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Scenarios of Solar Energy Use on the "Roof of the World": Potentials and Environmental Benefits

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Peripheral mountain areas in developing countries are often characterized by energy poverty but also by high solar energy potential. The Eastern Pamirs of Tajikistan are a prime example of this situation, with their lack of energy infrastructure, remoteness, pressure on local natural resources, and high incident radiation amounts. An integrative assessment of the potential for photovoltaic power generation is lacking for this region, as well as for many other mountain environments. We assessed the natural potential, feasibility, and likely effects of increased photovoltaic electricity generation, using climate data, biomass data, a spatial radiation model, and fieldwork- and literature-based scenarios of energy requirements and financial conditions. Results indicated that using a photovoltaic power plant to generate enough energy for boiling water is feasible in the study area within reasonable cost limits. This could significantly alleviate energy poverty, increase carbon sequestration by up to 1500 t/y, and reduce the loss of dwarf shrub stands by up to 2000 ha/y. Our results illustrate that the integrative approach presented in this article can be applied straightforwardly when some climatic measurements and field observations are available and that photovoltaic energy is an important renewable-energy resource for the sustainable development of peripheral high-mountain communities.

Keywords: *Eastern Pamirs; Tajikistan; solar energy potential; photovoltaics; high-mountain regions; radiation model; alternative energy resources; reduction of vegetation degradation; carbon emission savings.*

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Introduction

Remote mountain areas are examples of environments with energy scarcity but considerable renewable-energy potential (Förster et al 2011). In this context, the Eastern Pamirs of Tajikistan, often called the "Roof of the World," are of special interest to assess the feasibility and possible effects of alternative energy sources. The population is highly dependent on locally available fuel, such as biomass from dwarf shrubs and animal manure, to meet daily energy demands in a cold and harsh climate. This is mainly caused by a lack of energy infrastructure (because the remote location prevents connection to the national energy grid), the scarcity or high cost of imported energy (eg coal), and poverty (Wiedemann et al 2012; Kraudzun 2014; Kraudzun et al 2014). The harvesting of dwarf shrub biomass has led some researchers to raise the alarm about environmental degradation (Breu et al 2005; Breckle and Wucherer 2006; Hoeck et al 2007; Wiedemann et al 2012), although recent studies have indicated that the situation is not that severe (Kraudzun 2014; Kraudzun et al 2014; Vanselow and Samimi 2014). However, all studies conclude that increased development of renewable-energy resources is necessary for sustainable development (Hoeck et al 2007; Förster et al 2011; Wiedemann et al 2012; Kraudzun 2014; Kraudzun et al 2014).

This situation is of special interest against the background of large anticipated natural potential of renewable-energy resources: high altitude, pronounced aridity, and prevailing clear sky conditions lead to high solar irradiation, with up to 90% of extraterrestrial radiation reaching the surface under ideal conditions. The region's lack of infrastructure, peripheral location, widespread use of biomass for heating, and pressure on the environment, combined with the high natural potential of renewable-energy resources, are typical for many mountain areas worldwide, as illustrated by examples from Nepal (Bhandari and Stadler 2011; Poudyal et al 2012), Tibet (Wang and Qiu 2009; Limao et al 2012), Bhutan (Gilman et al 2009), Chile (Fthenakis et al 2014), and Greece (Katsoulakos 2011).

However, in the Eastern Pamirs and many other peripheral mountain regions, the natural potential for solar energy in general and photovoltaic (PV) power generation in particular has not has been assessed. Furthermore, the environmental effects of enforced PV energy development in the future—for example, reduced dwarf shrub clearance or increased carbon sequestration (cf Limao et al 2012)—remain unknown. Most research on renewable-energy resources in developing regions has focused on different methods of measuring the available solar radiation (Huld et al 2012), economic comparison of different techniques for rural electrification (Mainali and Silveira 2013), or environmental and social effects of installed renewable-energy infrastructure (Limao et al 2012). This study aims to integrate research on renewable solar energy from different fields—from resource assessment to the possible implementation of solar energy supply—by evaluating the potential effects of a solar energy utilization scenario in a high-mountain environment.

To close regional research gaps and provide a useful example of methodology for assessing the potential of renewable-energy resources in peripheral mountain areas, options for using solar energy to generate electricity should be examined, taking natural and socioeconomic factors into account. Therefore, the main objectives of this study were as follows:

1. Map amounts of monthly solar radiation and identify the inclinations that result in maximum annual incident radiation with a simple method applicable to other economically disadvantaged mountain regions.
2. Develop realistic scenarios of solar energy requirements and financial conditions to design a PV power plant in the region's largest settlement, based on available radiation amounts.
3. Estimate the potential environmental benefits of replacing biomass energy with solar energy.

Methodology

Study area

The Eastern Pamirs of Tajikistan form a high-mountain plateau with altitudes mostly between 3500 and 5500 m and covering more than 38,000 km^2, with an area approximately identical to the extent of the *rajon* (district) of Murghab (Figure 1). Murghab is also the name of the district's capital, and subsequent uses of the name in this article refer to the town. The climate is cold and arid, with a mean temperature of −1°C and average precipitation below 100 mm in the valleys (Murghab annual means 1998–2012, Tajik Hydrometeorological Service 2013). Because of these environmental conditions, forests and trees are absent, and dwarf shrubs (*Krascheninnikovia ceratoides, Artemisia* spp.) are the only locally available woody vegetation.

