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Energy Policy 35 (2007) 4391–4401

ENERGY POLICY

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Evaluating the potential of small-scale renewable energy options to meet rural livelihoods needs: A GIS- and lifecycle cost-based assessment of Western China's options

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Received 22 September 2006; accepted 14 February 2007

Abstract

The economics and livelihoods impacts of stand-alone, small-scale (less than 2 kW) renewable energy technologies for rural electrification are assessed using a representative sample of 531 rural households in three provinces of Western China. Over 20 small wind, photovoltaic (PV) and wind–PV hybrid configurations were evaluated for their potential to meet local electricity needs. The assessment integrates lifecycle costing and geographic information system (GIS) methods in order to provide a comprehensive resource, economic, technological and livelihoods assessment. The results of the analysis indicate that off-grid renewable energy technologies can provide cost-effective and reliable alternatives to conventional generator sets in addressing rural livelihoods energy requirements. Findings also demonstrate the existence of a sizeable market potential for stand-alone renewable energy systems in Western China. In support of market development for these technologies, policy recommendations are provided.

Keywords: Renewable energy; Rural development; GIS resource assessment

0. Introduction

Electricity service can bring tangible social and economic benefits to rural communities which represent 52% of the human population (UN, 2004). More than 2 billion rural residents in developing countries currently lack reliable electricity service (UNDP, 2004), indicating a significant livelihoods threat if the problem is not addressed. The Millennium Goals described by the 2002 World Summit on Sustainable Development include a recognition of this problem (UN, 2002). Reversing the historical trend of development patterns that have largely neglected such populations will not be easy, but the importance of doing so is increasingly accepted (Zhou and Byrne, 2002).

Small-scale diesel/gasoline generators have been used for decades to serve off-grid, rural electricity needs. But the technology poses a series of special technical, economic and environmental problems for rural communities (see, e.g., Byrne, 1996; Byrne et al., 1998, 2001). Micro-hydropower appears to be a more suitable solution, but is limited to areas where the resource is available (Martinot and Wallace, 2003). Wind and solar energy can offer viable sources of electrification in geographic areas of the developing world and may, therefore, be the most widely available options to meet off-grid electricity demand. The paper focuses on these two options.

1. Methodology

To evaluate solar and wind resource availability and the economic feasibility of such renewable energy options, a spreadsheet-based computer simulation model called *Rural Renewable Energy Analysis and Design* (RREAD)[2] was

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[2] RREAD was developed by the Center for Energy and Environmental Policy (CEEP), University of Delaware during a research project sponsored by the National Renewable Energy Laboratory in the US Detailed dissertation of the model and the project can be found in Shen (1998).

0301-4215/$ - see front matter
doi:10.1016/j.enpol.2007.02.022

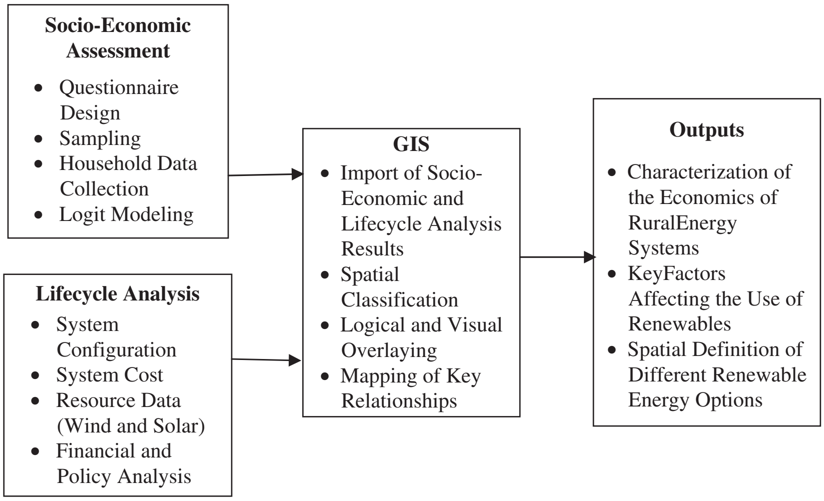

Fig. 1. Conceptual framework of the socio-economic assessment study.

created. This multidimensional simulation tool evaluates the energy and economic performance of off-grid renewable energy technologies including photovoltaic (PV), wind and PV/wind hybrid systems in comparison with conventional gasoline or diesel generators (Byrne et al., 1998; Shen, 1998; Zhou and Byrne, 2002). Hourly data on solar and wind resource availability are processed in RREAD in a technology performance model that includes efficiency and other specifications of renewable energy equipment in order to forecast energy output over the life of different devices. Costs, economics and social and environmental benefits are estimated over the lifetimes of small-scale renewable energy technologies and discounted to the present values in order to evaluate their likely economic impacts.

To assess the socio-economic potential of renewable energy options in rural settings, a comprehensive survey and rural household sample are used to obtain a statistically representative profile of rural energy users.[3] Household survey data, combined with socio-economic statistics, are analyzed with a logit regression model to identify social, economic and technical factors affecting the choice of rural renewable energy options. The model enables the research to isolate statistically robust explanatory variables that offer accurate estimates of household willingness to acquire different energy technologies.

