ESTIMATION OF STATISTICAL ELECTRIC ENERGY DEMAND PROFILES FOR RURAL ELECTRIFICATION WITH PHOTOVOLTAIC SYSTEMS IN NORTHERN BRAZIL

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Abstract. *This study presents an alternative approach on energy demand estimation for rural electrification projects. Instead of approaches based on field studies with extensive sample sizes or simplified basic needs assumptions, the presented approach uses regional socio-economic statistic datasets available from state agencies along with energy consumption data from the utilities' client data base. Developed and tested for the current Brazilian electrification program, consumption data of selected Brazilian municipalities were combined with socio-economic data of the same municipalities and analysed by multiple regressions. Extrapolating the correlations obtained, energy demand estimates for all of the hundreds of municipalities in northern Brazil can be produced. To adopt the estimates for the purpose of rural electrification projects, the impact of the remoteness of individual settlements as well as the impact of the progressively increasing electrification rate on the energy demand profile has further been investigated. The approach finally allows to use the statistical demand profiles in form of gamma distribution function as basis for the design of rural electrification programs and dimensioning of the energy supply system, which is especially critical in isolated solar power supply systems (solar home systems or PV-hybrid minigrids) where system size and thus investment cost has to be balanced with consumer satisfaction in meeting the energy demand.*

Key words: *rural electrification, energy demand, off-grid power supply, solar home systems, Gamma Distribution.*

1. Introduction

The objective of the current nation wide program "Programa de Universalização do Acesso e Uso da Energia Elétrica" is to offer electricity to all Brazilian citizens still without access to this modern form of energy, the majority of whom living in rural areas in northern Brazil and the north-eastern regions. Off-grid supply solutions like solar home systems or PV-hybrid systems are applied in this program for remote areas, where grid connection would not be feasible. As these off-grid stand alone systems are characterized by high up-front capital cost, the proper systems sizing is key for efficient use of funds. Sizing on the other hand depends on accurate demand estimates. To overcome shortcomings of the estimation methods in use, an alternative method for the electricity demand estimation has been developed.

2. Deriving energy demand from regional scale statistics

The methods currently in use for the estimation of energy demand are highly labour- intensive and time-consuming as they require primary data collection from individual households on site or are based on simplified assumptions on the consumption level to be encountered. To reduce cost and time in the planning of regional scale electrification measures, a statistic driven method has been developed which uses the observed correlation between energy consumption and socio-economic indicators to derive demand estimates on a regional scale. Such a principal approach is already in use for other purposes in infrastructure planning and market research and has now been adopted for this specific task.

2.1 Differences in energy consumption

The Starting point has been the observation of differences in energy consumption between different regions in Brazil which correlate to some extend with the region's socio-economic development indicators.

As an example, figure 1 plots the average electrical energy consumption of electrified households in different states of the Brazilian federation versus the Human Development Index (HDI) and the resulting linear regression graph. Similar correlations and significant determination coefficients (B) are documented as well for the international comparison of energy consumption and the gross domestic product per capita (GDP/cap) or the HDI (Alam et. al., 1991;

Smil, 2003). In fact a variety of socio-economic indicators show significant correlation with energy consumption on different spatial scales.

For the correlation analysis in Brazil, the socio-economic data taken into consideration are secondary statistical data collected and published by the national Brazilian statistics agency (IBGE; PNUD) which comprise a variety of socio-economic indicators at the level of municipalities.

These socio-economic data are compared to the available energy consumption data which comprises the consumption readings of the electrified households from 33 municipalities in the states of Acre, Pará and Tocantíns.

The differences in average energy consumption, as shown in Figure 1 for different states of the Brazilian federation, can be interpreted as inter-regional differences in energy consumption