Because energy requirements for cooking and heating are high and the local hydropower plant is unable to deliver sufficient energy, these dwarf shrubs are a major fuel source, along with animal manure and imported coal (Kraudzun 2014). Therefore, intensive harvesting of dwarf shrubs takes place; the whole plant is extracted, because the largest share of biomass is located within the root zone (Zandler et al 2015). Economically, the region is dominated by animal husbandry; besides their importance as an energy source, dwarf shrubs are essential winter forage for livestock (Kraudzun 2014). This concurrent use and the shrubs' slow regeneration have raised sustainability concerns and have increased demand for renewable-energy alternatives (Kraudzun et al 2014).

To assess the potential of solar energy, the town of Murghab and respective surroundings (20-km quadrat) were selected as the main study area, because more than half of Eastern Pamir's population lives there (about 7000 people in 1515 households; Kreczi 2011). A nearby Soviet-era hydropower plant, which is expected to be modernized in the near future, serves as a reference point for comparison. In addition, a local electricity grid exists, which allows for the distribution of energy without additional costs (Kraudzun 2014).

Assessing solar radiation amounts

Four automatic climate stations (Figure 1), erected for this study near different villages with different climatological conditions (altitudes; valley expositions, such as valleys oriented east–west or north–south; and compass directions), were used to assess the natural potential of solar energy. At these stations, global radiation, wind speed, wind direction, relative humidity, and temperature were measured at half-hourly intervals. Data used in this study were recorded from November 2012 to October 2013 (12 months) by the Pik Pionerka station and from January 2013 to December 2014 (24 months) by the 3 other stations. It was necessary to use data from these measurements, because existing official climate stations do not measure global radiation. A preliminary review of the data revealed that, although there is prevailing wind activity in the Eastern Pamirs of Tajikistan, the potential for wind energy is considerably lower than that for solar energy, even at favorable locations, and positive synergies are negligible. Therefore, this study did not assess wind energy.

To spatially map monthly solar radiation amounts for the study area, measured global radiation data and a global ASTER digital elevation model (METI and NASA 2009) were used to calibrate and validate a geographic information system (GIS)-based solar radiation model from ArcGIS software (Fu and Rich 1999). This approach was chosen because existing studies showed good

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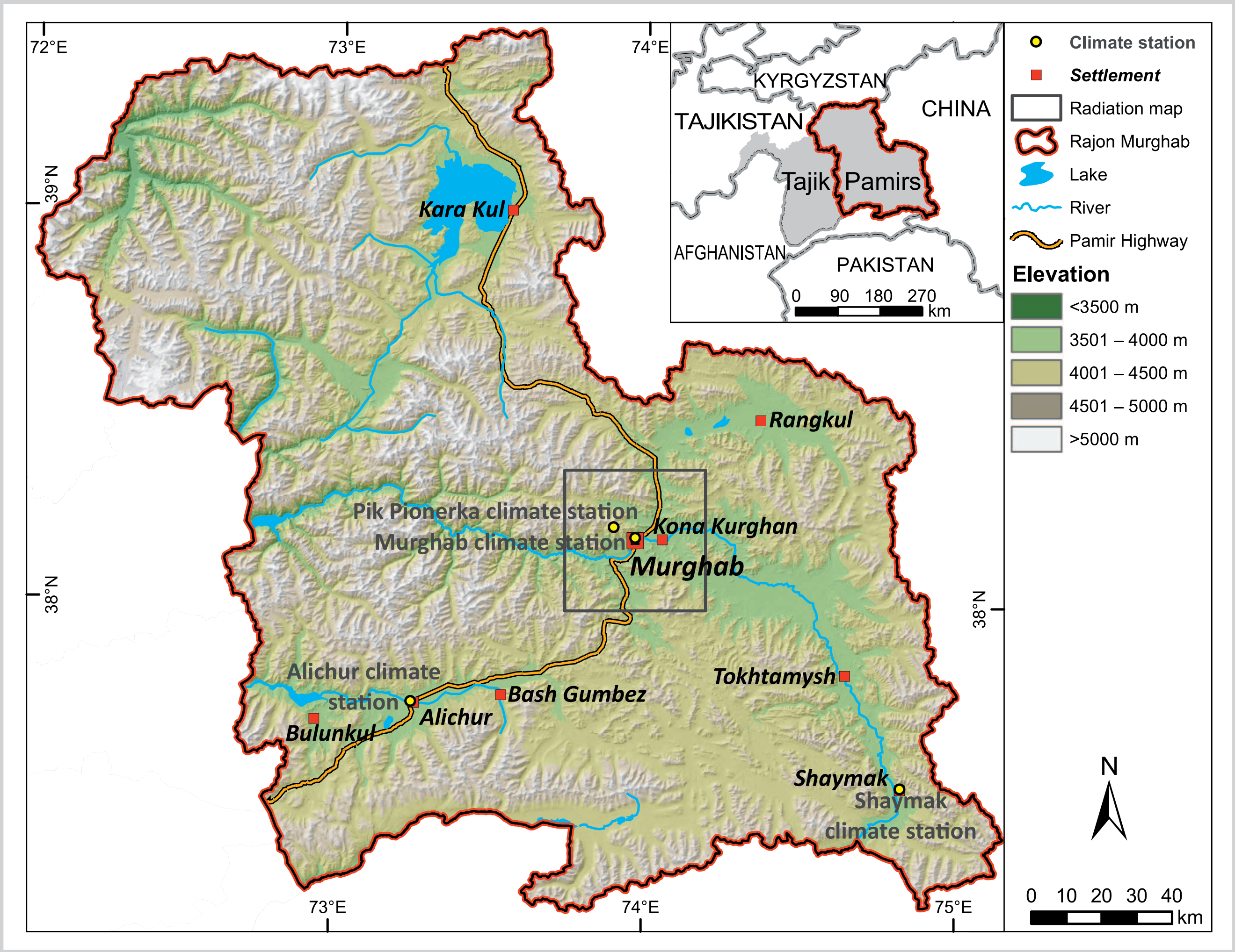
FIGURE 1 Map of the Eastern Pamirs of Tajikistan, climate stations, and the study area corresponding to the implementation area for the radiation model. (Map by Harald Zandler; elevation source: METI and NASA 2009)



