Design of Decentralized Energy Systems for Energy Access and Rural Development in Developing Countries

	スィルバ　エラン　ディエゴ
氏　　名	Silva Herran Diego
授　与　学　位	博士（工学）
学位授与年月日	平成２２年９月８日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）技術社会システム専攻
学位論文題目	Design of Decentralized Energy Systems for Energy Access and Rural Development in Developing Countries (開発途上国におけるエネルギーアクセス向上と地域発展に向けた分散型エネルギーシステム設計)
指　導　教　員	東北大学教授　中田　俊彦
論文審査委員	主査　東北大学教授　中田　俊彦　東北大学教授　若林　利男 東北大学教授　斎藤　浩海

論文内容要旨

This thesis addresses the design of decentralized energy systems in developing countries, making emphasis on the improvement of energy access conditions and the promotion of rural development based on the use of local energy resources. Energy models based on optimization methodologies have been developed to design energy systems. These models have been applied for the case of rural and remote areas of Colombia, a South American country which is a typical example of an urbanized developing country. Based on the outcomes guidelines for the design of energy systems suitable for rural areas in developing countries have been proposed. Three aspects of design regarded as fundamental for energy systems in rural areas of developing countries have been studied, namely the increased access to modern energy as the main purpose of design, the representation of regional differences in the design, and the incorporation of aspects related to rural development.

Chapter 1 introduced the background and goal of research, as well as the framework for research. Improving the conditions for increased access to modern energy in developing countries is fundamental to raise the quality of life of poor population in these countries. The large gap in access to modern energy in rural areas, compared to urban areas, is one of the major issues facing energy planners in developing countries. Solving this issue involves increasing access to electricity for 1.6 billion people and promoting the substitution of traditional biomass for 2.4 billion people in the world.

The theoretical background provided in Chapter 2 introduced the general concepts found in the literature dealing with the relationship between energy and development. In addition, the application of models for the design of energy systems in rural areas of developing countries has been reviewed. Energy system design has been traditionally aimed at procuring stability of energy supplies, promoting growth in macroeconomic output, and mitigating environmental impacts from energy use, namely greenhouse gases and air pollutants. Although these targets are fundamental to secure the sustainability of the energy system in terms of technical, economic and environmental aspects, energy access and rural development have to be equally considered

for the case of developing countries. Previous research on the application of energy models considering rural areas in developing countries has been classified according to five aspects of energy systems, namely the design of decentralized energy systems, the optimization of systems for allocation of agricultural resources, the assessment of impacts of rural electrification, the assessment of substitution of traditional biomass, and the incorporation of aspects related to rural areas into complex energy models. In summary, model applications have little or no description of regional differences. Moreover, they lack any integration of energy access and rural development targets along with the inclusion of regional differences.

In Chapter 3 the design of decentralized energy systems focuses on the electrification of remote areas using renewable energy technologies. Substitution of traditional biomass for cooking has been analyzed in addition to the introduction of these technologies to meet current electricity demand in remote areas. Employment generation has been used as indicator of the effect on rural development, and has been integrated with other aspects of system performance by means of a multi-objective method called goal programming. Application of the model for the case of localities outside the area served by the national electricity grid in Colombia shows that high cost of diesel fuel, due to long transportation distances, provides an opportunity to introduce renewable technologies that usually have high capital costs. Moreover, simultaneous integration of multiple aspects of system performance allows for more flexibility in the design, since aspects usually overlooked by other methodologies can be used directly as design criteria disregarding that such aspects are measured in different units. Substitution of traditional biomass for cooking with electricity from the renewable energy system can result in larger benefits than a diesel generation scheme, yet electricity costs increase sharply compared to the low cost of traditional biomass. Characterization of regional differences according to population size shows that fuel substitution is linked to the relation between demand and resource availability. Jobs derived from system operation have low incidence on global poverty reduction in remote areas, therefore other factors must be considered for measuring the effect of energy access on rural development.

