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Source: Mountain Research and Development, 32(1) : 83-91

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-11-00052.1>

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A Study of the Ecological Effects of Solar Energy Development in Tibet

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Due to the high altitude of over 4000 m, scattered inhabitation, and prevalent pastoral system, Tibet (Xizang Autonomous Region) is regarded as a unique geographic zone, possessing the most abundant solar energy

resources in China. Due to the extensive use of conventional energy, significant ecological problems, including deforestation, soil erosion, land degradation, and desertification, have emerged and are becoming more severe; it is proposed that these issues can be mitigated by the utilization of solar energy. Consequently, studying the ecological effects of solar energy development in Tibet is of substantial significance. Accordingly, the resources, current situation, and potential of solar energy in Tibet were examined, and a framework for analysis to support appraisal of ecological effects was formulated. On the basis of this framework, the carbon effect, vegetation effect, and nitrogen

effect were identified as the dominant ecological effects of developing solar energy in Tibet. The methodology to calculate and evaluate these ecological effects was then established and applied for our appraisal. The main conclusions are as follows: (1) based on the development scale of solar energy in 2008, the reduction of carbon emissions reached 539,100 tons, and the mitigation of carbon sink losses equaled 432,900 tons; (2) the large-scale utilization of solar energy can replace a large amount of conventional bioenergy sources such as fuelwood, dung, straw, and grass, resulting in reductions of forest destruction by 35.69 km² and grassland degradation by 77.23 km²; and (3) with a reduction of nitrogen loss of 10,612.7 tons per year, the development of solar energy in Tibet also has an obvious nitrogen effect.

Keywords: Solar energy; carbon effect; vegetation effect; nitrogen effect; reduction of carbon emissions; reduction of deforestation; reduction of nitrogen loss; Tibet; China.

Peer-reviewed: October 2011 **Accepted:** December 2011

Introduction

Located in the Qinghai-Tibet Plateau and with a highly complex terrain, Tibet (78°25'–90°06'E and 26°50'–36°53'N) is characterized by scattered inhabitation and a fragile ecology system. Tibet is lacking in traditional energy, and a large number of populations in rural areas do not have access to electricity. It is clear that both the national and local governments are unable to bear the prodigious cost of constructing long-distance power transmission lines for local farmers and herdsmen. With an average annual radiation intensity of 6000–8000 MJ/m², Tibet's solar energy resource ranks first in China (Research group of Tibet energy sustainability and development strategy 2009). Obviously, an effective and sustainable approach for Tibet to solve its electricity shortage is to utilize its advantage in solar energy resources fully.

With the most abundant solar energy resources and the largest utilization scale in China, the development of solar energy in Tibet has a point of reference value and can be regarded as the standard for other provinces in

China and even other countries. Furthermore, Tibet is regarded as the “inductive zone” and “sensitive zone” to climate change in Asia and even in the Northern Hemisphere. In addition to its unique environment, its energy supply, demand structure, and industrial development differ dramatically from those of other provinces, suggesting that solar energy development in this region will cause more complex and compound effects than elsewhere, including economic, social, environmental, and ecological impacts. Among the various effects, the ecological effect is of unique research value and of special significance when promoting the solar energy industry.

In recent years, relevant studies have been conducted, most of them published in Chinese. These studies have mainly focused on 2 areas: solar energy development in Tibet and the ecological effect of energy development and utilization in Tibet. In the first area, previous studies have focused mostly on the process, current situation, problems, countermeasures, and outlook of solar energy industry development in Tibet (Dawalalm et al 2007; Wang and Qiu 2009). Other topics, including the

TABLE 1 Distribution of solar energy resources in Tibet (sources: Research group of Tibet energy sustainability and development strategy 2009; Li 2008).