The final step involved the use of geographic information system (GIS) mapping technology to represent in spatial form the socio-economic potential of three renewable energy options for household electricity supply stand-alone small PV system (less than 0.15 kW), stand-alone small wind systems (less than 0.5 kW) and PV–wind hybrids with combined capacities of less than 0.6 kW. GIS methods offer the opportunity to pinpoint the potential size of rural renewable energy demand by combining the parameters of the logit model and lifecycle analyses of system resource and economic performance. The conceptual framework of our socio-economic assessment study is illustrated in Fig. 1.

2. Profile of the three provinces

Over the past three decades, China has dramatically expanded its power supply, including services to rural areas. As a result, over 95% of its rural population has access to electricity (China Statistical Bureau (CSB), 2000, 2003, 2005). Primary strategies for rural electrification have entailed the extension of power grids and the exploitation of small hydropower, or micro-hydro.

However, in spite of these efforts, over 30 million people living in the country's rural areas (more than half of whom reside in Western China) still lack access to electricity (Wang et al., 2004). Additionally, approximately 500–660 million people routinely experience unreliable power supply (Wang et al., 2004; China Statistical Bureau (CSB), 2000, 2003, 2005). Most residents in Inner Mongolia Autonomous Region (IMAR), Qinghai Province and Xinjiang Uygur Autonomous Region experience one or both of these problems.

Grid electric planning is unlikely to meet the needs of the region. Projected electricity demand between 2010 in the three provinces is provided in Table 1.

Table 1 indicates that electricity demand is forecast to increase by 39% from 2005 to 2010, with Xinjiang experiences the highest growth rate (61%). Compared to projected national average growth of 47.1%, electricity demand in the three provinces will be slower. Much of the new demand will be in urban areas and will be met by

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[3] As described below, CEEP collaborated with Chinese research partners from the Ministry of Agriculture and the Chinese Academy of Science to interview 531 rural households spread over 22 counties throughout Western China in order to characterize rural energy users in the investigated regions.

Table 1
Projected electricity demand for IMAR, Qinghai and Xinjiang (TWh): 2005–2010

	2005 (actual)	2010 (projected)	Growth percentage (%)
IMAR	35.0	42.0	20.0
Qinghai	18.0	24.9	38.3
Xinjiang	31.0	49.9	61.0
Subtotal	84.0	116.8	39.0
Nationwide	2474.7	3640.0	47.1

Source: State Grid Corporation (2006); IMAR Economic Information Network (2006); Liu (2006).

Table 2
Profile of IMAR, Qinghai and Xinjiang

Indicators	IMAR	Qinghai	Xinjiang
Area size (million km^2)	1.183	0.721	1.647
Population (million)	23.84	5.39	19.63
Rural population (million)	13.11	2.70	12.72
Average rural household size (persons)	4.5	5.1	4.8
Average farmer per capita net income ($)	320	250	280
Average net rural household income ($)	1440	1275	1344

Source: CSB (2005). *Note*: Net income refers to money earnings after routine costs of shelter, clothing, food, health care, tax and fees are deducted. The CSB estimate this amount based on in-person surveys.

additional power plants planned by the government. Only very small portion will be supplied by renewable energy.

But this projection does not include the needs of off-grid communities. To meet these needs, the grid would have to be extended. The cost of grid extension is estimated to be \$5000–\$12,750 km^{-1} (State Power Information Network, 2006). Population densities in remote areas can be as low as 3 persons/km^2. Electrification via grid extension in this region could therefore be prohibitive. For example, in Xinjiang, electrifying households in an area with a population density of 10 persons/km^2 would cost \$32,500 per household (State Power Information Network, 2006). Generally, the lifetime of grid lines in the area is about 20 years. Therefore, the annual capital cost of grid extension is \$1625 per household (State Power Information Network, 2006). The high capital cost of grid extension in these circumstances has discouraged government investment (Ma, 2004).

Government statistics on rural electricity use in IMAR, Xinjiang and Qinghai reveal electricity consumption to be approximately 500 kWh/year (Li, 2006). The grid-based electricity price to households in this area would then be roughly \$3.32 kWh^{-1}. By contrast, our research (see below) estimates per kWh costs from solar-wind hybrid system to range from \$0.26 to \$0.89, considerably less than the unsubsidized cost for grid service. For this reason, many families and villages in Western China cannot expect grid service to affordably meet their daily energy needs.

Table 3
Rural households without electricity in IMAR, Xinjiang and Qinghai

Regions	Total rural households	Rural households without electricity	Percentage without electricity (%)
IMAR	2,913,000	249,590	8.6
Qinghai	529,000	101,000	19.1
Xinjiang	2,650,000	316,200	11.9
Total	6,092,000	666,790	10.9

Source: CSB (2005); Wang et al. (2004).

The basic socio-economic profile in the three provinces is presented in Table 2. Rural family net incomes for the region are below China's national rural average of \$1500 (CSB, 2005).

2.1. Status of rural electrification in the three provinces

Some 666,790 rural households in IMAR, Qinghai and Xinjiang provinces lacked reliable power supply in 2004 (Wang et al., 2004). These households (including herdsmen, farming families and those with rural commercial businesses) are distributed among the three provinces as shown in Table 3.

2.2. Resource potentials in the three provinces

While wind resources in Xinjiang appear less substantial than those found in Qinghai or IMAR, the region's solar resource remains abundant. In fact, Xinjiang with Tibet registers more sunshine hours on average than other regions in China. Details regarding renewable energy resources in the three provinces are displayed in Table 4.