performance of comparable GIS-based radiation models (Hofierka and Kaňuk 2009; Kumar 2011), and it is considered an appropriate method in regions with strongly undulating relief (Tovar-Pescador et al 2006; Pons and Ninyerola 2008). Other methods, such as satellite-based derivation of radiation amounts, were not considered, because there is reason to believe that their results are uncertain in mountainous terrain (Huld et al 2012; Amillo et al 2014). The relative simplicity of this method also made it more feasible in other peripheral mountain regions, where extensive and costly measurement campaigns are unlikely to be conducted.

To assess the performance of the model, the weather station with the shorter available period and minimal angle of horizon (Pik Pionerka) served as a reference to derive atmospheric input parameters for the model (transmissivity, ie the capacity of the atmosphere to transmit energy), while the other 3 stations (Alichur, Murghab, and Shaymak) were used for validation and error calculation.

Global radiation measurements and the spatial model refer to incident radiation on a horizontal surface. However, to maximize the solar radiation amount that falls on a PV cell, solar panels have to be tilted toward the sun, so a conversion from horizontal to inclined radiation is necessary (Evseev and Kudish 2009). To model ideal panel inclinations, yearly radiation sums were modeled iteratively for different tilt angles (southern orientation) using 5000 points randomly located within the Murghab district and with slopes below 20° (Figure 2) to limit the analysis to areas more suitable for potential PV plants (cf Arán Carrión et al 2008). The ideal panel inclination was determined as the angle resulting in maximum total annual global radiation. This inclination and the 5000 random points were then used to construct a conversion model based on linear regression between monthly

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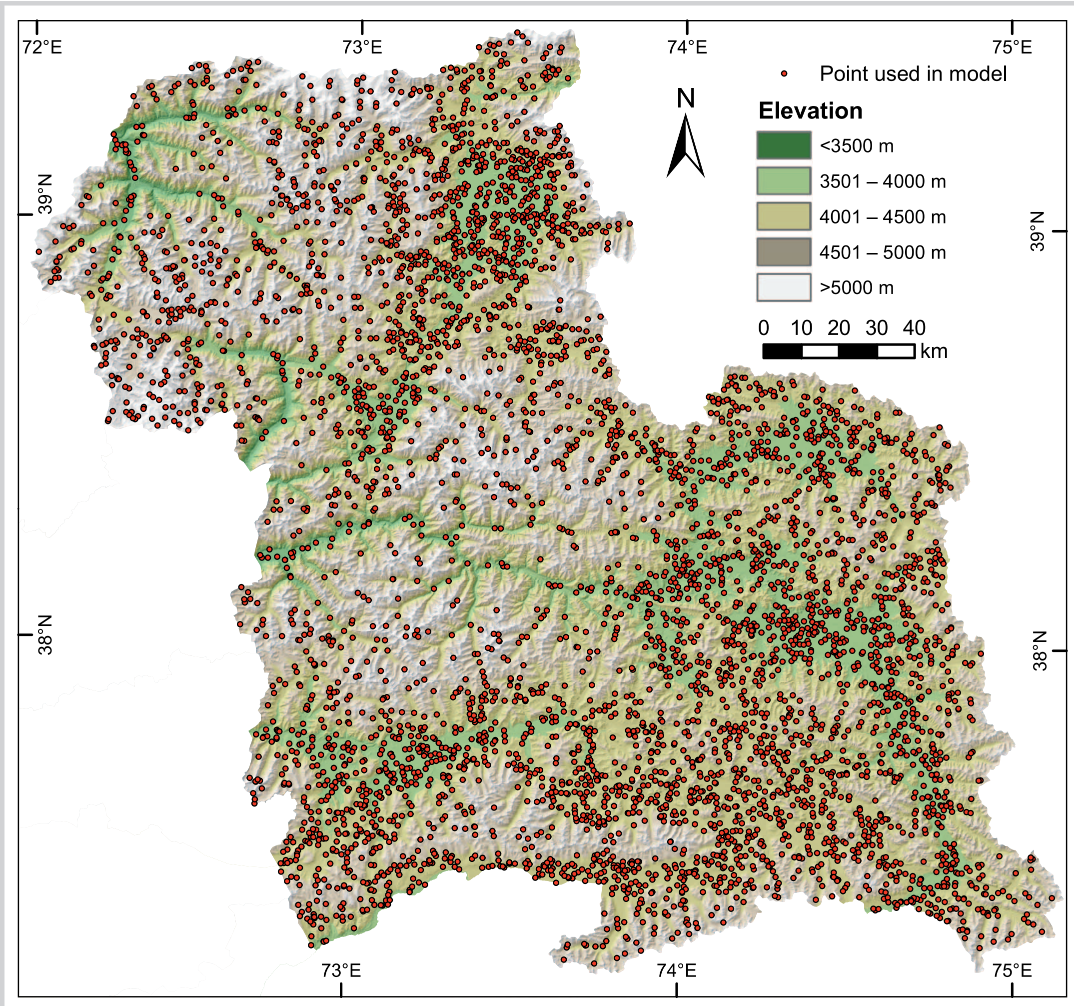
FIGURE 2 Locations of 5000 random points used for modeling ideal panel inclination. (Map by Harald Zandler)



