**Originally published as:**

Neupane, D., Kafle, S., Karki, K. R., Kim, D. H., Pradhan, P. (2022): Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis. - Renewable Energy, 181, 278-291.

**DOI:** https://doi.org/10.1016/j.renene.2021.09.027

# Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis

Deependra Neupane[a], Sagar Kafle[b,*], Kaji Ram Karki[c], Dae Hyun Kim[d], Prajal Pradhan[e]

[a]*Department of Electrical Engineering, Purwanchal Campus, Institute of Engineering, Tribhuvan University, Dharan sub-metropolitan City, Ward no. 8, Sunsari District, Province No. 1, Nepal*
[b]*Department of Agricultural Engineering, Purwanchal Campus, Institute of Engineering, Tribhuvan University, Dharan sub-metropolitan City, Ward no. 8, Sunsari District, Province No. 1, Nepal*
[c]*Department of Civil Engineering, Purwanchal Campus, Institute of Engineering, Tribhuvan University, Dharan sub-metropolitan city, Sunsari, Nepal*
[d]*Department of Biosystems Engineering, College of Agriculture and Life Sciences, Kangwon National University, Hyoja 2 Dong, 192-1, Chuncheon 200-701, Republic of Korea*
[e]*Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, D-14412 Potsdam, Germany*

**Abstract**

Renewable energies, such as solar and wind energy, play a critical role in achieving rapid decarbonization to limit global warming by replacing fossil energy. However, lack of knowledge on renewable energy potentials in developing countries is a barrier in making adequate policies to promote these energies. Thus, we have carried out a spatial and economic analysis of solar and wind energy potential at the provincial level for the first time in Nepal. Our analysis is built upon the spatial energy modeling based on technical, geographical, and economic suitability criteria, utilizing open-source geographical information system platforms. A significant amount of renewable energy could be harnessed in Nepal, i.e., up to about 47,628 MW and 1,686 MW from solar and wind energy, respectively. Similarly, Nepal has a co-location potential of about 890 and 267 MW of solar and wind energy. Karnali and Gandaki provinces have the highest solar and wind energy potential due to a large share of suitable locations with good resource quality. We estimate the $10^{th}$ percentile of Levelized cost of electricity generation of 91 USD/MWh for solar and 46 USD/MWh for wind. Our findings are helpful for the formulation of resource-specific policies of Nepal at a sub-national level.

*Keywords:* `Solar Energy; Wind Energy; Development Phases; Spatial Analysis; Economic Analysis; Nepal`

## 1. Introduction

Limiting global warming well below 2 °C requires rapid decarbonization towards net-zero greenhouse gas (GHG) emissions by 2050 [1]. Renewable energies play a critical role in achieving rapid decarbonization by replacing fossil energy. Globally, renewable energies, such as solar and wind energy, are rapidly growing due to their limited environmental impacts compared to fossil energies [2]. Solar and wind energy systems (also referred to as solar and wind power plants) work in stand-alone or in grid connections [3], and are applicable in both rural and urban areas. Hence, several studies have investigated solar and wind energy potential at local [4, 5], national [6], regional [7], and global scales [8].

*Corresponding author
*Email address:* `sagarkafle@ioepc.edu.np` (Sagar Kafle)

With declining installation costs, developing countries are expected to leapfrog directly to solar and wind energy [9]. An increasing number of studies are investigating the leapfrogging potential of developing countries. For example, Shiraishi and colleagues [10] highlighted solar energy potential for Bangladesh, accounting for roof-top solar energy systems in commercial and residential areas, with minimal conflicts in the agriculture sector. For India, Deshmukh and colleagues [11] reported an abundant but unevenly distributed solar and wind energy potential, with co-located solar and wind power plants meeting a third of the country's energy demand by 2030. At the local level, the study by Sadeghi and Karimi [12] identified suitable locations for solar and wind power plants in Tehran so that a stable energy supply could be ensured. Gerbo and colleagues reported solar power plants installed and generation capacity in the East Shewa Zone of Ethiopia by identifying suitable locations for grid-connected solar energy systems [13]. However, few studies have investigated the solar and wind energy potential for Nepal. These studies have mainly focused on the theoretical national potential, without considering the geophysical and sub-national variation in the country [14, 15, 16]. Additionally, a study on the overall economic feasibility of solar and wind energy in the country is also missing.

In developing countries like Nepal, where around 80% of the population still lives in rural areas [17] with scattered settlements [18], solar and wind energy can become significant contributors to the country's energy mix to ensure energy security. Stand-alone energy systems play an essential role in providing clean energy to all, as envisioned by Sustainable Development Goals (SDGs), i.e., leaving no one behind. Additionally, prioritizing rural populations for clean energy can also leverage the achievements of SDGs as a whole [19], which is considered a system of interacting components rather than just a collection of goals, targets, and indicators [20]. Simultaneously, the promotion of renewable energy also has overall positive effects on the water-energy-food security nexus [21].

Nepal's energy mix is still dominated by traditional biomass. For example, 74% of the total primary energy supply in 2017 (564 petajoules) came from biofuels [22]. Fossil energies, mainly coal and oil, also substantially contribute to Nepal's energy mix (i.e., 23%). Only a tiny share (i.e., 3%) of the energy mix comes from modern renewable sources, mainly hydropower. The contribution of solar and wind energy is negligible in Nepal's energy mix, although these renewable energies were introduced in the early 1970s. Thus, there is also a need to understand the different development phases of solar and wind energy in Nepal to formulate required plans and policies for accelerating these renewable energies' adoption. So far, this understanding is lacking.

In terms of clean energy, hydropower provides around 93% of Nepal's electricity production of 1,142 MW in 2018, mainly from large hydro-plants [23]. In the same year, only 2% of the electricity came from solar energy. Nepal's electricity demand could grow by 6–12 times between 2015 and 2030 under different economic growth scenarios [24]. This growth in electricity demand also considers the substitution of fossil energy use across the industry, transport, household, and service sectors. To meet such a rapidly growing electricity demand, Nepal has focused on using its large hydropower capacity. However, hydroelectricity energy production, especially from the peaking run of rivers, is affected by seasonal variation of water flow. Nepal has the potential to produce 79,704 MW of hydroelectricity, generating an average of 569,964 gigawatt-hours (GWh) of energy per year [25]. In additional to hydropower, solar and wind energy can also contribute to meeting the rapidly growing electricity demand, mainly by providing an optimum energy mix for a stable supply.

Our study aims to fill the above-highlighted knowledge gaps in Nepal's solar energy and wind energy potential. In it, we focus on understanding the different development phases of solar and wind energy in the country. This study advances the existing studies by estimating Nepal's solar and wind energy potential at a sub-national level. For this, we identify suitable locations for installing solar and wind power plants in Nepal considering geophysical factors, namely land-use and land cover, altitude, and slope. For each suitable location, we estimate the installed and annual generation capacity of the power plants. In terms of solar plants, our study focuses on solar photovoltaic (PV) systems because concentrated solar thermal plants are only suitable in the tropics. Additionally, we investigate the economic feasibility of the power plants. Thus, our approach goes beyond the existing studies that largely focused on estimating theoretical renewable energy potential at the national level. Our findings are helpful for the formulation of renewable energy plans and policies of the Government of Nepal at the national and sub-national levels.

## 2. Data and Method

To fulfill the aim of our research, we carry out both literature and spatial analysis. Our spatial analysis is based on various open access data (Table S1), adopting the method from Wu and colleagues [26] (Figure S1). We follow this method based on remotely sensed datasets because of the unavailability of ground-based meteorological station data for the whole country. With the availability of several data processing tools, geographical information system (GIS) based energy assessments have been adapted in several developed and developing countries. Since our data are provided in different spatial resolutions and projection systems, we resample and reproject all data into 30 m grid size with a Transverse Mercator Projection system. For resampling, the nearest neighbor interpolation sampling method is used because of its lower level of complexity. The nearest neighbor interpolation uses pixel replication as an up-sampling algorithm (i.e., to increase grids of an image) based on the nearby pixel value [27]. We use open-source Python GIS and QGIS Software [28] with grass GIS [29] and Python programming language for the spatial analysis. The sub-sections below elaborate on the data and method used for our literature and spatial analyses.

### *2.1. Literature Analysis*

We conduct a comprehensive literature analysis to understand the development phases of solar and wind energy in Nepal. Since there is limited peer-reviewed literature on this topic, our analysis mainly focuses on the grey literature. We identify this literature by screening the existing data and reports. Initially, we gathered information on the first solar and wind power plants established in Nepal. Then, we figure out the key institutions involved in this sector and their establishment years. Afterwards, we search and collect the related plans and policies of the Government of Nepal. We also look for implemented solar and wind energy projects initiated by private, government, and non-governmental organizations. After analyzing the available literature, we categorize the development of solar and wind energy into four phases.

### 2.2. Suitable locations

We identify suitable locations for solar and wind power plants based on the land-use and land cover map of Nepal [30] (Figure S2). This map is available at a resolution of 30 m in a Transverse Mercator Projection system. The land-use and land covers are divided into 12 classes. We consider grasslands, barren lands, and shrublands as suitable locations for the power plants among these classes. In addition to these land-uses, we also count for built-up areas as suitable locations for solar PV systems.