Figs. 2–4 illustrate the abundance of wind and solar resources in Western China. As Figs. 3 and 4 indicate, the wind resource in IMAR remains substantial in nearly all counties, while a smaller number of counties in Xinjiang and Qinghai offer promising resource conditions for wind development. Only a few counties in the northern reaches of Xinjiang and even fewer counties in north and central Qinghai provide reasonably good wind applications.

Compared with wind power potential, solar resources among the regions are distributed more evenly (see Fig. 2). Most counties in IMAR boast reasonably good solar radiation, with possibilities for small-scale, complementary solar-wind development. At the same time, nearly all counties in Qinghai receive significant solar radiation (>1800 kWh/m^2). Within the autonomous region of Xinjiang, solar potential appears especially encouraging. Its southern and western counties experience good to excellent solar radiation, with significant opportunities for

Table 4
Wind and solar energy resources in the three provinces

Regions	Wind energy density (W/m^2)	Hours of wind speeds above 3 m/s per year	Hours of wind speeds above 6 m/s per year	Total solar insolation per year (kWh/m^2)	Hours of sunshine per year
Resource-rich region	>150	>4000	>1500	>1500	>2800
IMAR	100–300	4000–7000	1000–4000	1400–1740	2800–3400
Qinghai	—	1168–5912	184–1304	1829–2014	4386–4476
Xinjiang	—	906–2700	18–876	1708–2006	4406–4704

Source: Deng and Jiao (2002).

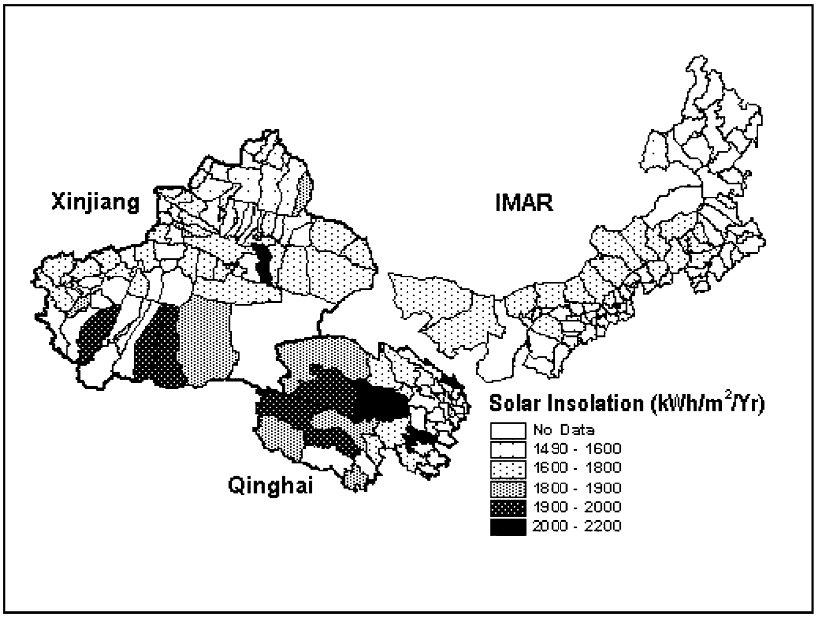

Fig. 2. Annual solar insolation in IMAR, Xinjiang and Qinghai (kWh/m^2/year).

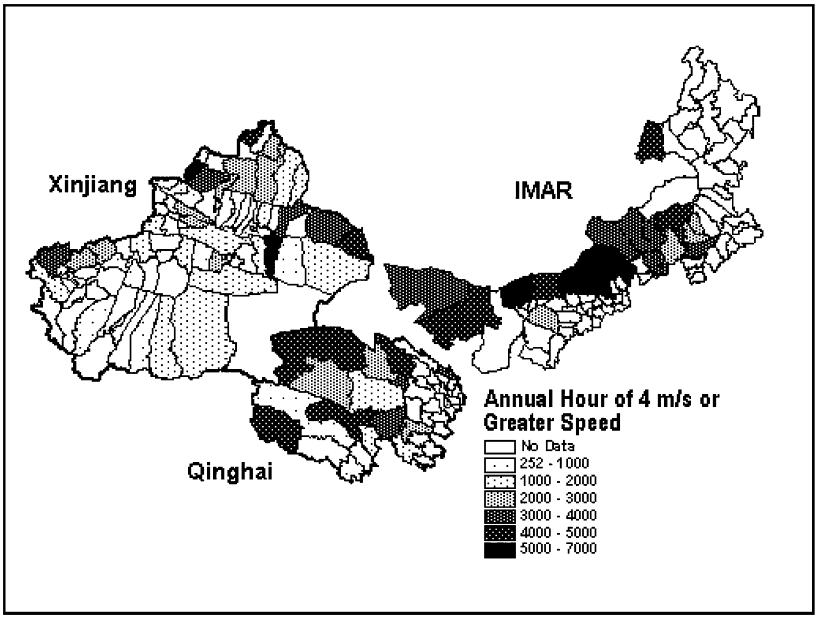

Fig. 3. Annual hours of wind resource (⩾4 m/s) in IMAR, Xinjiang and Qinghai.