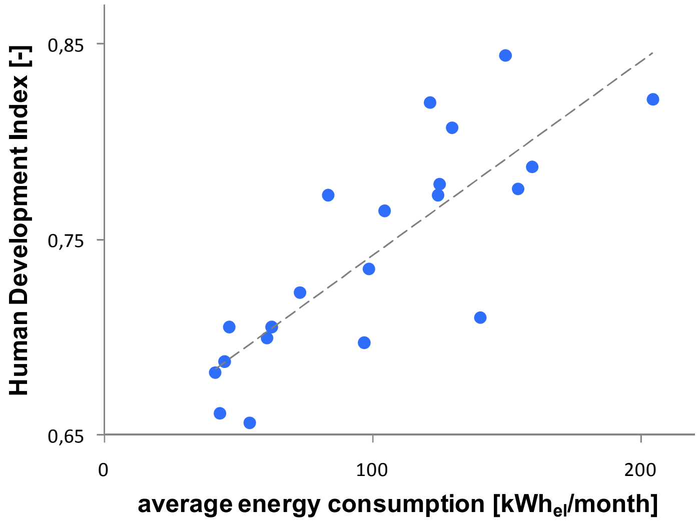

Figure 1: Average rural electric energy consumption versus Human Development Index (HDI) for several Brazilian states

When taking a closer look at how these averages in energy consumption are composed by the consumption of individual households, a significant variance is observed, as it is shown in Figure 2.

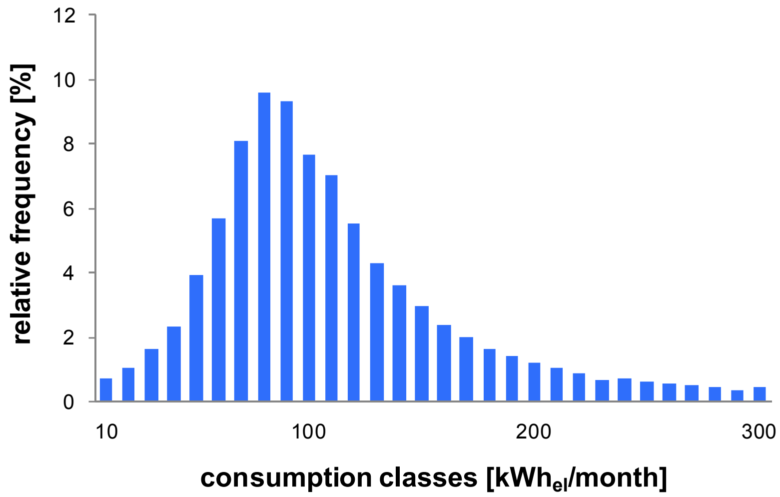

Figure 2: Observed intra-regional consumption distribution.

In fact, the inter-regional level of consumption, which can be described by the average energy consumption ($\bar{x}$), is composed itself by an intra-regional distribution of the varying household consumption, which can be described by the standard deviation (σ). By combining the differences in the inter-regional and the intra-regional scale, the energy consumption is described in its regional variability.

To derive the two consumption figures for all of the Brazilian municipalities, the observed correlation between the consumption data and the socio-economic data is used to establish regression formulas which are based on the available data of the 33 municipalities. The formulas allow the calculation of consumption figures ($\bar{x}$ and σ) for all of them as they can now be derived from the socio-economic data base that covers all of Brazilian municipalities. These estimated consumption figures can serve as demand estimates and can be modelled by the gamma distribution function.

3. Modelling the energy consumption through the gamma distribution

As different studies have shown, the distribution of energy consumption of a set of households can be modelled appropriately through the gamma distribution function (Narvarte, 2001; Morante and Zilles, 2001; Morante and Zilles, 2007). Testing the observed consumption distribution of the 33 municipalities proved that the gamma distribution function is appropriate to deliver approximations of the actual consumption distribution in a generalized form. By combining both estimates for $\bar{x}$ and σ and assuming a gamma shaped distribution, the energy consumption distribution for a set of households on a regional scale can be modelled. Figure 3 shows a gamma distribution derived through this approach together with the actual registered distribution for comparison.

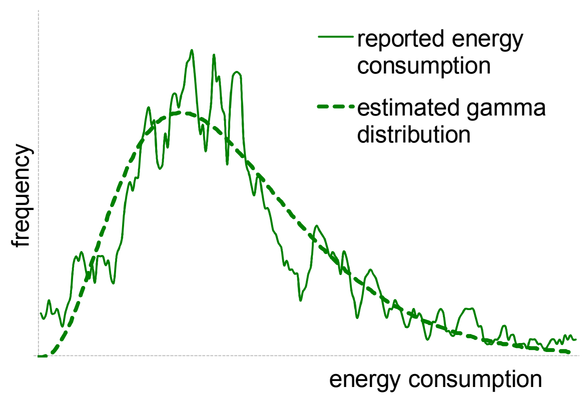

Figure 3: Comparison of reported energy consumption distribution and the estimated gamma distribution (scattered line) for a sample municipality.