The slope of a location plays a crucial role in determining accessibility for the installation and maintenance of the power plants. In Nepal, where most surface areas are hilly and mountainous regions, steep slopes could be a bottleneck for installation and maintenance. Therefore, we generate a slope map of the country by using the Digital Elevation Model provided by NASA Shuttle Radar Topographic Mission in 90 m resolution [31] (Figure S3). Based on Charabi and colleagues [32], we take a location with a slope equal to or less than 24° as a suitable one. This consideration excludes the highly sloppy regions with a lot of difficulties in plant installation.

Similarly, the performance and efficiency of solar PV systems depend on the tilt angle and direction in which it is faced [33]. Generally, south-facing is best suited in Nepal as it is located in Northern hemisphere. Therefore, we also apply the criteria of south-facing (i.e., aspect degree from 112.5° to 247.5°) to narrow down suitable locations, with the exception of built-up areas (Figure S4).

For wind power plants, the slope of a location drastically affects the wind flow characteristics and their installed and generation capacities. For steeper slopes, the mean wind velocity reduces to a more considerable extent [34] due to turbulence in the rough surface [35]. Thus, we use a slope threshold of 20% (i.e., around 12°) to identify suitable locations for wind power plants by taking an average from the literature that suggests a slope threshold between 10% [36] and 30% [37] (Figure S5).

Around 6,000 rivers and five major river systems crisscross the country and drain into the Ganges River [38]. The appropriate buffer distance from the river has to be kept for the power plants for safety and environmental regulation purposes. Therefore, we further narrow down the suitable locations by considering the buffer distance of 100 m [39] and 500 m [40] for solar and wind power plants, respectively. For this, we use the inland water data on rivers provided by the ICIMOD (Figure S6). This data has been created using the topographic zonal map published by the Department of Survey Nepal [41]. In Nepal, land with an elevation of more than of more than 4,000 m is covered with permanent snow and is currently difficult to access. Thus, we did not consider such locations suitable for solar and wind power plant installation.

### 2.3. Estimation of Solar Energy Potential

We use the solar resource map provided by Solargis [42] to estimate the solar energy potential of the identified suitable locations (Section 2.2). This map consists of information on solar PV potential based on global horizontal irradiance (GHI) at a resolution of 250 m globally (Figure S7). We use GHI as the primary data instead of the other data such as Global Tilt Irradiance data, following similar previous studies for developing and developed countries. The regions with GHI between 4.1 and 6.8 kWh/($m^2 \cdot$ day) are highly recommended locations for solar power plants [43]. Therefore, we narrow down the identified suitable locations by considering the locations with GHI of more than 4.1 kWh/($m^2 \cdot$ day) for our further analysis.

We estimate the installed capacity of solar PV systems in suitable locations by multiplying their surface area with land-use efficiency and land-use discount factor (two scenarios). We consider the land-use efficiency of 30 MW/km$^2$ based on the study by Ong and colleagues [44]. The land-use discount factor refers to the share of land that would not be utilized in the actual plant construction due to technical (e.g., solar PV spread), financial (e.g., limited budget), environmental (e.g., habitat of rare species), or social (e.g., land ownership conflicts) considerations. We assume two scenarios of the land-use discount factor, i.e., no or zero discount factor and 75% discount factor as optimistic and pessimistic estimates, respectively [11].

We calculate the total annual energy generation capacity in suitable locations based on an average capacity factor (CF). Here, we assume that all solar PV systems are south-facing fixed-tilt systems, with their tilt equal to the location's latitude. The CF depends on the solar irradiance on the tilted surface of PV panels, which depends on the GHI and the location's latitude. We establish a statistical model between annual GHI [in kWh/(m$^2$ · day)] and CF for different locations of Nepal (Figure S8), accounting for the system loss. For this, we randomly select 200 locations that would cover latitudes across the country. The annual average CFs for those locations are estimated based on solar meteorological data, namely, global horizontal, direct normal, and diffuse horizontal irradiance, from the National Solar Radiation Database, using NREL PVWatts calculator [45, 46]. We use a system loss of 14%, considering a module efficiency of 16% [47], the typical alternating current performance ratio of 88% [48], and an outage rate of 2% to determine the CF in the simulation. We then estimate CF for the suitable locations using the statistical model. We have applied the above-described procedure for the suitable locations of all land-use and land cover classes, with the exception of built-up areas.

We also narrow down the suitable locations for built-up areas by considering an average GHI level of more than 4.1 kWh/(m$^2$ · day). As the grid size of the data is 30 m × 30 m, we only analyze built-up areas with the surface area greater than or equal to 900 m$^2$. We use equation 1 to estimate the installed capacity of PV systems in the built-up areas.

$$Installed\,Capacity = A \times P_d \times R_a \times BFA_r \times PVA_r \; (MW) \tag{1}$$

In equation 1, $A$ is the total built-up areas in km$^2$. $P_d$ is the average power density of the rooftop solar PV system. We assume $P_d$ as 150 W/m$^2$ considering that the smallest practical residential solar PV system can exhibit a tangible energy production of 1.5 kW [49, 50]. This system requires an area of approximately 10 m$^2$ [49]. All the buildings or houses are not compatible with rooftop solar PV systems because they need a strong foundation and roof for installation. In Nepal, 28.26% of the total buildings or houses are roofed with galvanized sheets, followed by tiles or slates (26.68%), reinforced concrete cement (22.48%), and thatched or straw roofs (19.03%) [51]. The majority of buildings or houses is for residential purposes. Hence, we consider the roof available factor ($R_a$) as a share of buildings or houses with solid foundations and roofs for the solar PV system. We consider $R_a$ as 0.507, assuming that the galvanized and reinforced concrete cement roofs will provide adequate strength and foundation for the rooftop solar PV system.

The building footprint area ratio ($BFA_r$) refers to the ratio of the building rooftop area and the total area of the building plot. The built-up areas consist of different types of infrastructure, where residential and commercial buildings have a large share. Therefore, we consider $BFA_r$ value of 0.5 taking the average infrastructure-wide BFA ratio as suggested by Singh and colleagues [52]. Additionally, the complete rooftop area cannot be used to install solar PV systems due to several factors such as shading and rooftops used for other purposes. For considering these factors, we use the PV availability ratio ($PVA_r$) of 0.4 based on Gutschner and colleagues [53].

We estimate the annual generation capacity of the rooftop solar PV systems based on an average CF. Similar to other land-use and land cover classes, we determine the CF for the suitable locations by using the statistical model presented in (Figure S8).

### *2.4. Estimation of Wind Potential*

We narrow the identified suitable locations for wind energy by considering a threshold for minimum wind power density (Figure S9). For this, we use data on wind power density at 50 m above ground level at a 250 m resolution provided by the global wind atlas [54]. We consider a minimum wind power density of 105 W/m$^2$ as the threshold. This threshold is based on a study investigating wind resources at 16 different sites in Nepal [55].

We estimate the installed capacity for wind power by considering land-use efficiency, land-use discount factor (two scenarios), and the area of suitable locations that met the threshold criteria. This study applies a land-use efficiency of 9 MW/km$^2$ based on existing literature [11, 56]. Like solar energy, the two scenarios are no or zero discount factor as the optimistic potential estimate and a 75% discount factor as a pessimistic potential estimate [11].

For estimating the annual generation capacity, we use the installed capacity and the CF of the suitable locations. The CF for the particular location has been obtained using the data developed by Global Wind Atlas (Figure S10). The CF data has been generated for wind turbines (International Electrotechnical Commission wind class III) of 4.5 MW that at a hub height of 100 m, accounting for the air density [54]. These turbines are designed for locations having an annual average wind velocity of 7.5 m/s [57].

### *2.5. Project Opportunity Areas*

We group the identified adjacent and connected suitable locations for solar and wind power plants into a single area called "Project Opportunity Areas (POAs)" for further analysis. We merge these adjacent and connected raster cells into a single feature polygon. These POAs represent an appropriate minimum area of 900 m$^2$ for the installation of utility and commercial-scale solar and wind power plants. We characterize POAs based on different criteria (i.e., elevation, road distance, substation distance, and installed capacity) for estimating their annual electricity generation capacities and cost. We also investigate the co-location potential of solar and wind energy by overlapping POAs for solar and wind power plants. These locations would be suitable for installing solar-wind hybrid energy systems.