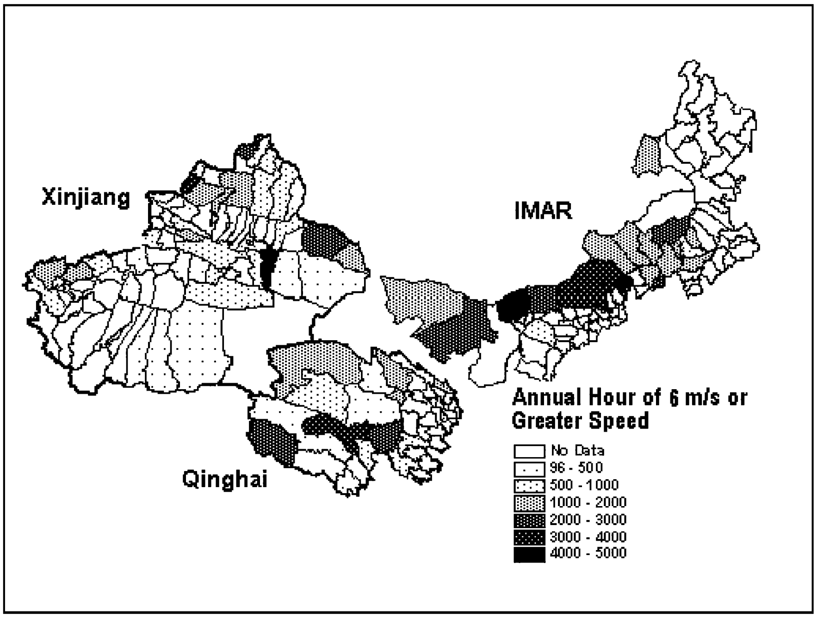

Fig. 4. Annual hours of wind resource (⩾6 m/s) in IMAR, Xinjiang and Qinghai.

developing solar PV home systems and community PV generation.

2.3. Existing institutional framework for rural electrification

Currently, rural electrification is administered by three central government agencies: the National Development and Reform Commission, the Ministry of Agriculture and the Ministry of Water Resource. Local agencies—Rural Energy Offices (REOs) and local utilities—implement the 5-year plans decided by the central government. Despite the fact that overall administrative responsibility resides with the national agencies, REOs and service stations play a significant role in rural energy development in China. Since 1999, grid-based electrification has been a major form of national economic reform. There has been a connected effort to create a uniform pricing policy for urban and rural areas, but low electricity consumption in remote areas, high T&D losses and costly extension have slowed the reform process (Peng and Pan, 2006). As a result, national and local policy has emphasized the improvement of off-grid electricity systems for many rural areas (Ma, 2004).

3. Economics of stand-alone renewable energy systems in Western China

3.1. Levelized cost analysis

Applying technical criteria of supply capacity and energy reliability to system design, more than 20 configurations of PV, wind and hybrid systems appear suitable for use by rural households at the scales depicted in Figs. 2–4. Favorable configurations for these systems can be grouped according to generating technology, with PV systems at 22–120 $\mathrm{W_p}$ and wind systems at 100–300 W. Among hybrid systems, the following configurations were identified: 35 $\mathrm{W_p}$ PV—100 W wind to 60 $\mathrm{W_p}$ PV—100 W wind; 35 $\mathrm{W_p}$ PV—200 W wind to 100 $\mathrm{W_p}$ PV—200 W wind; and 60 $\mathrm{W_p}$ PV—300 W wind to 120 $\mathrm{W_p}$ PV—300 W wind.

All systems utilize Chinese-made PV arrays except for the 120 $\mathrm{W_p}$ PV system (a US technology). Wind systems were also obtained from local Chinese manufacturers, and we were unable to identify US, European or Japanese companies who could offer wind turbines at the small power ratings described above, an indicator that rural energy needs are better understood technically within developing countries. Additional equipment offered by Chinese suppliers includes batteries and charge controllers, but DC/AC inverters are frequently imported in China.

Partially because the bulk of equipment for small-scale renewable energy systems can be made in China, system costs average less than \$7.39–\$7.55 $\mathrm{W_p}$ for PV configurations, \$1.70–\$2.78 W^{-1} for wind generators and \$2.28–\$3.54 W^{-1} for hybrid systems. While the China–US project secured a US Department of Energy grant creating a revolving loan fund for the pilot project, few financing options exist in general for off-grid energy development within China's rural communities (Byrne et al., 1998; Shen, 1998; Zhou and Byrne, 2002; Stroup, 2005).

Despite the absence of loan funds, the results of our survey of Western Chinese communities indicate that most, but not all, rural households believe they can afford small-scale PV, wind or hybrid systems. Designated costs for such systems range from \$150 to \$900 for stand-alone PV systems, \$225 to \$600 for wind systems and \$450 to \$1300 for hybrid systems. Depending upon income level, household savings accumulated over 2–5 years would typically be required for purchase of the renewable energy systems analyzed by CEEP for the China–US project (Byrne et al., 1998; Shen, 1998; Zhou and Byrne, 2002; Stroup, 2005).

As current trends in technological availability demonstrate, the development of a renewable energy sector to meet rural needs is underway in China. Presently, more than 60,000 small wind turbines are operating in IMAR, and approximately 400,000 small PV systems are in use across all three provinces (Stroup, 2005; see also Li, 2001). These systems have been manufactured by a growing rural industry in Western China, specializing in small-scale renewable energy systems.