Furthermore, the ability to calculate the probability of exceedance for the calculated gamma distribution allows to determine up to which extend an individual energy supply system with a given capacity will serve the demand of the various households represented by the gamma distribution.

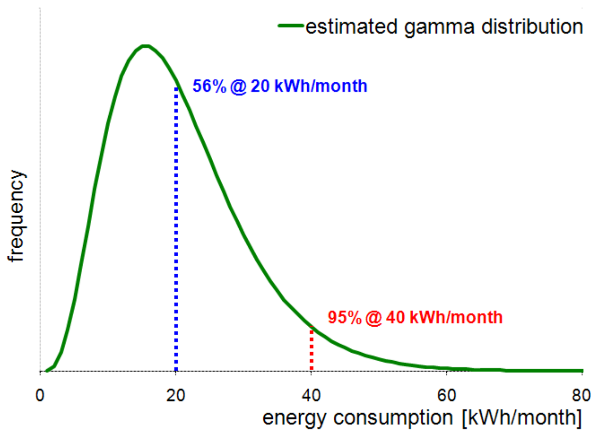

Figure 4: Calculation the probability of exceedance for different demands based on the estimated gamma distribution.

The figure 4 gives an example for these probabilities of exceedance based upon the estimated gamma distributions. In this example, the demand of 56% of the households can be served by systems capable of delivering 20 kWh/month whereas a system that would serve 95% of the households would need to deliver 40 kWh/month.

The overall structure of this approach is sketched in the following Figure 5.