Chapter 4 has addressed the design of decentralized energy systems for electrification using local biomass resources considering regional disparity. The target area has been disaggregated into urban, rural and remote areas, dividing them into regions with and without access to electricity. A linear programming model has been applied evaluating system performance from the perspective of electricity suppliers and households. Net local income in households has been used as indicator for rural development. For the case of a region in Colombia, electrification with local biomass highly benefits remote areas as an alternative to current diesel generation schemes. Using agricultural waste for electricity generation provides a source of local income at modest increase in electricity costs, in particular in rural areas. Increased use of local biomass for electrification must consider the potential growth in electricity demand due to fuel shift in order to improve the system performance in terms of conversion efficiency and costs. Promoting rural development through the use of local biomass resources is limited by high transport and fuel costs associated to biomass-based electricity. Implementation of cross-subsidies and electricity trade

among regions, and financing the system with carbon emissions reductions are potential mechanisms that may enhance financial performance of decentralized systems. The effect of decentralized systems on reduction of disparity is evident only in terms of the stability of resource supply, thus a comprehensive evaluation must include the contribution of local biomass to reduction of expenditures, and the capacity and willingness to pay of households for increased access to electricity.

Chapter 5 has addressed the design of decentralized energy systems for increasing access to modern energy services. For that purpose, the optimization model formulated in Chapter 4 has been extended, describing the demand of useful energy by services and the allocation of final energy sources in end-use devices for different regions. Moreover, payment capacity of household for energy services has been introduced as a constraint in the formulation. Application of the model for a region in Colombia shows that minimization of system costs results in changes at regional level. For instance, increase in the share of modern energy sources in total final energy supply is less than 5%, while shares rise between 5% and 15% in rural and remote areas, respectively. Among scenarios considered, an alternative scheme focusing on the use of local biomass resources provides the highest global share of modern energy sources, introducing modern energy for lighting and efficiency improvements in cooking due to penetration of improved biomass stoves in all regions, and biomass-based electrification in remote areas. Compared to the conventional scenario, alternative scenarios reduce system costs and energy expenditures in households, especially in remote areas, while mixed results are obtained for CO_2 emissions. Increasing access to modern energy services in the target area promotes fuel transition in rural areas, while the effect in remote areas is delayed significantly. Transition to modern energy does not affect significantly the system performance, and large benefits can be expected from higher penetration rates of electricity, LPG and gas in households.

In Chapter 6 an alternative approach for designing energy systems for increasing energy access and promoting rural development in developing countries has been proposed based on the conventional process for designing national energy systems. Contrasting features of energy systems in rural areas of developing countries compared to the conventional approach are the basis for introducing new concepts in the design process and for testing the suitability of energy model applications for system design. The alternative approach recognizes improving energy access conditions and promoting rural development as part of the design needs in addition to the fulfillment of energy demand. This requires a more detailed characterization of the demand by regions and energy services, considering a larger set of options in final energy sources and end-use devices, as well as a broader range of stakeholders in decision making. Consultation with local governments and communities along with the national government and energy suppliers, should point out specific targets and priorities among regions for achieving the design requirements. These requirements include securing better access to modern energy and improvement in development indicators in rural and remote areas, in addition to the available stock of energy resources, the technical stability of supply, system profitability, and compliance with regulations. The design concept in the alternative

approach extends the set of options including local resources, decentralized conversion technologies, and traditional and improved end-use devices. The final design must describe the quantity of resources and the capacities of technologies in the light of regional differences, and characterize system performance according to the achievements in energy access and rural development. Taking into account the alternative approach for energy system design, the capability of energy models to incorporate the aspects of system design of developing countries must be reconsidered. Suitability of models depends on the availability and quality of data needed to quantify and represent through mathematical expressions the features of rural and remote areas in developing countries.