3.2. Comparative cost analysis

Cost comparisons of household-scale PV, wind, PV/wind hybrid and conventional fossil-fueled small generators were prepared for 11 counties across the three provinces. The assumptions and parameters underlying the cost analyses of these systems are extensive, and receive detailed description in the original report to the National Renewable Energy Laboratory (Byrne et al., 2001).[4] Standard analytical techniques were used to estimate *levelized costs*,[5] enabling a full, life cycle cost comparison of the systems under study with each technology evaluated at its maximum energy (kWh) generation. In order to compare the economics of different technologies, we based our analysis on the combination of installed capital costs and operating, fuel and maintenance expenditures over the lifetime of each system.[6]

Our analysis indicates that the least-cost configuration for household-scale, stand-alone generation differs among the counties and provinces under study (see Table 5). Wind-only and hybrid systems provide the least-cost options for IMAR, while PV-only and hybrid systems represent the most cost-effective choices for Qinghai and Xinjiang. Small gasoline/diesel generators are higher cost in all cases. This is due to the significant cost of delivered fuel in rural areas.[7]

Table 5
System levelized costs in IMAR, Xinjiang and Qinghai[a]

System	Province	Output range (kWh/year)	Levelized cost ($/kWh)
Wind-only	IMAR	196–640	0.22–0.53
	Qinghai	27–342	0.25–1.20
	Xinjiang	38–212	0.23–1.53
PV-only	IMAR	37–225	0.45–0.62
	Qinghai	47–328	0.48–0.59
	Xinjiang	55–400	0.45–0.60
PV/wind hybrids	IMAR	256–860	0.24–0.58
	Qinghai	102–663	0.29–0.75
	Xinjiang	95–538	0.26–0.89
Gas/diesel gen-set	All	481–554	1.09–1.19

[a] The levelized cost is calculated using $\$5\,W_p^{-1}$ of PV (obtained from Wang et al. (2004) and \$88, \$194, \$285 for 100, 200 and 300 W wind turbines (from Deng and Jiao, 2002).

Importantly, in all three provinces, renewable energy systems are economically superior to conventional energy options, even before social and environmental benefits are included. The quality of the renewable energy resource influences the generating capacity of the PV and wind components by county or by province, but it does not affect the overall ranking of the most to least costly means of providing energy service. Nor does it significantly affect the magnitude of the cost differences among the technologies. The reason in that storage and power conditioning costs are substantial over the life of off-grid renewable energy systems, regardless of whether they are wind or solar powered.

The results of our levelized cost analyses suggest that wind–PV hybrid systems can meet increased energy demand at relatively stable costs for users in IMAR. In fact, such hybrids prove less expensive than gen-sets, which can suffer long downtimes in the interruption of service due to maintenance needs, parts failures and fuel shortfalls. For Qinghai and Xinjiang, hybrid systems are economically attractive for some, but not most, counties and must therefore be taken in promoting their use.

The lowest levelized cost for each county that could be provided by the 21 renewable energy systems was obtained through RREAD. To correlate the spatial wind and solar resource distribution with levelized costs, researchers at CEEP utilized ARCView geographic information software. More specifically, maps were created to display resource distributions for solar insolation, wind speeds of 4 m/s and higher and wind speeds of 6 m/s and higher (see Figs. 2–4 above), as well as levelized costs. The mapping of resource potential and cost enabled us to select the lowest cost system for each county in the three provinces (see Fig. 5 below).

By comparing resource conditions with levelized cost (Fig. 5), it is then possible to estimate rural demand for small-scale, stand-alone wind, PV and wind–PV hybrid systems. For IMAR, stand-alone wind offers the lowest

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[4] Updated 2004–2005 costs for several parameters were collected subsequent to the project report and are found in the Appendix.

[5] *Levelized costs* are defined as the total discounted costs of energy systems standardized over the evaluation period by obtaining a *levelized* annual discount factor using the annuity concept in financial analysis.

[6] Off-grid PV systems in rural China have an expected lifetime of 15 years while wind turbines normally last 10 years. Battery lifetime, as claimed by manufacturers, is 3 years for a wind-only or a small PV/wind hybrid system, 4 years for a PV-only system and 5 years for a large PV/wind hybrid system. Field experience, however, suggests that Chinese batteries normally last only 1 year for wind and small hybrid systems and 2 years for PV systems and large hybrids. The charge controllers and the DC/AC inverters typically have lifetimes of 10 years.

[7] Delivered fuel includes the sale price of the fuel plus its delivery to the user. In rural China, delivery can be arranged by truck; alternatively, the user can set aside one or more days to retrieve the fuel (in this case, the user's estimated time costs can determine the expense of delivery). In our surveys of households, vendor delivery was usually regarded as cheaper by households.