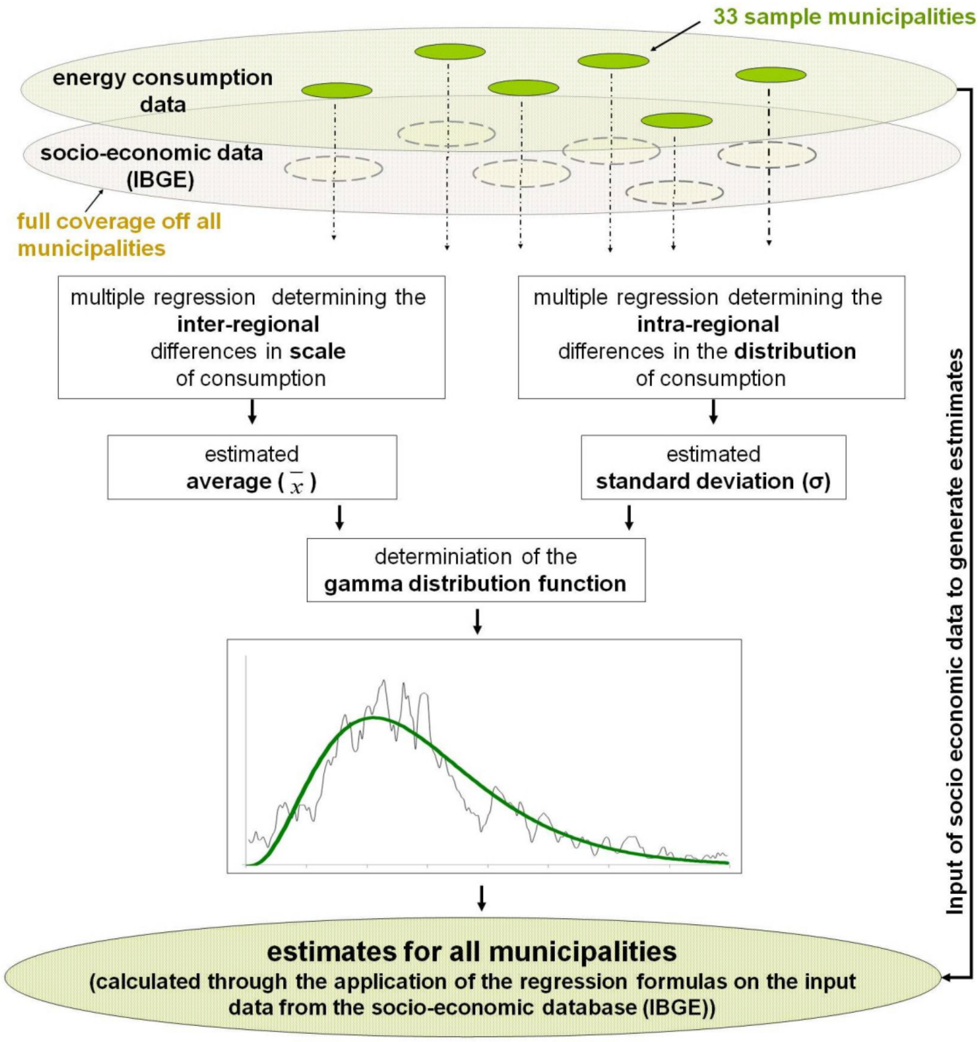

Figure 5: Structure to derive gamma distributed energy estimations.

4. Results of the stepwise, multiple regressions

As mentioned in the previous paragraph, the necessary estimations for the average and the standard deviation of the energy consumption is done by a stepwise multiple regression performed by a statistics software. This allows to identify the most suitable figures out of the set of plausible socio-economic figures as well as to determine the regression formulas and the archived correlation coefficients.

The primary statistical figures which were selected to establish the regression formulas for the two different estimates ($\bar{x}$, σ) out of the available data base, were:

I. **HDI sub index life expectancy (HDI-L)**
This sub index of the summary composed HDI showed the highest correlation coefficients for the consumption figures and has therefore been selected by the software.

II. **average income**
Variations in energy consumption due to monetary income figures are widely documented and verified, for example by econometric models for energy consumption.

III. **electrification rate**
The variable for the electrification rate has been introduced to eliminate the impact of different electrification rates in the municipalities. This effect is further described on the following pages.

The obtained estimates are archiving a 60% to 71% accuracy for the average energy consumption and a 39% to 67% accuracy for the standard deviation of the energy consumption, depending on the statistical figures used.

Table 1: Corrected determination coefficients (r^2_{corr} or B) for the estimates.

	determination coefficient B (corrected) average	determination coefficient B (corrected) standard deviation
variables (life expectancy, av. income, electrification rate)	**0,71** (equivalent to 71%)	**0,67** (equivalent to 67%)
alternative variables (av. income, electrification rate)	**0,60** (equivalent to 60%)	**0,39** (equivalent to 39%)

The archived accuracy translates into an average error margin of 7,46 kWh/month (equivalent to 9,4%) for the average energy consumption and 2,62 kWh/month (equivalent to 6,9%) for the standard deviation.

A critical review of the calculated results reveals that the highest correlation parameters between the consumption data base ($\bar{x}$ and σ) and the various items x of the socio-economic database were obtained through the HDI-L. Some studies are relating the HDI-L to the electric energy consumption and are showing significant correlation coefficients on the international scale (Smil, 2003). The inner Brazilian comparison throughout different regional scales shows similar correlation coefficients (r^2>0,57) and it can be concluded that it is very likely that it is no random correlation.

However, as the actual relation between energy consumption and life expectancy remains unclear, an alternative estimate which excludes the HDI-L achieves a significantly lower accuracy. As this alternative estimate is based upon the average income and the impact of the electrification rate alone, it leaves no questions concerning the validity of the variables used as they fully correspond with the findings of other studies (Dzioubinski and Chipman, 1999; Morante, 2000; Morante, 2004; Smil, 2003).

5. Extending urban demand profiles into rural areas

Option 1: **variations in energy consumption due to the relative location of the individual households**

A more detailed look upon the energy consumption data shows that the electrified households in the Amazon municipalities are predominantly located in the perimeter of the urban centres, while rural electrification generally reaching only inferior levels. This is typical for the structure and spatial coverage of centralized power systems in remote regions of the developing world.

Rural households are therefore underrepresented in the consumption data base which is affecting the estimates as rural households tend to have a lower average energy consumption compared to their urban counterparts. These differences in average consumption become evident when the actual consumption for individual households is plotted versus their corresponding distance to the next urban centre. Figure 6 on the right shows the decline of the actual average consumption of more than 20.000 individual households at increasing spatial distance from the next urban centre.