### *2.6. Cost Analysis*

We calculate the cost of solar and wind power plants in each POAs based on the Levelized cost of electricity (LCOE) to understand their economic feasibility. Our LCOE estimates consider the capital cost of power generation ($I_c$), annual cost of operation and maintenance of power plants ($O_{gc}$), capital cost of transmission lines ($T_c$), substations ($S_c$), and road construction ($R_c$), annual discount rate ($i$), and lifetime of power plants ($n$) (Table 1). These estimates are based on equations 2– 5. The total LCOE consists of LCOE for power generation (i.e., $LCOE_{generation}$), transmission lines (i.e., $LCOE_{interconnection}$), and road construction (i.e., $LCOE_{road}$). We assume that one road will be built for every 70 MW capacity power plant, a reasonable size commercial-scale solar PV system. The substation cost is considered for both power generation and grid side, accounting for the distance between the power plant and substation ($d_s$) and the nearest road ($d_r$). We calculate the distance between the center of POAs and the nearest substations of voltage level greater than or equal to 132 kV (under construction and existing) to determine the total cost for the interconnection. Similarly, our estimate also considers the minimum distance between POAs and the road network to calculate the cost for the road construction. For this, we use data on existing, under construction, or planned roads and substations from various sources [58, 59] (Figure S11, Figure S12).

$$LCOE_{generation} = \frac{I_c \times i_d + O_{gc}}{8760 \times CF} \tag{2}$$

$$LCOE_{interconnection} = \frac{(T_c \times d_s + S_c) \times i_d}{CF \times 8760} \tag{3}$$

$$LCOE_{road} = \frac{(R_c \times d_r) \times i_d}{CF \times 8760 \times 70} \tag{4}$$

$$i_d = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

Based on the estimated LCOE, we generated supply curves to analyze the amount of solar or wind energy that would be available at or below a given cost. Following the method of Kline and colleagues [60], supply curves are developed by plotting the cumulative generation capacity of POAs sorted based on their LCOE. We plot these curves for solar and wind energy, considering LCOE for power generation (i.e., $LCOE_{generation}$) and the total LCOE separately. This seperation is because solar and wind power plants can be stand-alone or connected to the national grid. Since the required policies to promote solar energy systems can vary for built-up areas and other land-use and land cover classes, we generate different supply curves accordingly.

Table 1: Parameters used to calculate the Levelized cost of electricity. These parameters consist of the capital cost of power generation (Generation Capital), the annual cost of operation and maintenance of power plants (Annual Generation Fixed O & M), the capital cost of transmission lines (Transmission interconnection Capital), substations (Substation Capital), and road construction (Road capital), annual discount rate (Economic Discount Rate), and a lifetime of power plants (Lifetime years).

| Parameters | Solar | Wind |
|---|---|---|
| Generation Capital [USD/kW] ($I_c$) | 1,210[a] | 1,200[a] |
| Annual Generation Fixed O & M [USD/kW] ($O_{gc}$) | 10[b] | 15[b] |
| Transmission interconnection Capital [USD/MW/km] ($T_c$) | 450[c] | 450[c] |
| Substation Capital [USD/MW] ($S_c$) | 70,000[c] | 70,000[c] |
| Road capital [USD/km] ($R_c$) | 60,000[d] | 60,000[d] |
| Economic Discount Rate (i) | 10%[p] | 10%[e] |
| Lifetime years (n) | 25[q] | 25[f] |

[a] Renewable power generation costs in 2018 [61]

[b] Renewable power generation costs in 2017 [62]

[c] Average of 132 kV, 220 kV, and 400 kV transmission line and substation costs [63, 11]

[d] Design and Appraisal of Rural Transport Infrastructure i.e.,Construction and Gravelling (average cost per km) [64]

[e] Macroeconomics Indicators of Nepal [65]

[f] Terms and condition for Tariff determination from Renewable Energy Source Regulations [66]

As shown in equations 2–4, the LCOE depends on several parameters. Hence, we conduct a sensitivity analysis to understand the dependency of LCOE on these parameters. Particularly, our sensitivity analysis considers a set of hypothetical optimistic and pessimistic values of these parameters, including other technical (i.e., maximum and minimum CF) and geographical factors (i.e., distance to the nearest road and substation). Table S2 provides details on these hypothetical values. For each of these parameters and factors, we estimate LCOE by changing its value to the hypothetical optimistic and pessimistic ones while keeping the values of other parameters and factors described above. The variation of parameters that results in an increment of the total LCOE compared to the reference values is considered the worst case. Similarly, the results with decrements of the total LCOE are considered as an optimistic case. We estimate the reference values based on parameter values in table 1, an average road and transmission distance of both cases, and a capacity factor of 15 % (solar energy) and 30 % (wind energy).

### *2.7. Estimating potential at national and sub-nation scale*

Nepal's 2015 Constitution has replaced a unitary government with a federal system consisting of seven provinces. With the implementation of federalism, the formulation of plans and policies of the energy sector on the provincial level is becoming a crucial issue for Nepal's sustainable development. As the country has been geographically diverse, the potential of different energy resources varies across the provinces. Therefore, to provide a foundation of renewable energy development at a sub-national level, we estimate solar and wind energy potential on the provincial and national levels.

About 23 % of Nepal is designated as protected areas [67], where limited human activities are permitted. Thus, we estimate installed and annual generation capacities of solar and wind power plants in those areas separately. For this, we used the data on protected and reserved areas from the IUCN and UNEP [68] (Figure S13). However, we do not exclude those areas while estimating the installed and generation capacities on national and province levels. We determined the potential in the protected areas, also considering their buffer zones.

## 3. Results

### *3.1. Solar and wind energy development timeline*

We categorize Nepal's solar and wind energy development into four phases: Introductory phase (1974-1996), Institutional setup (1996-2000), Home system development (2000-2017), and Upscaling (2017 - onward) (Figure 1).

**Introductory phase**: The introductory phase started when the first solar PV system was introduced by Nepal Telecommunication Center in 1974 to operate its communication transceiver located in Damauli, Tanahun district [69]. The first wind power plant was installed in 1987 with 20 kW capacity in Kagbeni in upper Mustang district [70]. In 1988, Nepal Electricity Authority initiated three decentralized electricity supplies from solar PV systems in Simikot, Tatopani, and Gumdadhi with 50, 30, and 50 kW, respectively began operation in 1989 [69]. To deliver electricity in rural areas, the first solar home program to electrify a village began in 1994 in Pulimarang village in Tanahun district with solar PV systems in 64 households [71].

**Institutional setup phase**: This phase started in 1996 after the formation of the Alternative Energy Promotion Center (AEPC), an independent institution to promote renewable energy in Nepal [72]. The establishment of this center stimulated various other renewable energy-related institutions in the country, both in the public and private sectors. In 1999, the Center for Energy Studies (CES) was established in the Institute of Engineering, Tribhuvan University, to train and produce highly qualified renewable energy experts [73]. An association of solar electric manufacturing and trading companies was registered in 2000 [74].

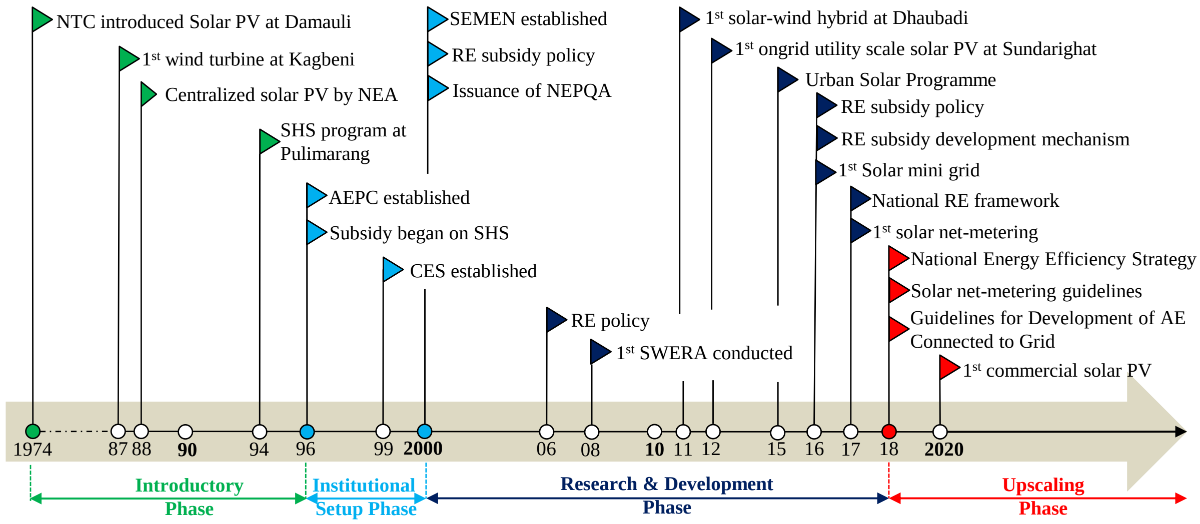


Figure 1: Solar and wind energy development timeline of Nepal, which has been categorized into four phases: introductory (1974-1996), institutional setup (1996-2000), home system development (2000 - 2018) and upscaling phase (2018-onward). Abbreviations used in the figure are – NTC (Nepal Telecommunications Center), PV (Photovoltaic), NEA (Nepal Electricity Authority), SHS (Solar Home Systems), AEPC (Alternative Energy Promotion Center), CES (Center for Energy Studies), SEMEN (Solar Electric Manufacturers Association Nepal), RE (Renewable Energy), NEPQA (Nepal Photovoltaic Quality Assurance), SWERA (Solar and Wind Energy Resource Assessment), and AE (Alternative Energy).