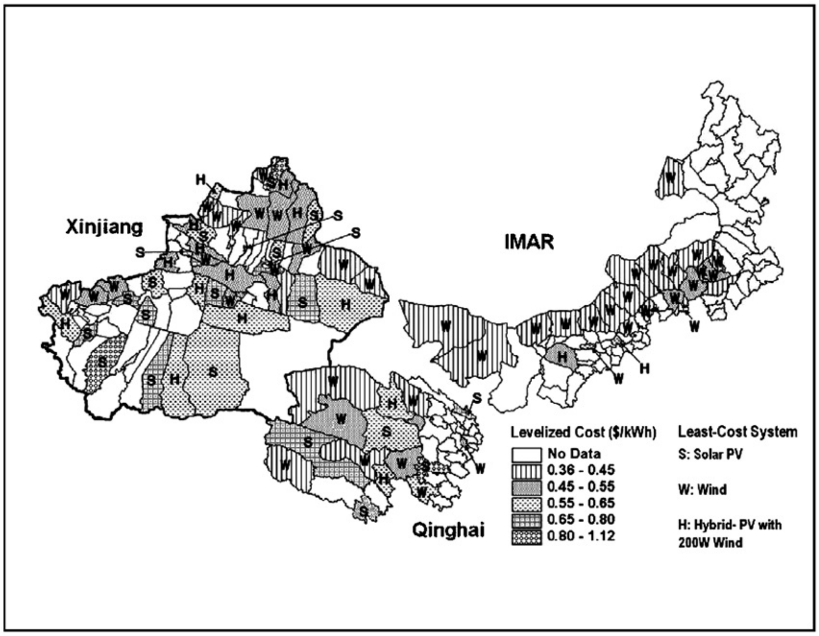

Fig. 5. Levelized cost distribution and system selected for counties in the Inner Mongolia Autonomous Region (IMAR), Xinjiang and Qinghai (*Source*: Byrne, 2005).

cost for rural off-grid users in most counties, but several counties remain where hybrid systems represent the least-cost option. In Xinjiang and Qinghai, small-scale, stand-alone PV systems serve as the most economical choice for the bulk of the region. Accordingly, demand for hybrid systems is expected to be modest for these provinces, but could prove increasingly important as household demand for electricity grows.

Together, Figs. 2–5 suggest the outline and structure of a clear renewable energy development agenda for Western China. The maps help identify the types of renewable energy systems best suited for specific counties, in terms of resource availability and economic value for rural households. In this manner, they may assist decision making in public policy, allowing provincial government planners and policymakers to set technology and market development priorities. Similarly, through business modeling for investment and related opportunities, the private sector can market renewable energy technology and invest in appropriate infrastructure as targeted to best serve rural community energy demand. Finally, international organizations can more accurately address regional needs in the design of technology transfer, joint ventures, capacity building and financing.

4. Socio-economic assessment and market potential study

4.1. *Household survey*

Our household energy survey administered in-person to 531 families in the region (see Zhou and Byrne, 2002, for details) provides comprehensive data regarding rural energy supply and consumption patterns in the three provinces, with particular emphasis on social conditions and preferences.

Table 6
Survey-based socio-economic profile of three provinces

Indicators	IMAR	Qinghai	Xinjiang
Annual gross household income ($)	3480	2881	2157
Annual household expenditure ($)	2374	1905	1245
Energy expenditure ($)	129	105	96
Annual net household income ($)	1106	976	912

Respondents in IMAR indicated that they rely on livestock for income generation, while households in Qinghai and Xinjiang depend on both agricultural and non-agricultural sources of income. Averages for energy and total household expenditures are presented in Table 6. Comparing Tables 2 and 6, it is evident that the surveyed populations have lower incomes. This is because the survey was administered exclusively to families in relatively remote areas without grid electricity access.

The survey also identified preferences and beliefs regarding the desired structure of a household electricity system. Conventional centralized models found in the US and other industrialized countries deliver electricity access via long transmission lines, a model increasingly adopted in developing nations under the rationale that centralized systems can enhance the quality of rural lives. However, the results of the household survey suggest that many residents of IMAR, Xinjiang and Qinghai disagree with this premise. According to respondents, decentralized off-grid energy systems for household use in rural areas represent a preferable alternative to conventional electricity delivery (see Byrne et al., 1998; Stroup, 2005).

In the context of electricity reliability, respondents were asked to share their concerns regarding possible energy shortages linked to the use of renewable resources. These issues have surfaced amid concerns that energy shortages remain inevitable with proliferation of renewable energy systems, as the variability of solar radiation and wind speeds determines resulting energy output. However, in considering such concerns, respondents from Qinghai and Xinjiang provinces suggest that rural users perceive renewable energy as reliable according to the technology utilized. More specifically, 69% of respondents in Qinghai believe PV systems to be reliable, while 26% and 4% of respondents, respectively, find PV/wind hybrid systems and wind turbine systems alone to be reliable. In Xinjiang province, 72% of respondents identify PV/wind hybrid systems as reliable, while 16% consider PV systems reliable and 11% perceive wind systems as such. As these findings in Western China demonstrate, renewable energy systems can indeed be regarded as reliable in meeting the needs of rural users, so long as appropriate technological configurations are offered.

Surveyed households also signaled their economic support for stand-alone renewable energy systems in meeting energy demands. In Qinghai and Xinjiang, more than 90% of respondents expressed their willingness to pay for renewable energy systems. In IMAR, more than half of respondents indicated that they would be willing to spend as much as \$1200 for such systems, while 44% supported purchase prices in the range between \$1200 and \$2400; some 3% signaled support for the purchase of stand-alone renewable energy systems exceeding \$2400 in price.

In the survey, none of the respondents preferred to buy generators or to develop other types of energy systems based on the use of fossil fuels. This finding may be attributed to the high costs of delivered fuel in the three regions and to extensive maintenance requirements often linked to fossil fuel-reliant generators. Both factors, as expressed through the opinions of rural energy users, make such conventional energy systems and fuels less reliable than renewable energy systems.