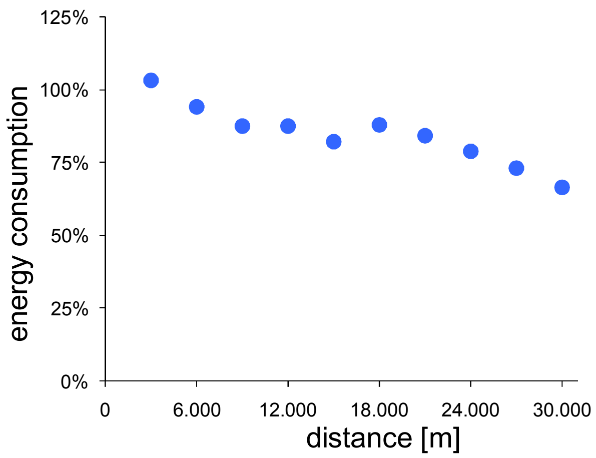

Figure 6: Line of sight distances between individual households and the next urban centre vs. average household energy consumption as in percentages of the average energy consumption of the whole municipality.

For the estimation of the energy demand on a sub-municipal scale, this fact can be addressed by a reduction of the calculated energy demand estimates according to the distance of the households on a project site to the next urban centre.

Option 2: **partial variation of the parameter "electrification rate":**

The identified rural-urban differences in energy consumption can serve likewise as an explanation for the influence that the variable "electrification rate" shows on the estimates.

If a partial variation of the variable "electrification rate" on the established regression formulas is applied while the two remaining variables (HDI-L; average income) of the equation remain unaltered, it shows that higher electrification rates are corresponding with lower average energy demand estimates. This simulates the observed decline in the average energy consumption that occurs as the electricity grid reaches further out into rural areas. The partial variation of the variable "electrification rate" is therefore used to calculate estimates for different electrification scenarios for the municipality as a whole. Alike the initial estimates, the altered estimations for the scenarios can be subsequently modelled by the gamma distribution. Figure 7 shows two demand distributions depending on different electrification scenarios (green and red). A third distribution (blue) represents the subset of households that are electrified due to the simulated variation of the variable electrification rate. Their demand distribution can be calculated numerically as it is the difference (or gap) between the distributions of the two scenarios (green and red) shown in Figure 7.

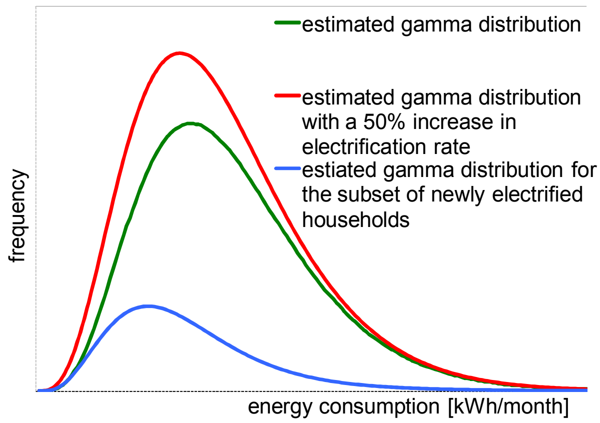

Figure 7: Results of the partial variation of electrification level for a municipality in Pará.

[note: graphs are not normalized]

These subsets of additionally attended households and their energy demand distribution can be calculated stepwise. The comparison of the demand distribution at the current electrification rate (green) with the distribution at a higher simulated electrification rate (red) is shown in Figure 8. The households that are to be electrified at last (red) are showing a different demand distribution with a lower average demand as the one of the households currently served (green). This allows to calculate the simulated demand distributions for the sets of households that are to be attained as the electrification campaign advances.

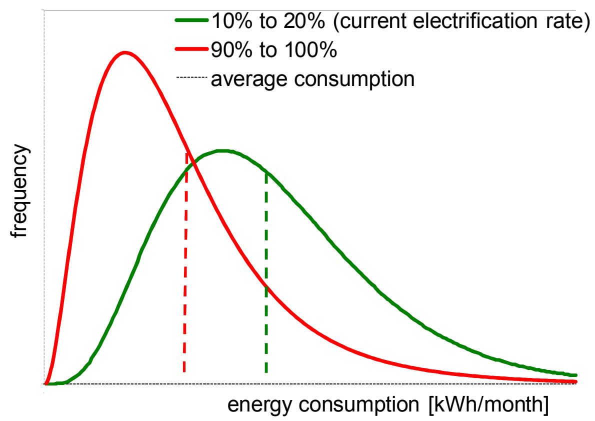

Figure 8: Gamma distributions for different subsets of households for partially varied electrification rates.