inclined radiation (dependent variable) and monthly horizontal radiation (independent variable).

The regression equation was applied to calculate monthly raster maps of incoming global radiation on an ideally tilted surface from the validated horizontal radiation raster. Such maps can be generated for the entire Eastern Pamirs to assess spatially resolved solar energy amounts but were restricted for this study to a rectangle with borders 20 km in each direction from the center of the town of Murghab (Figure 1). They represent the natural potential of solar energy and serve as a basis for site selection and derivation of mean global radiation amounts.

Developing scenarios for PV energy use

In the Eastern Pamirs of Tajikistan, small-scale use of PV systems for lighting or to power small television sets is popular (Kraudzun 2014), but larger implementations, which would be able to replace other energy sources used for heating, are absent. Therefore, descriptive scenarios of energy use are necessary to assess the potential of solar energy in the study area. Descriptive scenarios are not predictions but should represent plausible future developments (Nakićenović and IPCC 2000). Scenarios are frequently used to study the potential of renewable-energy resources (Lund 2007; Shrestha et al 2007). The scenarios used in this study were based on the following assumptions regarding financing and energy use.

The financial scenario assumed a maximum investment equivalent to the amount allotted by the KfW Development Bank in its plan for the modernization of the hydropower plant in Murghab: € 5 million (AHK 2013), or US$ 6,646,500 based on the average currency conversion rate for 2014 (Oanda 2015). This budget was hypothesized to be a reasonable investment in the regional energy infrastructure. Other financial assumptions may have introduced too much complexity,

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thus weakening comparability of the results to other studies.

The energy-requirement scenario was based on existing observations of household energy consumption habits, showing that electricity is used for boiling water, lighting, and television when available in the Pamirs (Kraudzun 2014; Mislimshoeva et al 2014). Therefore, quantitative household consumption was assessed for respective energy appliances. For boiling water, minimum household use was estimated at 10 L/d per household: 1.5 L for tea, 5 times a day, and 2.5 L for washing dishes. Water for household use is usually stored indoors roughly at room temperature. For boiling water, we used a 2400-W electric kettle to bring 1 L of 17°C water to boil 10 times; time to boiling was around 3 minutes. Considering natural variability in water temperature, as well as the potential for increased hot water demand, we estimated use of the electric kettle at 45 min/d.

For lighting, we assumed that each household had four 9-W lamps (enough to light one room, a corridor, the area in front of the house, and one additional room or toilet) and used them for 7 h/d. Time watching television (with a 14.2-W device selected for the scenario) was estimated to be 6 h/d per household.

Cooking and heating are important components of total energy consumption. However, because fueling these activities with PV energy seems unrealistic in the study area (due to their large energy requirements in this cold climate), they were not included in this study. Some preliminary rough estimates were carried out and are mentioned in the Discussion section.

Assessing the cost of a PV power plant

Calculation of required infrastructure and total cost were based on the annual energy requirement scenario and a modified approach following Chandel et al (2014). All formulas given in this section are deduced from Chandel et al (2014) if not stated otherwise.