Region	Annual average sunlight hours (h)	Average radiation intensity (MJ/m ²) in the past 10 years	Elevation (m)
Lhasa	3000	7886.0	3700
Shannan	2900	8444.6	3600
Qamdo	2180–2700	6137.1	3500
Xigaze	2600–2860	9180.1	4000
Nagqu	2800–2860	7644.4	4500
Nyingchi	1750–2010	5850.0	3000
Agari	3300	7910.8 ^{a)}	4500

^{a)}The average data for Agari over the past 10 years are derived from the Kyagar Weather Station.

potential of solar energy development and solar technology application, have also been emphasized in this first area. For the second area, only a few studies have been conducted to date, examining the ecological effects caused by the production and consumption of energy in Tibet (Wei et al 2004; Cai and Zhang 2006; Wang 2009). Most previous studies have used the case study approach and questionnaire-based analysis to appraise the ecological effects of rural energy consumption (Ping et al 2011) and bioenergy utilization (Zhou and Zhang 2007). For instance, Liu et al (2008) and Feng et al (2009) investigated the ecological effects of rural household energy consumption and bioenergy consumption in Taktse County and Panam County, respectively. In addition, the ecological effects of developing solar energy in some other areas in China and elsewhere have also been studied: for example, Zhang and Yang (2008) presented the ecological effect of solar energy on house design in rural China, and Marcos et al (2011) examined the emission reduction effect of using solar space heating and cooling for Spanish housing. But all in all, only few studies on the ecological effects of solar energy have been performed, especially for mountainous regions. In this paper, we focus on the ecological effects of solar energy development in Tibet and aim to provide a decision-making basis for establishing a solar energy development strategy in Tibet for the future.

Situation and potential of solar energy development in Tibet

Solar energy resources in Tibet

Due to its high altitude, high atmospheric transparency, and long hours of sunshine, Tibet is the region with the most abundant solar energy resources in the world. Its average radiation intensity is higher than 7000 MJ/m². The conditions of solar energy resources in the 7 cities and prefectures in Tibet are provided in Table 1.

Current use of solar energy

By 2008, Tibet had installed approximately 260,000 solar cookers and constructed 400,000 m² of solar water heaters and 3.5 million m² of solar-heated houses. Presently, more than 400 photovoltaic power stations have already been built, including more than 300 small independent photovoltaic power stations, with a capacity ranging from 10 to 30 kW each. The widespread utilization of solar energy in Tibet has solved the problem of inaccessibility to electricity of households in over 400 towns across 7 counties. In addition, the solar energy harvested is widely used in various sectors. For broadcast and television systems, over 320 solar television receiving and transmission stations, with a total capacity of 250 kW, have been installed. For telecommunication departments, various types of communication power stations—totaling a capacity of 380 kW—have been set up. For household use, over 1 million sets of photovoltaic solar energy currently feed solar lamps, with a capacity ranging from 5 to 75 W each. In general, solar energy products are widely applied in such settings as traffic lights, schools, border posts, and weather stations, with a cumulative installed capacity of 9 MW (Table 2).

Development potential

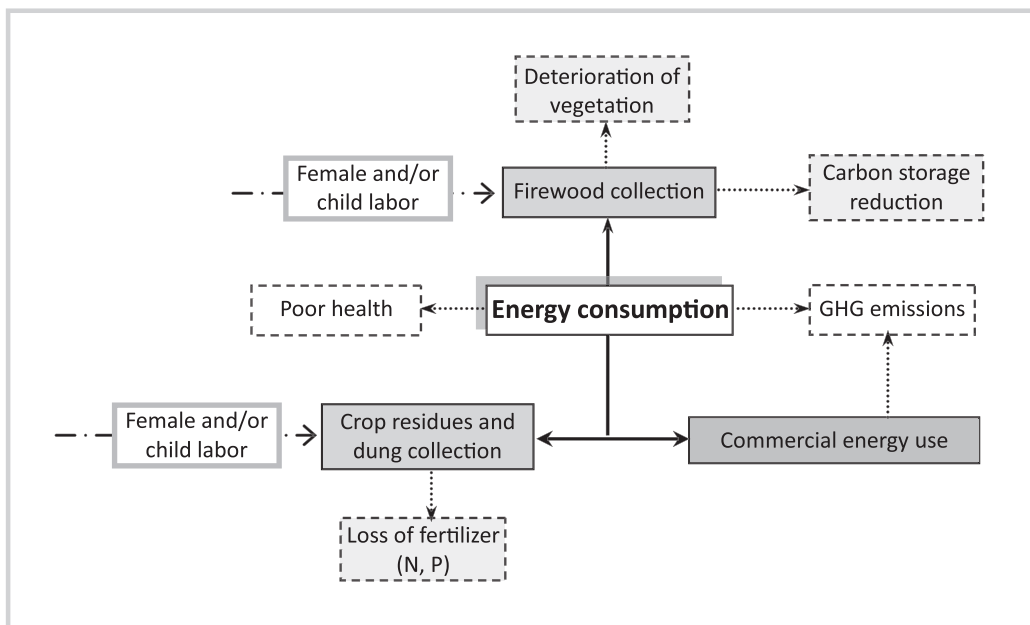
With its remarkable advantage in resources, Tibet has a large potential for solar energy development, suggesting solar energy will be vital in handling energy shortages in the future. At the end of 2005, 1.2 million people from approximately 200,000 farmer and pastoralist households did not have access to electricity (Research group of Tibet energy sustainability and development strategy 2009; Li 2008); these households relied on different types of traditional energy for lighting, such as butter, diesel, and candles. The agricultural and pastoral areas in Tibet are characterized by a vast landscape and sparse population, and the existing power grids and conventional energy are far from meeting the demands for electricity. Therefore, solar energy is considered to be an effective approach to solve the difficulty in supplying electricity to areas