[note: graphs are not normalized]

6. Spreadsheet tool to obtain demand profiles for municipalities in northern Brazil

To enable planners to be provided with the resulting demand estimates for their project, a simple spreadsheet application tool (MS Excel) has been developed (see Figure 9). It includes the socio-economic data base along with the regression formulas and provides planners with the needed demand estimates for the municipality as a hole, the expected demand of the next households to be electrified as well as it provides a demand estimate for a single project site in accordance with the observed decline in demand for consumers at more distant sites from the next urban center.

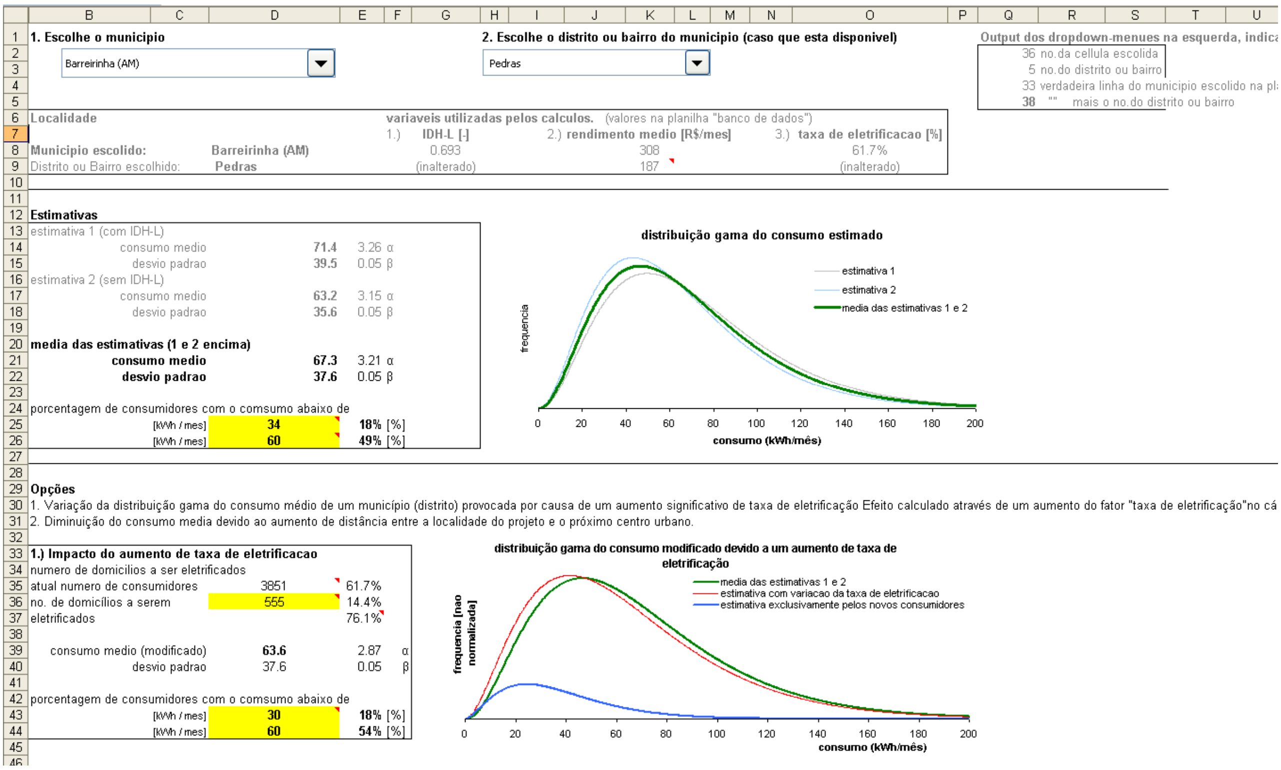

Figure 9: Screenshot of the spreadsheet tool developed to obtain the demand gamma distribution for any municipality or district/bairro (in case socioeconomic base data is available)

7. Relevance of developed approach for rural electrification programs

The presented method proposes a statistic approach for the estimation of energy demand on a scale. For an initial examination of possible options for power supply systems in a broader area, the proposed method can help to identify the appropriate options for the electrification. This is especially useful were the decision, whether renewable or conventional energy sources for off-grid applications should be implemented, depends as well on the expected energy demand characteristics on site.