Finally, survey results for IMAR, Xinjiang and Qinghai suggest that capital cost, equipment quality and after-sale services represent the most important criteria affecting purchasing decisions regarding renewable energy systems. In particular, maintenance and service issues related to battery malfunctioning and short battery life greatly affect attitudes toward renewable energy systems. Potential improvements in batteries, strategies for addressing after-sale services and policy interventions to improve system affordability thus appear crucial in developing the renewable energy sector in Western China. These actions would simultaneously encourage positive attitudes toward renewable energy options and improve the socio-economic conditions of rural life.

4.2. *Socio-economic potentials in the three provinces*

A socio-economic study was also undertaken by CEEP to estimate potential demand for rural renewable energy systems in Western China. The study utilized a logistical regression model (LRM) to identify key predictors of future users among different renewable energy systems. County and provincial statistics were also employed to estimate the demand for these systems. Under this approach, variables for household income and expressed interest in purchasing small-scale renewable energy systems have been matched with resource and system output data. The goal was to establish the proportion of households in each province preferring different configurations of energy systems for their families.

Results of the logistical regression analysis suggest that three general factors—household financial status (annual income versus annual expenses), household size and housing area—serve as key predictors of which renewable energy system a household is likely to favor. The LRM used in the research is interpreted using the odds ratio, which represents the probability of a success compared to the probability of failure. By using a mathematical method called maximum likelihood estimation, a LRM can be created to predict the natural logarithm of the odds ratio. From sample data, one can create the following model:

$$\ln(\mathrm{EOR}) = a_0 + a_1X_1 + a_2X_2 + \cdots + a_kX_k.$$

Here, EOR is the estimated odds ratio; a_i the regression coefficients; X_i the independent variables.

Once the LRM has been fitted to a set of data, one can calculate the estimated odds ratio, or EOR, by raising the constant e to the power equal to the natural logarithm of the estimated odds ratio. For this purpose,

$$\mathrm{EOR} = \mathrm{e}^{\ln(\mathrm{EOR})}.$$

The probability of success can be estimated after having the EOR:

$$\text{Probability of success} = \mathrm{EOR}/(1 + \mathrm{EOR}).$$

While rural households in Western China express strong preferences for renewable energy systems (either PV, wind or hybrid systems), the percentage of those willing to pay market prices is smaller than the percentage of those willing to own. This finding, in turn, may be explained by two phenomena. On the one hand, although a sizable interest in renewable energy technology appears evident in Western China, the organization of the sector—especially, its enterprise formation—is in its early stages of development. At the same time, the capacity of rural households to pay current prices for the technology remains limited. These conditions suggest that the rural renewable energy industry, if it is to grow, must overcome a series of economic barriers. A breakthrough in this regard could stimulate a more robust opening for widespread utilization of renewable energy technologies in Western China (Table 7).

Table 7
Analysis of demand for renewable energy systems in the three provinces: willingness to own and pay for renewable energy systems

Regions	Willingness to own (%)				Willingness to pay for renewable systems (%)
	PV	Wind	Small hybrid	Large hybrid	
IMAR	93.00	95.41	64.71	57.57	60.39
Xinjiang	91.18	78.92	73.38	66.18	51.11
Qinghai	95.19	92.82	70.26	63.54	61.55

Table 8
Market size[a] of renewable energy systems in the three provinces

Regions	Total units that could be sold (units)				Total capacity that could be sold (MW)	
	PV	Wind	Small hybrid	Large hybrid	PV	Wind
IMAR	195,793	200,867	136,234	121,202	9.79	20.09
Xinjiang	189,990	164,444	152,900	137,898	9.50	16.44
Qinghai	58,698	57,237	43,325	39,182	2.93	5.72

[a] Market size = number of unelectrified rural households in each province × % of willingness to own × % of willingness to pay.

Utilizing statistical data for non-electrified rural households in IMAR, Xinjiang and Qinghai (see Table 3), CEEP estimated the demand potential for stand-alone PV and wind systems by province/region with the following equation. Table 8 shows the results of these estimations.

5. A policy strategy for stimulating renewable energy development in rural commitments

Our research indicates that a number of reliable and economical PV and wind applications exist to adequately address rural electricity needs where grid electricity is unavailable and biomass and micro-hydro options are not significant. However, barriers—ranging from high initial costs to a lack of loan opportunities and an underdeveloped rural enterprise sector to diffuse the technology—institutional—can prevent small off-grid renewable energy applications from reaching their potential. An important lesson from China's program experience and our and others' research on this subject is that removal of major barriers can require a multidimensional response, including policy and institutional reform, market development, new financing initiatives and a concreted outreach and training effort. Below we offer a framework for addressing these multidimensional needs that can be deduced from the China case but which we believe is broadly applicable to rural off-grid commitments.

5.1. Building an institutional framework

An effective institutional framework is needed to promote renewable energy use, especially in rural areas where conventional grid connections are not feasible. In particular, renewable energy options should be integrated into national and local rural development planning. Additionally, rural electrification programs should include decentralized renewable energy technologies as an important part of the portfolio of technologies providing rural communities with cost-effective, reliable electricity services.