TABLE 2 Development scale of solar energy in Tibet (by the end of 2008).

Type of solar energy installation	Development scale		Technical parameters of solar energy utilization			Scale (tce)
	Scale	Unit	Important technical parameters	Value	Unit ^{a)}	
(1) Solar thermal utilization						
Passive solar houses	420,000	m ²	Amount of energy production per unit area after 1 year of operation	350	kgce/m ²	14,700
Solar cookers	260,000	Sets	Amount of energy production per set after 1 year of operation	13,700	kgce/set	356,200
Solar water heaters	400,000	m ²	Annual equivalent solar radiation received by unit area	1750	kWh/m ²	86,030
Solar greenhouses and tunnels	3,500,000	m ²	Annual equivalent solar radiation received by unit area	1750	kWh/m ²	752,760
(2) Solar photovoltaic power generation						
Village power supply system	7.500	MW	Average equivalent full-load hours	1750	h	1610
Household power source	0.400	MW	Average equivalent full-load hours	1750	h	90
Power station in desert area	0.100	MW	Average equivalent full-load hours	1750	h	20
Application in transportation, communications, meteorology, etc	1.000	MW	Average equivalent full-load hours	1750	h	220
Total MW and tce	9.000	MW				1,211,600

^{a)}kgce, kilograms of carbon emissions.

FIGURE 1 Framework of analysis for appraising the ecological effects of solar energy replacing traditional energy. (Adapted from Srinivasan 2008)



without a grid, implying that there will be an increasingly growing demand for solar energy products.

Data and methodology for the appraisal of ecological effects

Data sources

The data for the appraisal of the ecological effects of developing solar energy in Tibet are mainly derived from the following 3 sources:

- First-hand solar energy development data collected during field investigations when the authors were in charge of conducting the *Plan of New Energy Technology Development of the Twelfth Five-year Plan of Tibet* in September 2009;
- Data derived from previous studies, such as the *Tibet Energy Sustainability and Development Strategy* (Research group of Tibet energy sustainability and development strategy 2009) and the *Strategy of Alternative Energy Substituting Firewood in Tibet* (CERD, DFTAR 2007);
- The Tibetan ecosystem data provided by the Lhasa Plateau Ecosystem Research Station and the Chinese Academy of Sciences.

Framework of analysis

Among the various energy utilization patterns that currently exist in Tibet, the utilization of rural bioenergy has a significant impact on the ecosystem. In the bioenergy utilization system in Tibetan rural areas, farmers and herdsmen cut wood and collect grass, straw, and the dung of livestock as important energy sources for daily life; these bioenergy sources are utilized mostly

through burning. The material flow of this utilization pattern is a one-way flow that lacks material feedback to land systems, causing significant ecological and environmental problems, such as nitrogen loss and land degradation. In addition, the time spent for collecting and processing these bioenergy sources is considerable. Moreover, due to the outdated energy utilization technology, the utilization of bioenergy in cooking also has adverse effects on human health. In recent years, commodity energy has played an increasingly important role in energy systems, which greatly improved the energy conditions in agricultural and pastoral areas. However, the large amount of CO₂ emissions produced by commodity energy consumption in Tibet is also an energy and ecological problem that cannot be neglected.