The panel generation factor (PGF), a value based on available radiation amounts, is used to calculate the number of PV panels needed to generate the desired energy amount. Because a minimum amount of energy has to be provided consistently throughout the year, the month with the lowest incident radiation was taken as a reference for the PV design. Losses of 5% (eg by dust) were also included:

$$\mathrm{PGF} = \text{solar irradiance}\,\frac{\mathrm{kWh}}{\mathrm{day}}\times(1-0.05) \tag{1}$$

Required energy amounts from the PV modules (PV_{req}) was calculated by multiplying the energy needs of the scenario by 1.3 to allow for 30% energy losses in the PV system (Chandel et al 2014). Total watt peak (Wp) rating for PV modules was then derived as follows:

BOX 1: Technical data for the Solarworld Sunmodule Plus SW 275 mono PV panel

Module maximum power 275 W

Maximum power voltage 31 V

Maximum power current 8.94 A

Open-circuit voltage 39.4 V

Short-circuit current 9.58 A

Maximum system voltage 1000 V, direct current

Temperature coefficient of maximum power –0.45%/°C

Temperature coefficient of open-circuit voltage –0.3%/°C

Temperature coefficient of short-circuit current 0.04%/°C

Source: SolarWorld 2015.

$$W_{\mathrm{p}}\ \text{rating kW} = \frac{PV_{\mathrm{req}}}{\mathrm{PGF}} \tag{2}$$

Further calculations were based on PV module specifications. We selected the Solarworld Sunmodule Plus SW 275 mono (SolarWorld 2015; Box 1 in this article) for the hypothetical PV power plant. The cost of this module is US$ 331 (Europe Solarshop 2015b). The number of modules required was then calculated as follows:

$$\text{Number of required PV modules} = \frac{\text{Wp rating W}}{\text{module maximum power W}} \tag{3}$$

Inverters are necessary to convert the generated energy from DC to AC. Inverter size should be approximately 30% larger than the modules' total wattage (Chandel et al 2014). Satcon Power Gate Plus 100 kW PVS-0100-240 with integrated maximum power point tracking was selected as the inverter model, with a total cost of US$ 28,197.89 (KingSolarman 2015). The number of required inverters was then calculated as follows:

$$\text{Number of required inverters} = \frac{\text{number of PV modules}\times\text{Pmax kW}\times 1.3}{\text{100 kW (inverter wattage)}} \tag{4}$$

Because solar energy amounts are not equally available throughout the day, battery-based energy storage is necessary to allow a constant electrical power supply. Hoppecke 26 OPzS solar.power 4700/48-V batteries (Hoppecke Battery 2015) were selected as storage devices with a unit cost of US$ 35,029.71 (Europe Solarshop

TABLE 1 Modeling errors of the spatial solar radiation model.

Month	Error %	Absolute error (Wh/m²/d)
January	11.44	325
February	6.39	220
March	3.32	146
April	5.01	278
May	3.06	181
June	2.16	152
July	2.57	185
August	13.40	814
September	5.71	325
October	5.53	219
November	12.61	397
December	15.77	411
Yearly average	**7.25**	**304**

2015a). Maximum discharge of batteries was set to 40%, and a battery loss of 15% was assumed (Chandel et al 2014). Battery autonomy (influencing the maximum energy amount that has to be provided by batteries) was set to 1 day, and a discharge over 10 hours was expected (influencing the capacity of the batteries). The required number of batteries was then calculated as follows:

$$\text{Required battery capacity Ah} = \frac{\text{total energy requirements W}}{\text{battery voltage} \times \text{depth of discharge} \times (1 - \text{losses})} \tag{5}$$

$$\text{Number of required batteries} = \frac{\text{required battery capacity Ah}}{\text{battery capacity at discharge over 10 hours Ah}} \tag{6}$$

To control energy charging and unloading, additional inverters are necessary. We selected bidirectional Eaton Power Xpert Storage 2250 kW inverters with a unit price of approximately US$ 330,000 as storage control devices (Eaton 2014). The number of required battery inverters was then derived as follows:

$$\text{Number of required battery inverters} = \frac{\text{PVreq kW}}{\text{2250 kW (inverter wattage)}} \tag{7}$$

Finally, all costs for the theoretical PV plant construction were summarized. In addition to the material costs, installation costs of 15% were assumed (cf SMA 2015).

Assessing biomass and carbon savings

Kreczi (2013) found that on average, 3.3 medium-size dwarf shrubs are needed to bring 1 L of water to a boil. The mean weight of local dwarf shrubs, 234 g, was taken from measurements ($n = 243$) for the local allometric model presented in Zandler et al (2015). Carbon content of 18 oven-dried dwarf shrub samples was determined with the Thermo Quest Flash EA 1112 CHN elemental analyzer at the BayCEER laboratory of the University of Bayreuth. These values were used to calculate the maximum biomass and carbon savings that would result if dwarf shrub biomass use for water heating was replaced by PV energy and no other energy sources were used to heat water. To calculate the corresponding reduction of cleared dwarf shrub area, a mean value of 2087 kg of dwarf shrub biomass per ha of dwarf shrub stand was assumed, based on the biomass model presented in Zandler et al (2015).

Results

Modeled solar radiation amounts and potential energy requirements

Mean measured horizontal solar radiation at the validation stations during the reference period (2013–2014) was 1751 kWh/m^2/y. The monthly radiation model showed a coefficient of determination (R^2) of 0.96, a root mean squared error (RMSE) of 11.76 kWh/m^2/mo (relative RMSE of 8.06%), and a bias of −5.31 kWh/m^2/mo. Monthly variation of modeling errors showed higher errors in winter than in summer, with an annual average error of 7.25% (Table 1).