**Research & development phase**: This phase was started after the government formulated and launched programs and guidelines on renewable energy to provide electricity, mainly in rural areas. The first renewable energy subsidy policy was launched in 2000, updated in 2016 together with the renewable energy subsidy development mechanism. The technical standard for solar PV systems, called Nepal Photovoltaic Quality Assurance, was also developed and adopted in 2000 to disseminate Solar Home Systems (SHS). This standard has been revised periodically (i.e., in 2002, 2005, 2009, 2013, and 2015) [75]. The trend of SHS installation shows a steep rise after 2000 due to these policies and subsidies provided by the Alternative Energy Promotion Center through the Energy Sector Assistance Program [76]. The country has faced load shedding up to 16 hrs a day in the dry season during this phase [77, 78]. Hence, the government also formulated policies to encourage SHS in urban areas to address load shedding problems [79], which also promoted SHS in Nepali cities. In 2008, the first solar and wind energy resource assessment was conducted in Nepal, providing estimates of its renewable energy potential [14]. In 2017, the National Renewable Energy framework, National Energy Efficiency Strategy, and Solar net-metering guidelines were developed. Formulation of the Solar net-metering guidelines opened the door to add the extra generated electricity from SHS to the national grid.

**Upscaling phase**: Realising the need and importance of grid-connected renewable energy, the government formulated the guidelines in 2018, which opened the door for commercial electricity generation from solar, wind, and biogas. As a result, several projects have been developed for installing solar power plants in Nepal. So far, 14 projects received a license to construct the solar plants in different parts of the country, with a total installed capacity of 84.5 MW [80]. Similarly, 31 projects received a license to survey the potential installation locations of solar power plants, with a total installed capacity of 377.6 MW [80]. In June 2020, Nepal's first commercial solar power plant (25 MW, near Devighat hydropower stations) started producing electricity, connecting 1.25 MW in the grid, with construction still in progress [81, 82]. Similarly, another 8.5 MW of electricity was added to the national grid in October 2020 by the private sector-run Butwal Solar Power Project, located in Rupandehi [83].

### 3.2. Solar and wind energy potential

Out of the total area of Nepal (1,47,523 km$^2$), grasslands, built-up areas, barren lands, and shrublands cover about 15,353 km$^2$, 544 km$^2$, 12,643 km$^2$, and 3,428 km$^2$, respectively (Table S3). These land-use and land cover classes share about 21% of the country's area, which are considered suitable locations for solar and wind power plants. Karnali province has the highest area of these land-use and land cover classes at a sub-national level, with a share of 43% of the total provincial area. This province has the largest area of grassland and barren land that is suitable for installing solar and wind power plants. Province 2 has the lowest area of these land-use and land cover classes, which is only about 8% of the total provincial area. This province lies in the lowland region, where agriculture is the dominant land-use and land cover class. Additionally, this province also has a large number of intermittent rivers. Thus, suitable locations for solar and wind power plants are limited in this province due to the required buffer distance to the rivers.

#### 3.2.1. Solar energy potential

Nepal has a total annual solar energy generation capacity of 57,519 GWh with a total installed capacity of 47,628 MW, considering the land-use discount factor of zero (Table 2). This potential is about 7.4 times the total energy available in the national grid in 2020 (i.e., about 7,741 GWh) [81]. Nepal's major solar energy potential is located in the northern Transhimalayan and hilly regions (Figure Figure 2 top) because of the availability of high solar insolation. Nepal has about 250 km$^2$ of suitable locations for solar power plants, which have a CF greater than 15%, i.e., the average CF required for utility and commercial-scale solar power plants, and an average daily GHI larger than 5 kWh/m$^2$. Thus, in terms of utility and commercial-scale solar power plants, Nepal's annual solar energy generation capacity is limited to 11,558 GWh, considering the land-use discount factor of zero, which is the only 20% of the total capacity.

Nepal's solar energy potential varies across its provinces both in terms of generation and installed capacities (Table 2 and Figure 2 top). Gandaki province has the largest solar energy generation capacity, but the largest installed capacity is in Karnali province. We observe this variation because the average CF of Gandaki province is larger than that of Karnali province due to relatively higher global horizontal irradiance (Figure S7). Bagmati Province has the lowest solar energy generation and installed capacities because of relatively low resource quality (i.e., a low CF) and steeper slopes, narrowing down the suitable locations. Interestingly, although Province 2 has the lowest area of land-use and land cover classes suitable for solar and wind power plants, it has the third-highest solar energy generation and installed capacities. This province has the majority of suitable locations with a low slope, low altitude, and south-facing.

Table 2: Solar energy potential in Nepal's seven provinces in terms of annual generation and installed capacities, together with area of the suitable locations. The estimated solar energy potential is presented for two scenarios: zero and 75 % land-use discount factor, taking 30 MW/km$^2$ land-use efficiency. Co-location potential refers to wind energy installed capacity in the suitable locations for the solar power plants, considering zero land-use discount factor with land-use efficiency of 9 MW/km$^2$.

| Provinces | Area ($km^2$) | Zero land-use discount factor | | 75% land-use discount factor | | Co-location potential with wind energy (MW) |
|---|---|---|---|---|---|---|
| | | Generation Capacity (1000 MWh) | Installed Capacity (MW) | Generation Capacity (1000 MWh) | Installed Capacity (MW) | |
| Province 1 | 200.7 | 6,647 | 6,195 | 1,662 | 1,549 | 18 |
| Province 2 | 254.9 | 8,894 | 7,817 | 2,223 | 1,954 | 4 |
| Bagmati | 121.8 | 4,100 | 3,706 | 1,025 | 926 | 6 |
| Gandaki | 263.4 | 11,321 | 7,960 | 2,830 | 1,990 | 137 |
| Province 5 | 243.2 | 8,839 | 7,338 | 2,210 | 1,834 | 20 |
| Karnali | 287.4 | 10,660 | 8,661 | 2,665 | 2,165 | 61 |
| Sudurpashim | 191.6 | 7,059 | 5,952 | 1,765 | 1,488 | 20 |
| Total | 1,563.3 | 57,519 | 47,628 | 14,380 | 11,907 | 267 |

Nepal has the built-up areas of 543 km$^2$ (Table S3). However, only about 10% of this area is suitable for rooftop solar PV systems, resulting in a total installed capacity of about 8,100 MW. We estimate the total annual solar energy generation capacity of about 9,600 GWh in the country. At a sub-national level, the potential for rooftop solar PV systems varies across the provinces (Figure S14). Bagmati province has the highest generation capacity because around 40% of Nepal's built-up areas is located in this province. Moreover, Bagmati province also has the highest population density in the country, with a total population of around 5 million people [84]. Due to the lowest share of built-up areas, Karnali Province has the lowest potential for rooftop solar PV systems.