In this study, we regarded solar energy as an alternative to replace the current conventional energy sources used in Tibet. As previously mentioned, solar energy can be widely applied in heating, power generation, and other fields, meaning that it will replace the conventional bioenergy and also increase its importance as commodity energy.

Considering the current energy system and its ecological effects and the characteristics of solar energy, we formulated a framework of analysis for the appraisal of ecological effects (Figure 1). According to Figure 1, we chose the carbon effect, vegetation effect, and nitrogen effect as the main indices for the evaluation of the ecological effects of solar energy development in Tibet.

Appraisal of ecological effects

(1) *Carbon effect*: The carbon effect (C) involves two aspects, namely, carbon emissions reduction (C_r) and the

mitigation effect of carbon sink losses (C_s). The former refers to the effect brought about by the reduction of carbon emissions when traditional energy has been replaced by solar energy; the latter refers to the mitigation of the loss of carbon sink in the forest and grassland ecosystem via the reduction of forest and grassland damage by replacing biomass, such as fuelwood, with solar energy.

The calculation formula for the carbon emission reduction effect is as follows:

$$C_r = \sum_{i=1}^n (E_i \times \alpha_i) \times \lambda, \tag{1}$$

where E_i represents the developmental scale of solar energy utilization type i ; α_i is the energy production of unit scale of solar energy utilization type i after 1 year's operation; and λ is the carbon emissions intensity of the unit energy consumption in Tibet. It should be noted that solar energy in Tibet is generated and consumed entirely locally, with no input of solar energy from external sources.

The λ variable can be calculated as follows:

$$\lambda = \frac{\sum_{j=1}^n (A_j \times \lambda_j)}{\sum_{j=1}^n A_j}, \tag{2}$$

where A_j represents the consumption quantity of energy type j and λ_j represents the carbon content of energy type j .

The calculation formula for the mitigation effect of carbon sink loss is as follows:

$$C_s = \frac{S_f}{f} + \frac{S_g}{g}. \tag{3}$$

In this formula, S_f and S_g denote the forest stock volume and grassland stock volume replaced by solar energy, respectively, and f and g represent the carbon sink amount of unit forest and grassland stock volume, respectively. S_f can be obtained by multiplying the total amount of solar energy substitution by the ratio of forest energy consumption to the total energy consumption, and f can be obtained by dividing the total carbon sink amount of the forest ecosystem by forest stock volume. S_g and g can be calculated by the same method as that used for S_f and f , respectively.

Thus, the calculation formula for the carbon sink effect can be further detailed:

$$C_s = S_f \times \frac{M_f}{P_f} + S_g \times \frac{M_g}{P_g}, \tag{4}$$

where M_f and M_g represent the carbon sink amounts of the forest ecosystem and grassland ecosystem,

respectively, and P_f and P_g denote the forest and grassland stock volume, respectively. Taking into account the fact that the carbon sink in the forest ecosystem is dominant, this study focused on the calculation of S_f .

(2) *Vegetation effect:* The vegetation effect (V) mainly refers to the area of deforestation and grassland degradation that is reduced after replacing conventional bioenergy with solar energy.

Thus, the vegetation effect can be further calculated as follows:

$$V = V_f + V_g = S_f \times \frac{R_f}{P_f} + S_g \times \frac{R_g}{P_g}, \tag{5}$$

where V represents the overall vegetation effect; V_f represents the forest vegetation effect that characterizes the area of deforestation reduced and can be obtained by multiplying the stock volume of deforestation reduction by the area occupied by the unit forest stock volume; V_g is the characterization of the grassland vegetation effect that characterizes the area of grassland degradation reduced and can be calculated by the same method as that used for V_f ; and R_f and R_g indicate the areas of forest and grassland, respectively. P_f and P_g are identical to those in Equation 4.