Modeling of ideal panel inclinations showed good performance (R^2 of 0.94 to 0.99) and led to an optimum tilt angle of 26°S to maximize annual solar radiation. Solar incident radiation on ideally inclined surfaces exceeded radiation on horizontal surfaces by 11.1% when averaged over the whole raster.

Suitable areas for potential PV plants, characterized by flat terrain and minimum inclined radiation values of more than 3 kWh/m^2/d in December, are mainly located to the east of Murghab (Figure 3A). The potential PV site that was the focus of the study is about 1660 m from the nearest grid-connected houses and has a mean slope of 3.8° (Figure 3B). At the study site, the average minimum radiation on an ideally inclined surface was lowest in December (3.04 kWh/m^2/d) and highest in July (7.33 kWh/m^2/d) (Table 2).

The energy demand scenario showed a household energy requirement of 2.14 kWh/d, for a total energy requirement of 3237.86 kWh/d for Murghab.

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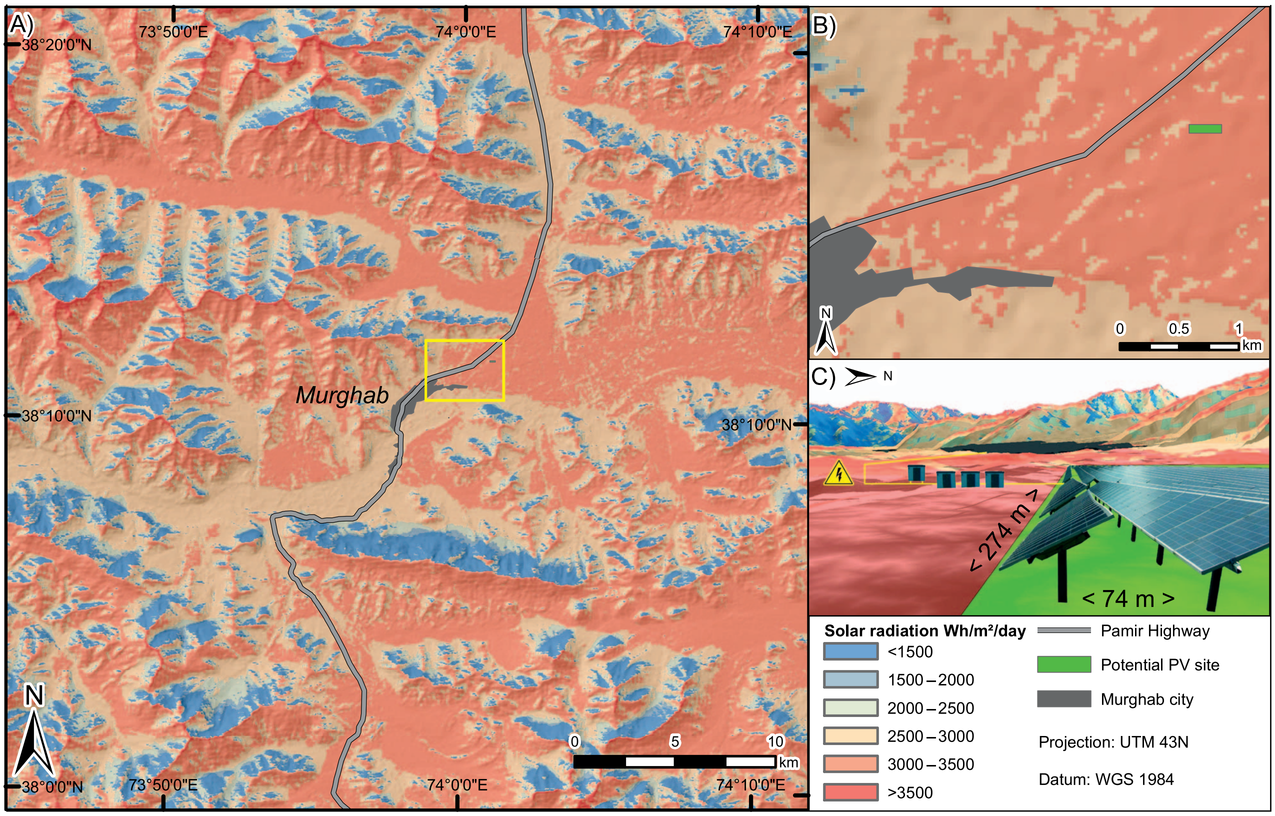
FIGURE 3 (A) Modeled minimum (December) solar radiation amounts on a 26° inclined surface for the study area. (B) Close-up of the surroundings of the potential PV site. (C) Three-dimensional illustration of the topography at the potential PV site. (Figure by Harald Zandler)



PV power plant specifications and cost

The minimum PGF of 2.88 (December) resulted in a need for 5309 PV modules to meet the necessary watt peak rating of 1459.98 kWh. Transformation from direct current (DC) alternating current (AC) required 19 inverters. Furthermore, 57 batteries and 2 battery inverters were needed to provide continuous energy. This design would cost US$ 4,949,709 for materials; adding 15% to cover labor expenses would bring the total cost to US$ 5,692,166. Variations in solar radiation over the year would result in a minimum energy production of 2.25 kWh/d per household in December and a maximum of 5.44 kWh/d per household in July (Table 3).