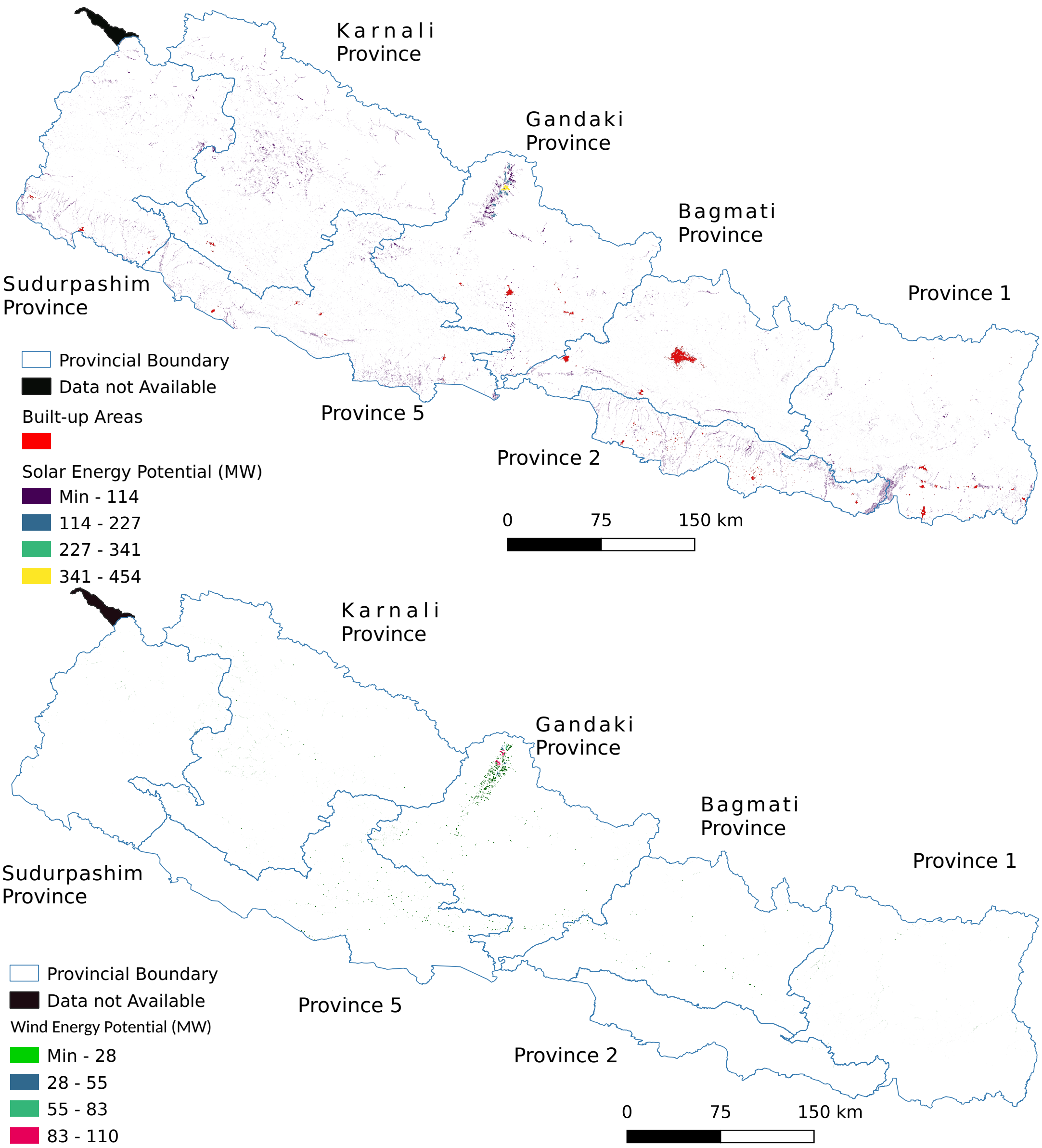


Figure 2: Spatial distribution of solar (top) and wind (bottom) energy potential in seven provinces of Nepal in installed capacities. Only locations with minimum installed capacities of 0.03 MW and 0.01 MW for solar and wind energy are plotted. These installed capacities are based on zero land-use discount factor with land efficiency of 30 MW/km$^2$ for solar and 9 MW/km$^2$ for wind. For solar and wind energy, suitable locations with a high energy potential are observed in the northern part of Gandaki province, while southern lowland regions have relatively low potential. Bagmati province contains the most concentrated built-up areas.

### *3.2.2. Wind energy potential*

Nepal's wind energy potential is lower than its solar energy potential. The country has a total annual wind energy generation capacity of 3,788 GWh with a total installed capacity of 1,686 MW, considering the land-use discount factor of zero (Table 3). Nepal has about 145 km$^2$ of suitable locations for wind power plants. About 55 km$^2$ of these locations has a wind power density of more than 300 W/m$^2$. These locations with a high wind power density mostly lie in the northern hilly region of the country (Figure S9). Similarly, around 50 km$^2$ of suitable locations have a CF of more than 30% that is required for utility and commercial-scale wind power plants.

Nepal's wind energy potential also varies across its provinces, with a large share of the potential concentrated in Gandaki province (Table 3 and Figure 2 bottom). This province has a majority of locations with CF greater than 30%, although several locations with suitable land-use and land cover classes need to be narrowed due to their elevation of greater than 4000 m. Gandaki and Karnali provinces possess about 80% of the country's wind energy potential. These provinces consist of places (e.g., Manang, Mustang, and Tansen) with a high wind power density (i.e., greater than 105 $W/m^2$) (Figure S9). Additionally, they have locations with relatively high wind speeds with altitudes below 4,000 m and an appropriate slope for wind power plant installation (Figure S5). Because of a low wind power density and a low share of suitable locations, Province 2 has the least wind energy potential.

Table 3: Wind energy potential in Nepal's seven provinces in terms of annual generation and installed capacities, together with areas of suitable locations. The estimated wind energy potential is shown for two scenarios: zero and 75% land-use discount factor, taking 9 $MW/km^2$ land-use efficiency. Co-location potential refers to solar energy installed capacity in the suitable locations for the wind power plants, considering zero land-use discount factor with land-use efficiency of 30 $MW/km^2$.

| Provinces | Area ($km^2$) | Zero land-use discount factor | | 75% land-use discount factor | | Co-location potential with solar (MW) |
|---|---|---|---|---|---|---|
| | | Generation Capacity (1000 MWh) | Installed Capacity (MW) | Generation Capacity (1000 MWh) | Installed Capacity (MW) | |
| Province 1 | 11.9 | 163 | 109 | 41 | 27 | 59 |
| Province 2 | 0.7 | 13 | 7 | 3 | 2 | 13 |
| Bagmati | 2.5 | 28 | 24 | 7 | 6 | 21 |
| Gandaki | 91.0 | 2,945 | 1,137 | 736 | 284 | 458 |
| Province 5 | 5.7 | 91 | 54 | 23 | 14 | 68 |
| Karnali | 21.9 | 380 | 245 | 95 | 61 | 203 |
| Sudurpashim | 10.8 | 168 | 111 | 42 | 28 | 68 |
| Total | 144.5 | 3,788 | 1,686 | 947 | 422 | 890 |

### *3.3. Project opportunity areas (POAs)*

We identify about 6,600 POAs for solar that have a CF greater than 15 % and 990 POAs for wind power plants with a CF greater than 30 % across the country. For solar energy, the largest POA has an area of 15.1 $km^2$. 12.2 $km^2$ is the largest area of the POAs for wind energy. Considering a land-use discount factor of zero, only about 10% of the POAs would accommodate solar power plants of an installed capacity greater than 1 MW. Among these POAs, only 980 POAs have a CF greater than 15 %. Similarly, wind power plants of an installed capacity greater than 1 MW could be developed only in about 149 POAs, considering the land-use discount factor of zero. Only 66 of these POAs have a CF greater than 30 %.

The POAs are spatially distributed across the country. We characterize each POA based on its average elevation, LCOE, installed capacity, and resource quality (i.e., global horizontal irradiance for solar energy and wind power density for wind energy) (Figure 3). This characterization shows that most POAs lie in higher elevation regions because of better resource quality, increasing the CF and reducing LCOE.

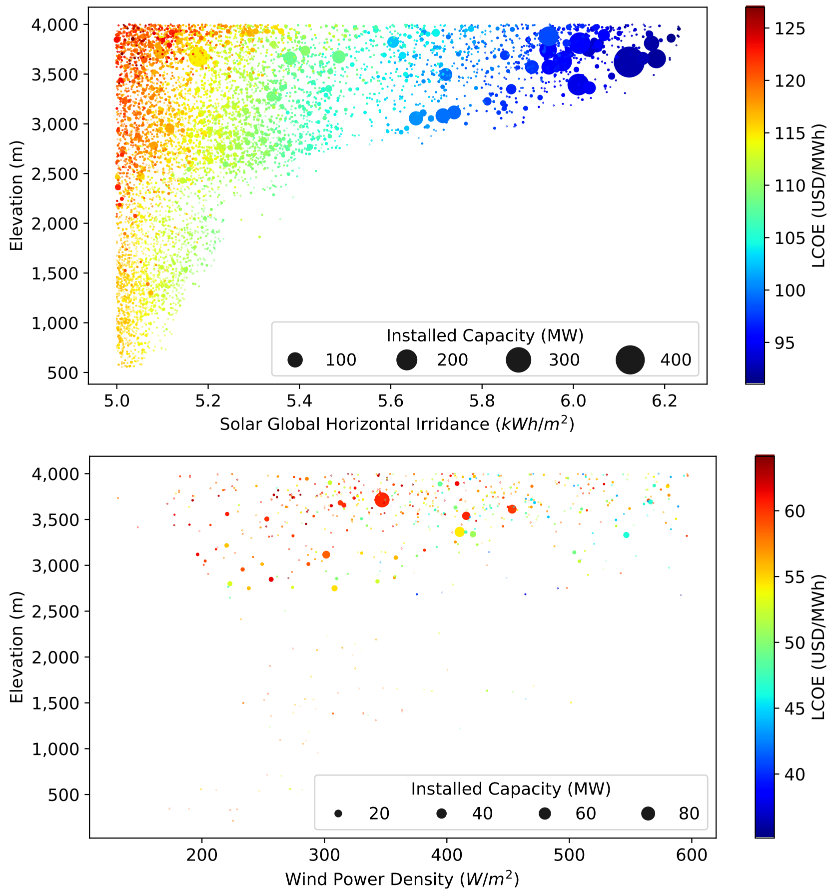


Figure 3: Characteristics of the project opportunity areas (POAs) concerning resource quality (i.e., global horizontal irradiance for solar energy and wind power density for wind energy), installed capacity, elevation and total Levelized cost of electricity (LCOE) of solar energy (top), having capacity factor greater than 15 %, and wind energy (bottom), having capacity factor greater than 30 %. The bubbles show the sizes of POAs in terms of installed capacity, considering the land-use discount factor of zero. In the figure, the maximum installed capacity of solar and wind is 454 MW and 94 MW, respectively.

### *3.3.1. Distance to roads and substations*

For solar power plants, about 75% of the POAs lie under 20 km distance from the nearest road and 70% of the POAs under 20 km distance from the nearest substation. Within this distance from both infrastructures, about 3,300 GWh of solar energy can be generated annually, considering a land-use discount factor of zero. However, most POAs with the CF greater than 15 % are about 53 km far from the road and 28 km far the substation networks. Looking at the cumulative installed capacity with normalized substation and road distance, we see that most POAs for solar energy are near to or within the country's existing road network (Figure S15). This finding is good news for the development of solar power plants in Nepal because installing power plants in the POAs far from roads and substations would increase the overall cost.

For wind power plants, about 44% and 50% of the POAs lie under 20 km distance from the nearest road and the nearest substation (Figure S16). Within this distance from both infrastructures, about 175 GWh of wind energy can be generated annually, considering the land-use discount factor of zero. Most POAs with a high resource quality (i.e., a wind power density of greater than 300 W/m$^2$) lie far from the road and substations due to Transhimalayan and hilly regions with high resource quality but with poor road and substation networks. Similarly, most POAs having a CF greater than 30 % are around 60 km and 43 km far from the road and substation networks. This finding shows that wind energy POAs are relatively far from the road and substation networks than those for Nepal's solar energy POAs.