General outcomes of this thesis, summarized in Chapter 7, show that shifting from foreign fuels and traditional biomass to local resources in the form of biomass and other renewable resources for energy supply provides significant benefits to rural households, in particular in remote areas. Essential parameters that drive the design of the system include the availability of local resources in each region, the cost of transporting fuels, the capital cost of conversion technologies using local resources, the priority given to different design targets, and the payment capacity of households for energy expenditures. Main findings indicate that energy system design differs among regions. On one hand, alternative systems using local resources are more suitable design for remote areas. On the other hand, penetration of local resources in rural areas is limited due to the proximity to supply centers of fuels and electricity. In general, the effect of alternative systems on local development is greater in remote areas. Nevertheless, if use of local resources is promoted, larger benefits are observed first in rural areas. Regarding access to modern energy, increasing the share of modern energy forms and services not always has negative impact on system performance. For instance, use of local resources may increase supply costs, but significant benefits may offset such cost increments. Substitution of traditional biomass is constrained by large cost differences between these fuels and modern options. Substitution of wood for cooking depends on large availability of local resources, on the internalization of benefits resulting from fuel substitution, and on the inclusion of other design criteria in the design process.

This research contributed to the application of mathematical models for the design of energy systems in developing countries with high rates of urban population. Since reduction of disparity is a major factor for improving the quality of life in urbanized countries, models introduced in this research focused on the characterization of options for energy supply in remote areas, and the description of regional differences in terms of energy supply and demand. The regional dimension of energy system design leads to more suitable models, which have involved a considerable effort for the collection and processing of data disaggregated by regions. Future tasks for research include the incorporation of other aspects of rural energy systems in design, in particular the description of spatial configuration of the system, the assessment of effects across different income groups, and the application of other methodologies such as geographic information systems and dynamic models.

論文審査結果の要旨

開発途上国のエネルギーアクセスを向上させるためには、地域に散在するエネルギー資源の利活用技術と、それを支援する地域社会のシステム設計が重要である。なかでも、小水力発電等の分散型電源やバイオマス資源は、地域の気象条件や生態系に密接に関係するので、エネルギー需給システムの詳細なモデル化と特性評価に基づくシステム設計がきわめて重要となる。本論文は、開発途上国(Colombia)を、既存のエネルギー供給設備の整備状況に基づいて都市部(urban)、地方部(rural)、遠隔地(remote)の三地域に分類して、各地域の特徴に合致するエネルギーシステムを設計することを目的としている。エネルギーシステムの適正要素と需給均衡を最適化モデルによる解析によって初めて解明したものであり、全編7章から成る。

第1章は序論であり、本論文の目的、構成、背景について述べている。

第2章では、開発途上国を対象とするエネルギーアクセス研究の先進事例を調査し、それら研究手法の理論的なアプローチ手法を総括している。エネルギーの近代化の効果を、人間開発指数、国連ミレニアム開発目標、低炭素化など多様な観点から洞察している。

第3章では、遠隔地を対象として、再生可能エネルギー利用の分散型電源と既存のディーゼル発電機との組合せから成るエネルギーシステムを、多目的最適化手法を用いて設計している。集落規模を大中小の三領域に分割して解析し、各規模に応じた集落電化の恩恵を、コストベネフィット、雇用、土地利用等の各視点から明らかにして、重要な設計指針が得られている。

第4章では、三地域を対象として、偏在するバイオマス資源を用いる分散型発電を新設して、既設の系統電力網を補完するエネルギーシステムを、線形最適化手法を用いて設計している。多様なバイオマス発電機器の変換効率等の影響を詳細に解明し、経済性、CO_2排出量等の各観点から最適なシステム構成を明らかにして、有益な設計指針を導いている。

第5章では、熱エネルギー需要に着目して、その用途（調理、暖房、照明）と熱源（薪炭、灯油、軽油、LPG）の組合せを、線形最適化手法を用いて解析している。供給資源の近代化に伴う影響を系統立てて解明し、エネルギーシステム設計にきわめて重要な成果を得ている。

第6章では、以上で得られた知見をもとにして、開発途上国のエネルギーシステムの設計指針をまとめていて、地域特性、技術性能を内生化した具体的な設計方策を明示している。

第7章は、結論である。

以上要するに本論文は、開発途上国のエネルギーアクセス向上と地域社会の発展に向けた分散型エネルギーシステムの設計指針を初めて明らかにし、エネルギー供給の最適構成と社会への影響を明示したもので、熱工学およびエネルギーシステム工学の発展に寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として合格と認める。