The layout of the PV plant placed 13 PV modules in an array, resulting in 409 arrays in 20 rows. Considering a pitch distance of 2 m plus the module length, this resulted in a total area of the potential PV site of 274 × 74 m (Figure 3C).

Potential biomass and carbon savings

Maximum potential savings in fresh dwarf shrub biomass in Murghab were calculated to be 4270 t/y, which corresponds to 2046 ha of dwarf shrub area when considering average biomass stocks. With a carbon content of 45.44%, these values result in a maximum decrease in carbon extraction of 1533 t/y (219 kg per capita).

Discussion

Performance of solar radiation model

This is the first study to assess solar energy resources in the Eastern Pamirs of Tajikistan and may serve as a methodological example for other peripheral mountain areas. The measured solar radiation amounts are comparable to some of the world's most favorable areas for PV development, such as Oman (Gastli and Charabi 2010), Spain (Arán Carrión et al 2008; Pons and Ninyerola 2008), Nepal (Poudyal et al 2012), and Tibet (Limao et al 2012). The spatial solar radiation model performed as well as or better than similar approaches (Tovar-Pescador et al 2006; Pons and Ninyerola 2008; Kumar 2011) in terms of R^2, RMSE, and percentage error rate, and it showed a similar pattern of errors over time, with higher relative errors in winter than in summer (Pons and Ninyerola 2008). Huld et al (2012) reported good performance by satellite-based methods to derive solar radiation amounts at lower altitudes, and this approach may be an important

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TABLE 2 Mean solar radiation amounts within the area of the potential PV site.

Month	Solar radiation (kWh/m^2/d)	
	Horizontal surface	Inclined surface (26°S)
January	2.54	3.64
February	3.12	4.11
March	4.46	5.28
April	5.08	5.43
May	5.90	5.82
June	7.07	6.71
July	7.61	7.33
August	5.27	5.45
September	5.37	6.11
October	4.24	5.39
November	2.86	4.02
December	2.10	3.04
Yearly average	**4.63**	**5.19**

TABLE 3 Variation in anticipated energy production by the potential PV plant, taking losses into account.

Month	kWh/d/ household	PGF
January	2.70	3.46
February	3.05	3.90
March	3.91	5.02
April	4.03	5.16
May	4.32	5.53
June	4.97	6.38
July	5.44	6.97
August	4.04	5.18
September	4.53	5.81
October	4.00	5.12
November	2.98	3.82
December	2.25	2.88
Yearly average	**3.85**	**4.93**

alternative when no ground-based measurements are available; however, their approach produced higher errors than ours in mountainous terrain. We believe that the method presented in this article is a reliable and simple way to derive spatial solar radiation amounts in mountainous regions.

The negative bias of our model showed that solar radiation is slightly underestimated; derived energy amounts may therefore be regarded as conservative estimates. The modeled increase in solar radiation from a horizontal to an ideally inclined surface is in the same range as the value of 10–12% reported in other studies (Hartley et al 1999; Arán Carrión et al 2008). Hence, calculations of solar radiation available to the PV panels constitute a stable foundation for estimating potential amounts of generated energy.

Feasibility of PV energy generation

The estimated cost of approximately US$ 5.7 million for the potential PV plant is slightly lower than the estimate for a comparable hydropower project in Murghab (AHK 2013), discussed in more detail later. When expressed as investment cost per installed kilowatt peak, the price (US$ 3900) is near the upper end of the range calculated for PV plants by Ondraczek (2014). Because these costs are related to grid-connected PV plants without energy storage, the cost of the PV plant presented in this article (which does allow energy storage) is financially reasonable.

This study did not include an economic assessment of different energy supply systems but instead focused on using PV energy to heat water; it showed that PV energy for this purpose can be generated within certain limits and at a reasonable cost. The results would differ substantially if additional heating needs had to be met by PV energy. For example, if the plant had to supply enough energy for 2 hours of cooking with a 1500-W electric stove, the cost would more than double to nearly US$ 14 million. If heating with a 2000-W electric device for 6 h/d were added, the cost would rise to more than US$ 45 million, 8 times the cost of the current scenario. Thus, using PV energy for heating and cooking is not feasible in the current situation.

The KfW Development Bank's planned modernization of the Murghab hydropower plant provides an opportunity to compare potential solar and hydro energy amounts. The planned hydropower plant will have an installed maximum capacity of 800 kW (AHK 2013). Without losses, this would result in a daily maximum production of 19,200 kWh, which corresponds to a budget of US$ 6,646,500. PV energy, when losses and expenses for energy storage are not considered, would result in approximately 1.4 times higher generated daily energy amounts in the most favorable month (July) with the same budget.