At sub-national scale, most POAs with a long road distance (i.e., an average distance of solar and wind POAs from the nearest road is about 48 km) are in Karnali Province. This province has a poor road network that would result in a high cost for installing solar and wind power plants. Interestingly, Province 2, located in the lowland region, has the abundant road and substation networks required for the power plants, resulting in lower costs compared to other provinces (Figure 15 and Figure 16 ). In this province, the average distance of solar energy POAs from the nearest road and substation is only about 4 km and 14 km, respectively. Additionally, power plant construction is relatively easy in this province due to its flat topography. In the past few years, the construction of several new hydropower plants with planned substations has increased the national grid accessibility in many regions across the country. This increased accessibility would promote the installation of solar and wind power plants across Nepal. For example, Province 1 consists of several planned substations (e.g., Arun substation hub, Damak substation, and Inaurwa substation) [85], which provides an optimistic future for on-grid solar and wind power plants in the province.

### *3.3.2. Protected Areas*

Since about 23% of Nepal's area is covered with protected areas, a large share of POAs is located in these areas and their buffer zones. Specifically, 509 $km^2$ out of 1,563 $km^2$ of solar energy POAs and 93 $km^2$ out of 144 $km^2$ of wind energy POAs lies in Nepal's protected areas and their buffer zones. In other words, the power plants need to be installed in these locations to harness around 37% and 78% of the country's total solar and wind energy generation capacities. Within the protected areas, the maximum solar and wind energy potential is found in the Annapurna Conservation Area, i.e., 11% of the total solar and 63% of the total wind energy installed capacities, generating about 8,498 GWh and 2,816 GWh of electricity annually. Since specific regulations need to be followed for any infrastructure development in the protected areas and their buffer zones, installing solar and wind power plants would be a challenge in these locations. Thus, the federal and provincial governments should maintain a delicate balance in biodiversity conservation and provision of energy security while developing solar and wind power plants in the protected areas and their buffer zones.

### *3.3.3. Co-location potential*

About 30 $km^2$ of the POAs are suitable for both solar and wind power plants. The solar and wind energy potential of these POAs are also known as co-location potentials. These POAs have a total installed capacity of 267 MW and 890 MW of solar and wind energy, respectively (using zero land-use discount factor). In other words, these locations are suitable for hybrid solar and wind power plants. In terms of generation capacity, 1,247 GWh of solar energy and 567 GWh of wind energy can be harnessed from these locations annually. These suitable POAs for both solar and wind power plants are mostly located in the northern part of Gandaki province as it consists of 50% or 15.27 $km^2$ of these locations.

#### 3.3.4. Levelized cost of electricity (LCOE)

About 10% of the total solar energy POAs generates more than 1,214 GWh of energy per year, which has a total LCOE below 120 USD/MWh, considering zero land-use discount factor (Figure 4). For wind energy, around 37% of POAs has a total LCOE below 80 USD/MWh, which would generate more than 2,800 GWh of energy annually (zero land-use discount factor). Interestingly, most POAs with a low LCOE are located in the high altitude region as power density increases considerably (Figure 3). Solar PV systems seem more expensive than wind power plants in terms of generation capacity because of the low CF of solar PV systems compared to wind power plants. For example, about 3,146 GWh of wind energy can be generated annually at the total LCOE of 91 USD/MWh and below, near the starting LCOE for solar energy. However, the total LCOE for wind energy escalates quickly with minor changes in energy generation. Additionally, due to the modular design, less maintenance requirements, and ease of installation relative to wind power plants, solar PV systems can be rapidly promoted to meet the country's energy demand. Moreover, rooftop solar PV systems in built-up areas are the most expensive option, although their LCOE does not consist of roads and interconnections. This high cost is associated with the low CF in the built-up areas, i.e., an average value of 13.6 %. Besides, stand-lone systems in built-up areas require storage, which would increase the LCOE further. Both for solar and wind energy, a large share of the total LCOE comes from generation costs. The costs for interconnection and roads are on average about 8.9 USD/MWh and 8.8 USD/MWh for solar and wind energy, respectively.

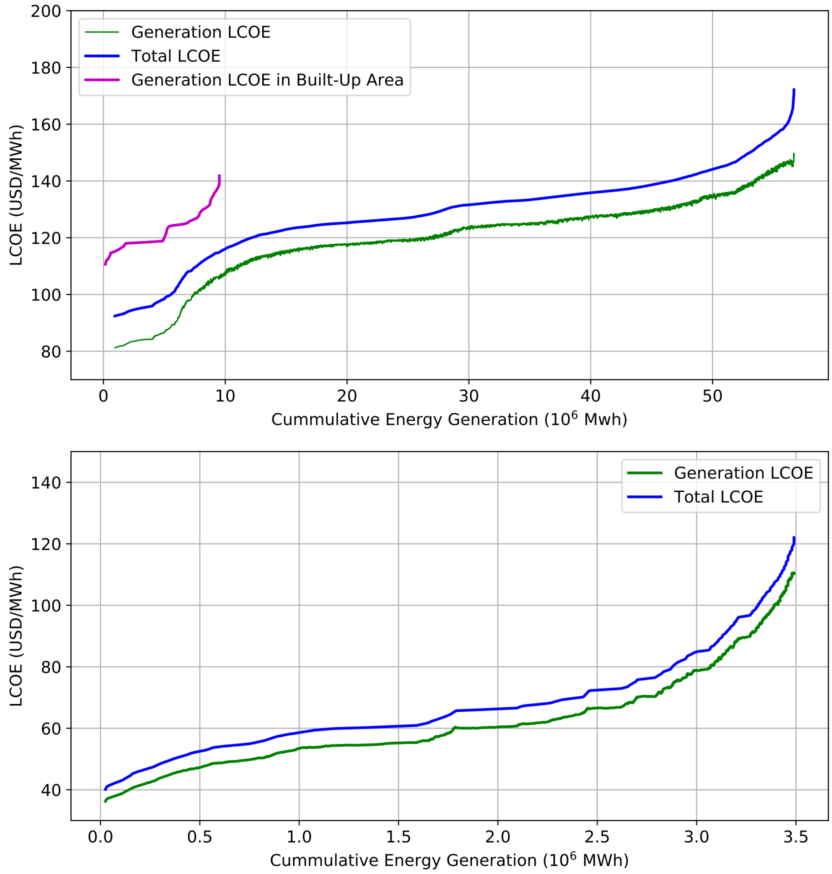


Figure 4: Supply curves of solar (top) and wind (bottom) energy based on the Levelized cost of electricity generation (LCOE) and generation capacity of the project opportunity areas (POAs). These curves are developed by plotting the cumulative generation capacity of POAs sorted based on the total LCOE (blue line) and the LCOE for power generation (green line) separately. For solar energy, the curve for built-up areas is also plotted (pink line). The estimated $10^{\mathrm{th}}$ and $90^{\mathrm{th}}$ percentile of LCOE are 91–138 USD per MWh for solar energy and 46–86 USD per MWh for wind energy.

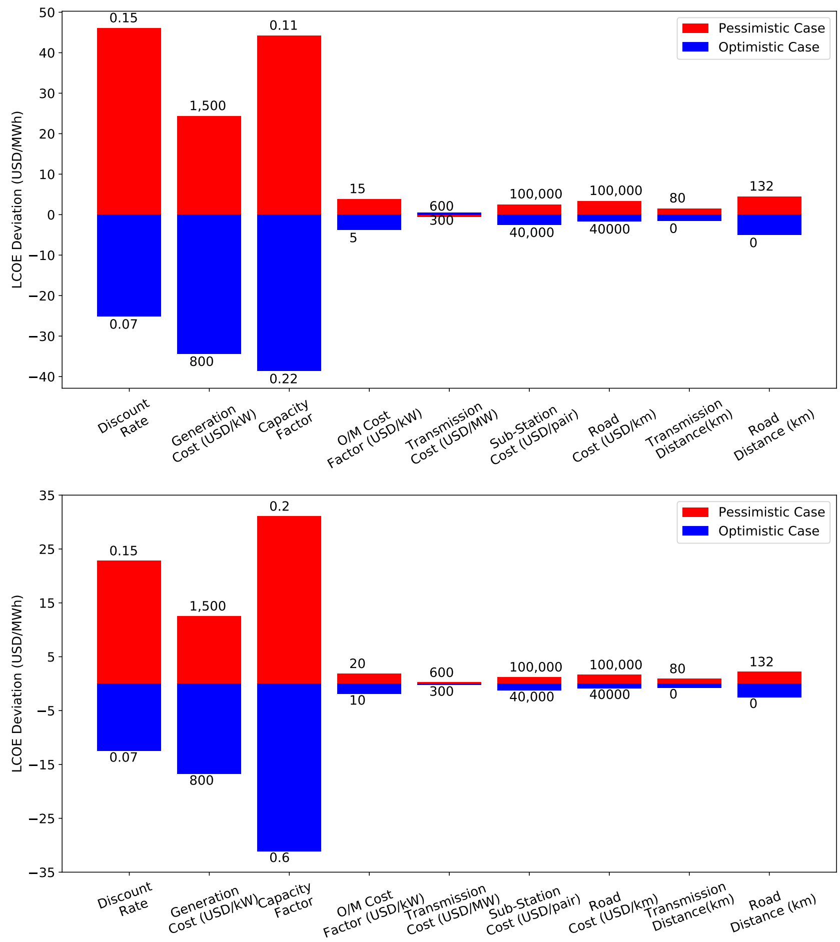


Figure 5: Sensitivity of estimated the Levelized cost of electricity (LCOE) for solar (top) and wind (bottom) energy for pessimistic and optimistic cases. The pessimistic case shows an increase in the total LCOE compared to the reference values due to the variation of parameters. Similarly, the optimistic case represent a decrease in the total LCOE. The reference values of LCOE are 121.46 USD/MWh and 62.21 USD/MWh for solar and wind energy, respectively, which are based on parameter values in Table 1, an average road and transmission distances of both cases, and the capacity factor of 15 % (solar energy) and 30 % (wind energy).