8. Outlook

The use of up to date statistics for the socio-economic database is expected to verify the achieved results and possibly enhances the accuracy of the results. By the end of 2010, updated socio-economic data will be provided through the latest census (IBGE) which will presumably reduce some of the shortcomings of the database used. A further enhancement in accuracy can likely be achieved if the smaller and more homogeneous administrative unit of districts were selected to perform the initial regression instead of the larger municipalities used in this study.

9. Conclusion

The presented method has been proven to provide statistical estimates of the electric energy demand in form of the gamma function based on readily available socio economic data and samples of electricity consumption data. The geographic resolution of the estimates obtained depends on the availability of socio economic indicators which in Brazil are provided on a municipal or in some cases district level. Demand profiles for remote rural areas and off-grid electrification can be obtained through partial variation of the parameter electrification rate under the assumption that remote rural areas will be part of the very last potential consumers to be electrified.

The statistical approach and use of a gamma distribution of the energy demand will allow to design isolated power supply systems to certain levels of consumer satisfaction (probability of exceedance to meet the energy demand) or to design off-grid rural electrification programs on a municipal level to certain levels of consumer satisfaction (meeting a certain percentage of the consumers energy demands). Demand profiles for remote rural areas to be used for rural electrification programs and isolated PV and PV-Hybrid system design can be obtained for all municipalities in Northern Brazil using the spreadsheet tool developed under the study.

With the update of the socio-economic statistics of the IBGE Censo Demográfico 2010 to be published in late 2010, the developed method can rely on updated data and the accuracy obtained so far is expected to be further improved. It is expected that this approach is capable to become a useful tool in the estimation of the electrical energy demand on a regional scale for the rural and scarcely electrified parts of Brazil and elsewhere in the world.

Acknowledgements

This study has been developed in cooperation with the Utility Eletrobras in support of the Brazilian electrification program "Programa de Universalização do Acesso e Uso da Energia Elétrica", under the framework of the German Brazilian technical cooperation program, performed by the GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit GmbH) and financially supported through the Federal Ministry for Economic Cooperation and Development (BMZ). We also would like to thank also Eletroacre, CELPA and CELTINS for providing consumption data.

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ESTIMATIVA DE PERFIS ESTATÍSTICAS DA DEMANDA DE ENERGIA ELÉTRICA PARA A ELETRIFICAÇÃO RURAL COM SISTEMAS FOTOVOLTAICOS NO NORTE DO BRASIL

***Resumo**. Este trabalho apresenta uma metodologia alternativa para a estimativa da demanda de energia em projectos de eletrificação rural com sistemas fotovoltaicos. Contrária às metodologias baseadas na coleta excessiva de dados de campo ou em estimativas simplificadas, esta metodologia usa dados sócio-econômicos disponibilizados pelo IBGE e informações de consumo de consumidores dos bancos de dados das concessionárias. Desenvolvido e testado no atual programa de eletrificação rural, "Programa de Universalização do Acesso e Uso da Energia Elétrica", dados de consumo dos municípios selecionados foram analisados junto a dados socioeconômicos dos mesmos municípios e processados através de uma análise de regressão múltipla. A extrapolação das correlações obtidas possibilita calcular estimativas de consumo para todos os municípios da Macro-região Norte do Brasil. A metodologia usa a distribuição gama pela modelagem da distribuição da demanda. Isso permite a determinação de sistemas de geração de energia, tanto na aplicação de sistemas interligados quanto isolados, seja em casos de uso de sistemas fotovoltaicas domiciliares ou sistemas híbridos fotovoltaic-diesel. Para adaptar as estimativas para projetos de eletrificação rural, o impacto da distância entre o local do consumidor e o próximo centro urbano, assim como o impacto de um crescimento sucessivo do índice de eletrificação à demanda de energia elétrica, é estudado.*

***Palavras chaves:** eletrificação rural, demanda de energia, sistemas isolados de geração, sistemas fotovoltaicos domiciliares, distribuição gamma.*