A number of other limitations to the potential for hydro energy may have to be considered. A modernization of the hydropower plant may not lead to significantly increased energy amounts, because the intake channel will not be substantially enlarged (Kraudzun 2014) and water is a limited resource in this arid environment. Especially

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in winter, when temperatures as low as −30 to −40°C occur, a large amount of water in the catchment of the hydropower plant is frozen and does not contribute to river discharge and energy generation. Similar to comparable Asian high-mountain regions (Wang and Qiu 2009), this shows that PV energy is an important alternative to hydro energy in the Eastern Pamirs.

Solar thermal applications (eg solar thermal collectors), another important renewable-energy alternative, were not considered in this study, because frequent and prolonged freezes occur even in summer, which makes their operation more complex, and simpler systems still face freezing problems during cold periods (Wang et al 2015). More sophisticated, indirect systems containing antifreeze require pumps and an additional conventional boiler. Such a system may be difficult to realize in the Eastern Pamirs of Tajikistan, because it requires high amounts of extra energy (for pumps and a conventional boiler), the installation of a hot water system in the households, and experienced personnel for maintenance. Furthermore, the evaluation of the respective potential is subject to supplementary considerations such as energy exchange rates between the environment and the heat transfer fluid. Therefore, the feasibility assessment of thermal solar energy systems requires further research that takes long-term temperature data into account.

Anticipated effects of PV energy use

Access to modern energy through the PV plant in our scenario would most likely alter the energy situation in the Eastern Pamirs. Characteristics of energy poverty like the inconveniences related to energy supply (Mirza and Szirmai 2010), indoor pollution (Nussbaumer et al 2011), and dependence on biomass (Groh 2014) may be significantly reduced. In particular, the use of dwarf shrubs, presently the most popular fuel for boiling water (Wiedemann et al 2012; Kraudzun et al 2014), is likely to decrease as electric kettles come into use. With a maximum reduction in dwarf shrub clearance of 20.5 km^2/y, a PV plant not only would lower the pressure on vegetation resources but may also have positive effects on livestock breeding, because dwarf shrubs are an important source of forage in the region (Vanselow 2011). This would in turn result in increased availability of animal manure, an equally important source of energy for heating in the region (Kraudzun 2014) and thus indirectly improve the local energy supply.

With a carbon savings potential of 219 kg per capita per year, greenhouse gas emissions could be lowered significantly. Comparison with other regions is problematic because of different scales and environments. However, our results are higher than those of Limao et al (2012), who found that 432,900 t of yearly carbon savings can be gained by decreasing the use of woody biomass for energy and increasing the use of solar energy in Tibet. This converts to a per capita value of 158 kg, using regional population figures provided by the National Bureau of Statistics of China (2005).

Methodological limitations

Only 2 years of climate data were available to calibrate and validate the radiation model presented here, and it is difficult to know whether these data are representative of average climatic conditions. However, they conform substantially with data from the official climate stations averaged over 15 years (Tajik Hydrometeorological Service 2013). Furthermore, precipitation data from the Tropical Rainfall Measuring Mission (TRMM 2014) indicate that our period may be representative of the long-term average. Because precipitation data may be a proxy for cloudiness and therefore solar radiation, we expect that solar radiation data used for this study are largely representative of the long-term average.

Similarly, the field observations that formed the basis of our scenarios on energy requirements did not allow comprehensive insight into the energy consumption habits of local households. An extensive survey on the potential use of electric energy would be needed to enable more accurate scenario specifications.

Economically, our feasibility assessment was based on comparison with another energy project in the same region. A better evaluation of economic feasibility would improve comparability with other peripheral mountain regions. However, because commonly used economic indicators are also based on a number of assumptions and highly variable input factors (Branker et al 2011), additional research and a sensitivity analysis would have been necessary, which was beyond the scope of this study. Research on the temporal variation of discharge volumes, in conjunction with the specifications of the planned local hydropower plant, would also be required to calculate monthly generated electricity amounts and thus allow an objective comparison of PV and hydro energy potentials. Finally, because both the scenarios and the estimates of dwarf shrub biomass use and savings were based on assumptions and subject to temporal variations, it is important to consider the associated uncertainties of the study.

Conclusion

The approach presented here integrates different areas of renewable-energy research to assess the natural potential, feasibility, and effects of increased PV electricity generation in a peripheral mountain region. We derived the first atlas of solar resources in the Eastern Pamirs of Tajikistan from field measurements. Results showed a high natural potential for solar energy. Good modeling performance indicates the suitability of the method in other mountain areas for which

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some climate data are available. The modeled radiation amounts, combined with realistic scenarios based on our observations, another energy project in progress in the region, and existing research, suggest that basic energy for heating water can be generated with PV applications within reasonable cost limits.

Realization of the PV power plant hypothesized for this scenario would considerably change the region's energy situation by increasing the sustainability of local energy resource use, alleviating energy poverty, and fostering carbon sequestration. More generally, this study showed that PV energy has great potential to improve the sustainable development and livelihoods of remote mountain communities, because similar conditions exist worldwide. Therefore, solar energy constitutes a suitable alternative to other renewable-energy resources in mountain environments. We recommend that future studies concentrate on the assessment of the local potential and effects of hydro energy systems based on field measurements and on likely changes in household energy consumption in response to increased availability of electric energy.

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