Looking at the sensitivity of the total LCOE, our analysis highlighted that it is more sensitive to the economic discount rate, generation capital, and the CF than other parameters and factors (Figure 5). The discount rate depicts the financial or interest rates available in a region. Hence, changes in the interest rates could affect the country's adoption of solar and wind energy. A low-interest rate would make solar and wind power plants cheaper, resulting in promotion on solar and wind energy, and vice versa. The generation of capital depends on technological advancements. Therefore, declining generation capital costs due to advancements in solar and wind energy technologies would further encourage solar and wind power plants.

Similarly, the CF depends on the resource quality of the location and technology used. A large-scale environmental degradation, including climate change, could negatively impact the resource quality, reducing the CF, whereas technological advancements could increase it. Therefore, nature conservation, including climate change mitigation, would help to promote solar and wind energy by maintaining the current resource quality. Interestingly, the total LCOE is less sensitive to the availability of road and substation networks. However, these infrastructures would be a bottleneck for solar and wind energy development because of the substantial time required for their construction in developing countries like Nepal. Nevertheless, the road and substantiation networks are also promoted by other infrastructure development within the country, including hydropower. Thus, the appropriate prioritization of POAs based on high resource quality and distance to existing infrastructure would be a starting point for installing utility and commercial-scale solar and wind power plants in Nepal.

## 4. Discussion

### *4.1. Possibility of solar and wind power plants*

Our study highlights that Nepal has an abundant resource of solar energy (i.e., up to 47,628 MW) and a relatively lower potential for wind energy (i.e., up to 1,686 MW) compared to that of other developing countries (e.g., Bangladesh [10] and India [11]). These estimates are greater than the solar and wind energy potentials reported by Windsor and colleagues [14] because of the use of high-resolution datasets and our consideration of stand-alone energy systems. They estimated 2100 MW and 489 MW for grid-connected solar and wind energy across the country, using low-resolution datasets (i.e., 10 km spatial resolution). For solar energy, we estimate that the country's total annual generation capacity of 96,00 GWh is located within its built-up areas, which is similar to the value reported by Gautam and colleagues [86]. However, Nepal has only harnessed a small fraction of these resources. Since the country's solar energy potential is about 10% of its hydropower potential [25], the possibility of solar PV systems contributing substantially to the national grid cannot be ignored in Nepal's future energy security. Although having a low potential, wind energy also has the advantage of ensuring energy security in high altitude rural areas that are not connected to the national grid via stand-alone systems.

Nepal's most suitable locations for solar and wind energy lie in Transhimalayan and hilly regions that are the least developed and remote areas of the country. Harnessing these resources can be an excellent opportunity for these areas for their economic development. However, most of these areas need to tramp over through the steep regions with a high geographical gradient, challenging installing power plants, transmission lines, and substations, and transporting required equipment. Apart from Transhimalayan and hilly regions, the suitable locations in the lowland region mostly lie near the main river and stream areas. Although we consider buffer regions to narrow down the suitable locations, these water bodies could be a potential risk for power plants, more for solar than wind ones, during the rainy season due to flooding.

### *4.2. Economics viability for solar and wind energy*

Our findings also provide a basis to understand the economic viability of solar and wind energy, which is missing in the existing literature. We present that the cost of solar energy remains almost constant for an extensive range of energy generation capacity due to its wide spatial availability. However, solar power plants are more expensive than wind power plants due to their relatively low average capacity factor. Solar and wind energy systems are currently not cost-competitive with hydropower in Nepal due to hydropower's lower cost. The current power purchasing rate of hydropower in the country is about 70 USD/MWh in the dry season [87] with an average LCOE of about 50 USD/MWh in South Asia [61]. This LCOE is lower than the estimated $10^{\text{th}}$ and $90^{\text{th}}$ percentile of LCOE for solar energy

(91–138 USD/MWh) and wind energy (46–86 USD/MWh) for Nepal. Therefore, appropriate subsidies and policies are needed to make solar and wind energy competitive with hydropower.

Globally, the generation costs of solar and wind energy are declining year by year, i.e., around 90% since 2009 in solar PV module and 60% for wind turbines [61]. This decrease in the LCOE has resulted in an increase in solar and wind energy installation rates throughout Nepal in recent years. For example, 1.64 MW of solar energy has been connected to the national grid, and solar power plants of a total capacity of 60.5 MW are under construction [81]. The cumulative number of SHS systems promoted across the country are 410,430 with a total installed capacity of 9.91 MW [88]. Though no stand-alone or grid-connected wind power plant have been installed, wind-solar hybrid systems have generated 563 kW of electricity in the country [89]. Moreover, the National Planning Commission has the target to install 481 solar power plants (1 MW installed capacity) and one wind power plant (0.2 MW installed capacity) in the country by 2022 to provide clean energy to remote areas that are not connected to the national grid [90]. With technological advances, economies of scale, and market dynamics, the cost of solar and wind power plants will continue to decline while the price of solar and wind energy will also decrease in the future. These changes will further promote solar and wind energy in the country. Nevertheless, the economics of solar and wind generation depends on several factors, including location and government policies [91].

Similarly, the marginal economic value of both wind and solar energy decreases as their share of overall energy generation increases [92]. Additionally, renewable energy based on stand-alone or grid-connected microgrids and distributed generation could optimize the overall cost of electricity. Moreover, location-specific strategies for the energy sector have to be developed and implemented to ensure improved energy and economic balance. For instance, wind power plants need to be promoted in locations suitable for wind energy. This strategy would promote the efficient use of local resources, increasing employment, and improving the life of local people.

### *4.3. Infrastructure Development*

Our study also highlights the link between infrastructure development and the promotion of solar and wind energy in Nepal. On the one hand, appropriate infrastructure, mainly road and substation networks, is needed to encourage solar and wind power plants. On the other hand, the development of solar and wind energy in remote locations would also improve infrastructure accessibility, including roads, interconnection, and the internet. About 30% of Nepal's total road length is earthen type [93], which is affected during the rainy season. Most of Nepal's transmission network comprises 132 kV voltage level (i.e., 2,819 circuit km), with only 153 circuit km of 400/220 kV lines [94]. The road accessibility in higher altitude locations is relatively low and still challenging for route development, especially in Karnali Province. Only about half of the rural population in Nepal lives within 2 kilometers of a road in good or fair condition [95]. However, the good news is that more than 900 MW of hydropower plants are under construction, and more than 2,000 MW has been planned in Nepal [85]. The suitable locations for solar and wind power plants in the vicinity of under construction or planned hydropower plants can be prioritized. This prioritization would help to develop energy corridors in different locations of the country. Furthermore, the energy cost can be reduced as they will share common road and substation networks.

### 4.4. Energy Planning

Our findings also contribute to sound energy planning in Nepal, promoting an optimum energy mix. Currently, hydropower contributes most of Nepal's electricity. However, electricity generation fluctuates seasonally because most power plants are of the Run-Of-River and Peaking Run-Of-River types, causing severe power shortages during winter [96]. The county is still relying on 240 MW to 550 MW of imported electricity to meet its demand [81]. Therefore, sound strategies for an appropriate energy mix have to be followed for a better, reliable, and more stable supply of electricity in the country. For example, commercial solar power plants can be a solution because they can be constructed in a shorter time than hydropower plants. Additionally, the seasonal fluctuation of solar and wind energy in potential sites is relatively low in Nepal. The average seasonal fluctuation in wind speed (which defines the power) for some of the suitable locations of Nepal like Jumla, Kagbeni, Nagarkot and so on is not more than $\pm 30\%$ [55]. Similarly, the average solar power fluctuation is not more than 33% in different suitable locations in the country [97, 98]. Additionally, major rural areas of the country can be electrified without a direct connection to the national grid by realizing solar and wind energy-based micro-grids.

While considering solar and wind energy, the requirement of energy storage for integrating solar and wind power plants into the country's energy planning cannot be ignored, mainly for stand-alone systems. Energy storage systems provide regulation and reserve capacity, and hence, alleviate the negative impacts of solar and wind energy because of their diurnal patterns [99]. In the national grid, the operation of major hydro projects (Peaking Run-Of-River and storage) can be synchronized with the diurnal patterns of solar and wind energy to ensure a stable electricity supply.