(3) *Nitrogen effect:* The nitrogen effect refers to the amount of nitrogen loss reduced by replacing bioenergy, such as fuelwood, straw, and dry cow dung, with solar energy. The formula for the nitrogen effect is as follows:

$$N = \sum_{k=1}^n S_k \times n_k, \tag{6}$$

where S_k represents the scale of bioenergy k substituted by solar energy and n_k represents the nitrogen content of bioenergy k .

Appraisal of the ecological effects of solar energy development in Tibet

Carbon effect

(1) *Effect of a reduction in carbon emissions:* Considering the shortage of energy data in Tibet, we chose the year 2005 as the baseline to appraise the ecological effects of solar energy development. The data for energy consumption and carbon emissions are shown in Table 3. Moreover, according to the data for solar energy development collected in September 2009 mentioned above, the year 2008 (Table 2) was selected to assess the developmental scale of solar energy.

According to Equation 2 and the data in Table 3, the carbon emissions per unit of energy consumption in Tibet can be calculated as 0.636 tons/tons of coal equivalent (tce). Based on Table 2, the solar energy

TABLE 3 Energy consumption and carbon emissions in Tibet (2005).^{a)} (Table extended on next page.)

Type of energy source	Physical quantity		Standard quantity (standard coal)		
	Scale	Unit	Standard coal coefficient	Unit	Scale (tce)
1. Coal	68,200	tons	0.71	kgce/kg	48,700
2. Oil	200,000	tons	1.43	kgce/kg	285,700
3. Liquefied petroleum gas (LPG)	19,700	tons	1.71	kgce/kg	33,800
4. Electrical power (not thermal power)	1412.00	GWh	0.12	kgce/kWh	173,500
1) Hydropower	1276.70	GWh	0.12	kgce/kWh	156,900
2) Geothermal power	113.30	GWh	0.12	kgce/kWh	13,900
3) PV (including solar-wind hybrid energy)	22.60	GWh	0.12	kgce/kWh	2800
5. Bioenergy	2,690,000	tons	–	–	1,382,900
1) Fuelwood	1,020,000	tons	0.57	kgce/kg	582,400
2) Livestock and poultry dung	1,190,000	tons	0.47	kgce/kg	560,500
3) Straw and others	480,000	tons	0.50	kgce/kg	240,000
Total tce, TJ, and t	1,924,700				

^{a)}The percentages 87%, 85%, and 85% in this table refer to the oxidation rates while burning fuelwood, livestock and poultry dung, and straw and others, respectively. kgce, kilograms of carbon emissions. Sources: Wang 1999; Cai and Zhang 2006; IPCC 2006; Liu 2007; Research group of Tibet energy sustainability and development strategy 2009; DES 2010.

development scale in 2008 was 1,211,600 tce; however, this is the ideal scale of solar energy development. In fact, because a variety of solar energy equipment in operation may require overhauling and maintenance and because the solar energy produced may be left unused or wasted, the final effective utilization scale of solar energy in Tibet is actually less than the ideal size. Based on existing research on energy utilization in Tibet and the field investigation that we carried out (as mentioned above), we suggest that approximately 60 to 80% of Tibetan solar energy equipment can be utilized effectively. Here, for the convenience of our calculations, 70% of the ideal size was considered as the actual value, ie the effective energy for Tibetan solar energy development in 2008 was 848,100 tce, equal to 70% of the ideal size of 1,211,600 tce. According to Equations 1 and 2, we estimate that the effective use of solar energy in 2008 has reduced carbon emissions by 539,100 tons.

(2) *Mitigation effect of carbon sink loss*: The mitigation effect of carbon sink loss refers to the reduction in carbon sink losses caused by the mitigation of forest and grassland destruction by replacing bioenergy, eg fuelwood, with solar energy. Using the data in Table 3, we calculated that the ratios of (1) fuelwood, (2) livestock and

poultry dung, and (3) straw and the other three types of biomass accounting for the total energy consumption were 30.26, 29.12, and 12.47% in 2008, respectively (Table 4). Because less carbon sink loss occurred with the utilization of livestock and poultry dung and straw, we primarily focused on the decreased carbon sink loss due to the reduction in deforestation.