5.2. Creating renewable energy markets

Market transformation strategies can help to prime the economic environment for introduction and expansion of renewable energy applications. One important option here involves the establishment of renewable energy enterprise zones (REEZs), to encourage investment in industrial infrastructure and to spur low-cost manufacturing of renewable energy systems. A second option centers on the adoption of renewable energy set-asides, by which provincial and local governments set specific targets to increase their use of renewable energy.

5.3. Improving services and training for renewable energy technologies

Successful commercialization of renewable energy technologies often depends upon social acceptability. In this context, there exists a need to improve service arrangements for renewable energy systems, so that rural users have access to adequate repair and preventive maintenance assistance at the local level. A network of renewable energy service stations can be organized to diffuse off-grid systems, service them and spur technical improvements responsive to local users' evolving needs (see Fig. 6).

Central and local governments need to build strong relationships between themselves, rural users, rural renewable energy enterprises and polytechnic universities and

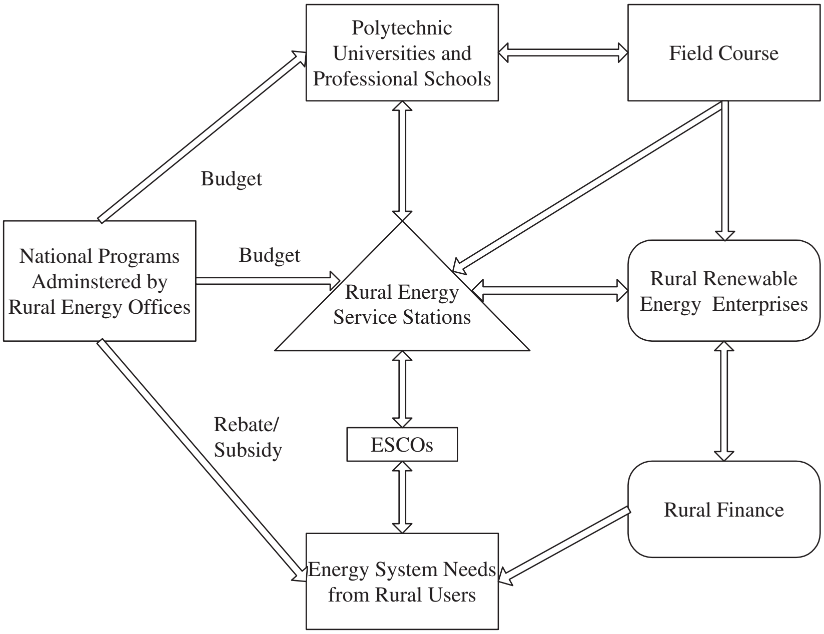

Fig. 6. A rural energy service infrastructure.

professional schools to disseminate renewable energy technologies. A central governmental agency can provide budgets and other assistance to regional and local governments (provincial, county level REOs and township rural energy stations) to support future project designs and respond to needs of the rural users. It should also provide budgets to polytechnic universities and professional schools for renewable energy-related field courses, which require and support students to participate in internships in local rural energy stations and renewable energy enterprises. These students can provide technical and service support for rural users, and can be responsible for collecting data on site continuously. Third, energy service companies (ESCOs), under the supervision of renewable energy service stations, can provide on-demand maintenance service packages so that small household can better manage their systems.

Users may also need training in basic operation skills such as correct appliance connections and battery usage, as well as routine maintenance procedures for filling batteries with water and cleaning PV panels or wind turbine blades. User training can be conducted at Rural Energy Service stations and can additionally emphasize energy demand management skills to help end-users manage daily energy use, thus reducing the need for large storage requirements. Such comprehensive training, along with increased knowledge of system design, improved product quality standards and expanded renewable energy services, can help to ensure continuing user satisfaction. In turn, user confidence and trust in these technologies can ultimately lead to renewable energy's quicker penetration in rural areas.

Beyond the governmental role, some polytechnic universities can encourage students in renewable energy related majors to work in short-term internships (1–3 months) in various renewable energy enterprises or service stations to build capacities of these organizations. These university programs can collect valuable feedback from users on design issues. For example, the weight of some PV systems designed for herdsmen is very light, so that these systems could be easily packed and moved in the summer with animal herds. Normally, the systems are separated in two wooden boxes with carrying handles. One contains the PV module (1–5 kg); the other contains the battery, controller and two DC lights that are wired and ready for use (around 5.5 kg).[8]

5.4. *Expanding microfinancing in rural areas for renewable energy systems*

Finally, the potential market for microfinance services in rural areas is substantial, especially when one considers that the services provided by existing financial institutions to rural households are poor (Zhou, 2006). To develop a microfinance industry in rural areas, an appropriate, market-based legal and regulatory regime for micro loans is needed. Toward this end, the creation of professional microfinance institutions such as those in Sierra Leone, Madagascar, Senegal (UNCDF, 2006) would be useful. As well, existing financial institutions should be encouraged to provide microfinance services to rural communities.

Acknowledgements

We would like to thank Dr. William Wallace, Senior Technical Advisor of UNDP/GEF Project Commercialization of Renewable Energy in China, for his guidance and

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[8] Qinghai Solar Power Company, 2005.

support. We also wish to express our gratitude for the cooperation of China's Ministry of Agriculture, the Chinese Academy of Sciences (Institute of Policy and Management) and Center for Renewable Energy Development and the Inner Mongolia New Energy Office.

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