5 min.wage	5 - 10 min.wage	10 – 20 min.wage	More than 20 min.wage	Without income	Not-declared income	Average consumption per month (kWh/month)
2009	96	120	140	162	185	208	221	124	182	153
2010	97	121	142	164	187	209	222	125	184	155
2011	99	123	143	165	189	210	223	126	185	157
2012	101	124	145	167	191	211	224	127	187	160
2013	103	126	147	169	192	212	226	129	189	162
2014	105	127	149	171	194	213	227	130	190	165
2015	106	129	150	173	196	214	228	131	192	167
2016	108	130	152	175	198	215	229	132	194	169
2017	110	132	154	176	200	216	230	133	195	172
2018	112	133	156	178	201	217	231	134	197	174
2019	114	135	157	180	203	218	232	136	199	177

The average monthly consumption by income range reaches high values. For example, in the range up to 1 minimum wage (R$ 415.00) the average consumption would grow about 20% at the forecast horizon. Even if kept the current tariff level, such growth would imply a rise in spending of households with electricity, which seems implausible. However, this evolution is based on assumptions of unchanged technology and unchanged consumer habits.

The technological component of energy conservation is expressed on the reduction of the specific consumption of new appliances that gradually renew their stock in the households, incorporating more efficient equipment. This dynamic reduce the average consumption of appliances and the total consumption in the households. The other conservation component is related to consumption habits and represents the shape and intensity of the use of electricity. The combined effect of these two components results in the reduction of the average monthly consumption as well as of the electricity burden in the household budget. Therefore, it is possible to establish energy conservation scenarios establishing ceilings to the growth rate of the average consumption per unit consumer. Thus, each ceiling value is an energy conservation scenario (Table 6).

Table 6. Scenarios for the growth rate (%) of the average residential consumption per unit consumer

Scenario	Up to 1 min.wage	1 – 2 min.wage	2 - 3 min.wage	3 - 5 min.wage	5 - 10 min.wage	10 – 20 min.wage	More than 20 min.wage	Without income	Not-declared income
1: growth rate limited to 20%	20	14	14	13	11	6	6	10	10
2: growth rate limited to 10%	10	10	10	10	10	6	6	10	10
3: growth rate limited to 5%	5	5	5	5	5	5	5	5	5
4: growth rate limited to 0%	0	0	0	0	0	0	0	0	0

Next, Fig. 3 shows the evolution of the average monthly consumption per unit consumer for four energy conservation scenarios. In all scenarios the average consumer does not reach the pre-rationing levels (year 2000) at the end of the ten-year horizon. However, as shown in Fig. 3, the total residential consumption exceeds 2000 levels by 2007.

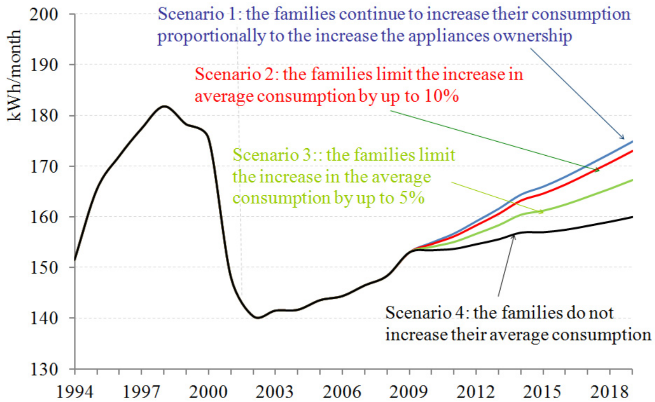

Fig. 3. Electricity residential consumption per unit (kWH/month) forecast in the residential sector

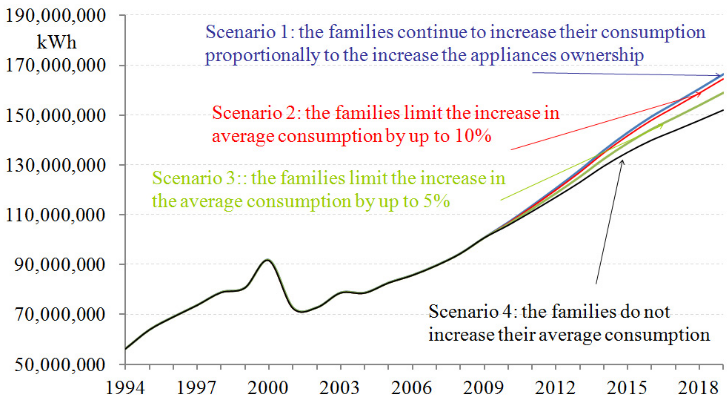

Fig. 4. Total electricity consumption forecast in residential sector

4. Conclusions

The methodology presented allows integrate macroeconomic scenario, demographic projection, income distribution and the appliances ownership in the long-term forecast for the electricity consumption in the residential sector. In addition the proposed methodology allows incorporate the effects of energy conservation in the demand forecast. The proposed methodology has been used successfully in predicting the electricity consumption and the number of consumers units in the residential sector at national and state level.

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