The fuelwood replaced by solar energy was 449,500 tons in 2008 (Table 4). Given the ratio of biomass to stock volume in Tibet as 0.91 tons/m³ (Fang et al 1996), we determined that the forest stock volume replaced by solar energy was 494,000 m³. According to the *Report on Forest Inventory of Tibet* (AFIP 2001), the total stock volume of standing trees in Tibet was 2,294.48 million m³, and the annual growth of stock volume was 20.968 million m³, with an average amount of carbon sink of 23.924 million tons annually, ie the annual amount of carbon sink unit growth of stock volume was 0.88 tons of C/m³ (Wang et al 2007). Thus, we calculated that under the solar energy development level of 2008, 494,000 m³ of forests could be protected against deforestation, implying that 432,900 tons of carbon sink loss can be avoided.

Vegetation effect

With the replacement of bioenergy by solar energy, vegetation damage can also be reduced due to the

TABLE 3 Extended. (First part of Table 3 on previous page.)

Type of energy source	Standard quantity (calorific value)			Carbon emissions		
	Net calorific value	Unit	Calorific value (TJ)	Carbon content	Unit	Carbon emissions (tons)
1. Coal	20.91	TJ/kg	1425.93	25.80	kg/GJ	36,800
2. Oil	41.82	TJ/kg	8363.20	20.00	kg/GJ	167,300
3. Liquefied petroleum gas (LPG)	50.18	TJ/kg	988.53	63.10	kg/GJ	62,400
4. Electrical power (not thermal power)	3.60	TJ/kWh	5077.55	0.00		0
1) Hydropower	3.60	TJ/kWh	4591.01	0.00		0
2) Geothermal power	3.60	TJ/kWh	407.43	0.00		0
3) PV (including solar-wind hybrid energy)	3.60	TJ/kWh	81.27	0.00		0
5. Bioenergy						957,000
1) Fuelwood	16.73	TJ/kg	17,060.52	45% (87%)		399,300
2) Livestock and poultry dung	13.80	TJ/kg	16,420.81	39% (85%)		394,500
3) Straw and others	14.64	TJ/kg	7024.80	40% (85%)		163,200
Total tce, TJ, and t		56,361.33			1,223,400	

reduction in deforestation and straw and sod collection. From the *Report on Forest Inventory of Tibet* (AFIP 2001), the stock volume of unit area in Tibet is $13,800 \text{ m}^3/\text{km}^2$. As mentioned above, the forest stock volume after the replacement of bioenergy by solar energy is $494,000 \text{ m}^3$. Thus, it can be calculated from Equation 5 that the reduction of forest destruction will reach 35.69 km^2 by developing solar energy in Tibet.

According to the data provided by the Center of Energy Research & Demonstration, Department of Science and Technology of Tibet Autonomous Region (CERD, DFTAR 2007), the annual use of one solar cooker will replace 1.37 tce of conventional energy, protecting nearly 1000 m^2 of grassland shrubs from being cut. According to Table 4, the solar energy development in

Tibet will take the place of 105,800 tce of straw and other alternatives, such as sod, indicating that such biomass sources will be saved instead of damaged or destroyed. With the assumption that all of the saved biomass could be exchanged to sod, the development of solar energy can prevent 77.23 km^2 of grasslands from destruction.

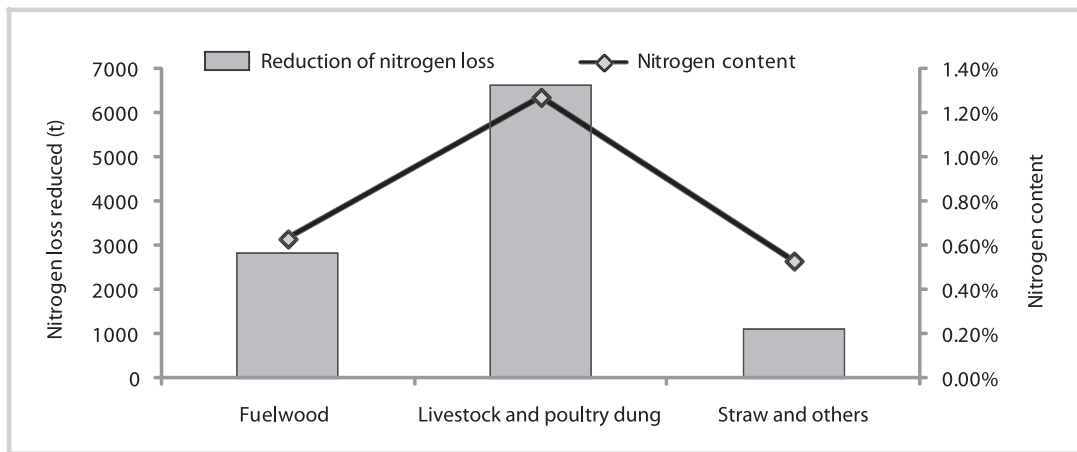
Nitrogen effect

Conventional bioenergy sources, such as firewood, straw, and livestock and poultry dung, are widely used as domestic fuel, causing significant nitrogen loss. With the developmental scale of 848,100 tce in 2008 mentioned above, solar energy will be substituted for 256,700 tce of fuelwood, 247,000 tce of livestock and poultry dung, and

TABLE 4 Amount of bioenergy replaced by solar energy in Tibet (2008).

Source of bioenergy	Proportion (%)	Amount of bioenergy replaced (tce)	Physical quantity of bioenergy replaced (t)
1) Fuelwood	30.26	256,700	449,500
2) Livestock and poultry dung	29.12	247,000	524,400
3) Straw, other bioenergy sources	12.47	105,800	211,500
Total	71.85	609,400	1,185,400

FIGURE 2 Nitrogen effect of solar energy development in 2008.



105,800 tce of straw and other bioenergy types each year. By use of the conversion ratio between the physical quantity and the amount of standard coal of these 3 types of biomass in Table 4, and using their nitrogen content as shown in Figure 2, the nitrogen loss reduced by solar energy development in 2008 can be calculated to be 10,612.7 tons (Figure 2), according to Equation 6.

Conclusions

Due to the data shortage and difficulty of data collection in Tibet, this study primarily focused on the entire Tibetan region and temporarily ignored the differences between different regions. Using 2005 as the baseline, we collected data on the development scale of solar energy in 2008 to appraise its ecological effects. Further study could include the following:

1. Tibet has obvious regional disparities in terms of environment, socioeconomic development, and energy supply and demand structure. In the future, the ecological effects of solar energy development could be estimated and calculated according to the different conditions of each region in Tibet, suggesting that the appraisal results will be more concise and practicable.
2. In recent years, Tibetan solar energy has witnessed rapid growth. The scale of solar energy development and the utilization efficiency of solar energy equipment have also increased significantly. However, due to inadequate repair, maintenance, and technical services, the actual utilization scale and efficiency differ greatly from the ideal. Therefore, further research can examine several scenarios to understand and study the ecological effects of solar energy development under more ideal conditions.
3. In fact, the development of solar energy in Tibet has an effect on more aspects than merely the ecological one. For instance, the extensive application of solar energy in rural areas has positive social and health effects. In addition to these positive effects, some negative effects should also be taken into consideration, eg the high cost of solar energy product installation and maintenance. Therefore, a more systematic evaluation involving various effects induced by solar energy development in Tibet will provide more accurate and comprehensive scientific support for policy formulation and raise a valuable case for other countries to develop solar energy in mountain areas.
4. Clearly, the appraisal of the ecological effects caused by solar energy development in Tibet will bring valuable implications for other mountain areas with similar characteristics. Thus, mountain areas with abundant solar resources, scarce fossil energy sources, fragile ecosystems, scattered inhabitation, and weak electrical grid systems should promote solar energy, which will produce positive ecological effects. For instance, it might be considerably important for the Xinjiang Uygur Autonomous Region and Qinghai Province in China to advance solar energy. In addition, other mountain areas, such as Nepal, Pakistan, and Kyrgyzstan, should also consider developing solar energy.

ACKNOWLEDGMENTS

Research for this study was supported by the National Natural Science Foundation of China (Grant No. 41171110), the "Strategic Priority Research Program—Climate Change: Carbon Budget and Related Issues" of the Chinese Academy of Sciences (Grant No. XDA05010205), and the Independent

Innovation Projects of the Institute of Geographic Sciences and Natural Resources Research (Grant No. 200904003). The authors would like to thank the anonymous referees for their valuable comments and corrections to this paper.

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