In the context of cities and urban areas, solar energy potential in the built-up areas can be utilized to supply electricity to houses and provide surplus electricity to the national grid. With the declining cost of rooftop solar PV systems, the increasing cost of fossil fuel, and promoting policies such as solar net-meeting, solar PV systems could be an excellent alternative to conventional energy sources for households. Commercial small-scale PV systems in urban areas reduce the stress on the grid and convert households from electricity consumers to producers.

### 4.5. Policy Implications

Our study also contributes to developing sound policies for the promotion of solar and wind energy in Nepal. Our solar and wind energy development timeline shows that Nepal's policies mainly focus on small-scale solar and wind energy systems over the last few decades. These policies need to be updated to wider solar and wind energy adoption in the country at a utility and commercial scale. However, the lack of adequate information on the spatial and economical distribution of renewable energy resources in developing countries is a barrier to policymaking. Our study provides new insights into Nepal's spatial distribution and economics of solar and wind energy to overcome this barrier. Based on our findings, several policies to balance energy accessibility and energy economy can be formulated.

First, Nepal needs to develop adequate plans and policies to utilize its solar and wind energy based on utility and commercial-scale power plants, going beyond small-scale systems. However, these plans and policies can vary sub-nationally based on location-specific solar and wind energy potential. For example, Gandaki province may prioritize installing solar-wind hybrid energy systems to harness its co-location potential. Due to a large share of built-up areas, promoting solar-net metering would be adequate in

Bagmati province, reflected in Nepal's *'Every home, energy home'* policy [100]. Similarly, large-scale plants can be promoted in Karnali province because it has many suitable locations. Additionally, the current and planned hydropower corridors can also be prioritized for solar and wind power plants to use their road and substation networks.

Second, the cost of solar and wind power plants is higher than hydropower plants in Nepal. This cost competitiveness is a bottleneck in a wider-scale adoption of utility and commercial-scale solar and wind power plants. For these renewable energies, Nepal provides subsidies for small-scale home and institutional systems but not commercial-scale plants. To attract the private sector in solar and wind energy generation, Nepal needs to establish appropriate incentives, including tax offsetting policies for utility and commercial-scale solar and wind power plants. Similarly, the policies on international investment need to be reviewed to ease the administrative work for foreign investors in the renewable energy sector.

Third, appropriate plans and policies are also needed to stimulate and promote solar and wind energy research in the country. For example, our analysis is based on global datasets and despite being it is high-resolution data, proper ground validation of this data is missing. Thus, Nepal needs to generate national high-resolution data on solar and wind energy by measuring and monitoring these resources at different locations in the country. Such national high-resolution ground validated data would be crucial to estimate Nepal's solar and wind energy potential more accurately.

Fourth, the existing or planned substation may not have adequate capacity to integrate the power generation from nearby solar and wind plants. So appropriate planning is needed for the up-gradation and expansion of existing substations and transmission systems.

Fifth, relative cost-effectiveness, social equability, environmental impacts, and investment modalities need to be considered at while formulating policies to promote the energy sector. This holistic approach would help to mobilize resources and ensure required processes are implemented to achieve the SDGs as a whole, going beyond SDG 7 – clean and affordable energy. In the post-COVID-19 Era, the promotion of renewable energies would play a vital role in the socio-economic recovery of the country [101].

### *4.6. Limitations*

Our estimates of solar and wind energy potential also consist of a few limitations. The first limitation is associated with the data and methods we have applied in our study. For example, the accuracy of our estimates could be improved by using high-resolution data, which is a significant problem for remote sensing-based studies in developing countries. However, we make use of the highest resolution data available for Nepal. We have resampled some raster data to match with other data using the nearby sampling method, which also has added some uncertainties in the study. However, this uncertainty and error still share a very low significance in the study.

Second, this study has not considered the geological constraints such as flood zone and earthquake fault zones. The land-use discount factor may not be uniform throughout the country because of land conflicts and geological deformities such as erosion zones, flooding zones, fault zones, military and airport zones. Thus, our study can be advanced further by following a multi-criteria analysis to identify priorities for solar and wind energy for Nepal, as done for other countries [10, 11, 12, 13]. Nevertheless, our study considers two land-use discount factors with a pessimistic scenario of 75%. Additionally, we narrow down our suitable locations, considering a 500 m buffer to rivers.

Third, we consider a linear regression model between the CF and average global horizontal irradiance in the POAs. However, this relation could also be non-linear. Nevertheless, our linear model also has a high r-squared value of 0.95. Additionally, our analysis could have also used data on Global Tilt Irridance instead of GHI to simply the study. Nevertheless, applied correlation between the CF and global horizontal irradiance, considering the appropriate tilt angle and slope exclusion, would also give similar results. Further, it is possible to install solar PV in the direction other than south-facing. However, the performance would drastically reduces with changes in facing angle (similar to azimuth angle) relative to southern part [102, 33] for Nepal. Hence, possibility of installation of solar PV other than southern region has been ignored, which would result in slight underestimation of the solar energy potential. Nevertheless, these locations would have a higher overall cost due to their lower generation capacity.

Similarly, we estimate the solar energy potential considering fixed tilted solar PV systems and the wind energy potential for International Electromechanical Commission class III wind power plants. These considerations provide conservative estimates of solar and wind energy in Nepal, which could be higher if tracking solar PV systems or higher class wind power plants are considered. Additionally, installing a 4.5 MW wind turbine would be a challenge in most locations in Nepal due to a need to transport the long wind blades in mountain roads. Thus, it might be better to estimate the wind energy potential based on lower capacity turbines. However, the global wind atlas does not provide CFs for smaller turbines. There are two implications of assuming a large wind turbine in our analysis. It ignores the energy that could be generated in the suitable areas for lower capacity wind turbines. Next, it may overestimate energy potential of suitable location of a high capacity wind turbine because of a need to replace it with a lower capacity one during installation due to difficulties in transportation of the long wind blades. Hence, appropriate ground based data has to be analysed before implementation of wind turbines in the suitable sites, choosing the adequate capacity wind turbines.

Fourth, since 42% and 35% of Nepal's total land area is covered by hilly and mountainous regions [103], a terrain factor has to be used to determine the actual path length of transmission and road length. However, we have considered the minimum distance in our estimates, which needs to be improved to account for the terrain's effect on the road and transmission network construction. Nevertheless, our study is the first to consider these factors while investigating the economic feasibility of solar and wind energy in Nepal.

Fifth, the costs incurred due to variability and uncertainty of renewable energy generation are not included in our analysis. The actual generation cost is more likely to be site-specific to its ground measurements and geography. Nevertheless, we provide the first estimate that can provide a sound basis for further studies.

## 5. Conclusion

In summary, we provide estimates of the spatial and economic potential of solar and wind energy in Nepal at the province level for the first time. Our findings highlight that the upper mid-northern part (mountain region) and eastern lowland of the country have a vast potential for solar and wind energy due to higher solar radiance and wind speed. Many identified suitable solar and wind energy locations are also nearby existing and under-construction substations and hydropower. Looking at the cost, we found that solar power plants are more expensive than wind power plants. However, the suitable locations for wind energy are limited and also concentrated in high altitude areas. As federal and provincial governments are planning to generate electricity from solar and wind energy and private companies are showing interest to invest, the results revealed by this study will be helpful for planners, decision-makers, and entrepreneurs. However, further research is needed to improve the accuracy of our estimates by using high resolution ground-validated and bias-corrected datasets, considering multiple criteria to narrow down suitable locations, and accounting for different classes of wind turbines and different types of solar PV systems. Future research needs to investigate strategies for the optimum energy mix for solar, wind, and hydro energy systems to meet Nepal's future energy demand, ensuring reliable and stable electricity supply.

## Acknowledgment

We acknowledge Ram Prasad Dhital, Purna N. Ranjitkar, and Guna R. Khanal for valuable suggestions in our study and Stefanie L. Becker for language editing. P.P. acknowledges funding from the German Federal Ministry of Education and Research (BMBF) for the BIOCLIMAPATHS project (grant agreement No 531 01LS1906A).

## References

[1] J. Rockström, O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, H. J. Schellnhuber, A roadmap for rapid decarbonization, Science 355 (6331) (2017) 1269–1271. doi:10.1126/science.aah3443.

[2] I. Dincer, Environmental impacts of energy, Energy policy 27 (14) (1999) 845–854. doi:10.1016/S0301-4215(99)00068-3.

[3] V. Khare, S. Nema, P. Baredar, Solar–wind hybrid renewable energy system: A review, Renewable and Sustainable Energy Reviews 58 (2016) 23–33. doi:10.1016/j.rser.2015.12.223.

[4] A. Lopez, B. Roberts, D. Heimiller, N. Blair, G. Porro, Us renewable energy technical potentials. a gis-based analysis, Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States) (2012).

[5] J. R. Janke, Multicriteria gis modeling of wind and solar farms in colorado, Renewable Energy 35 (10) (2010) 2228–2234.

[6] A. Aly, S. S. Jensen, A. B. Pedersen, Solar power potential of tanzania: Identifying csp and pv hot spots through a gis multicriteria decision making analysis, Renewable energy 113 (2017) 159–175.

[7] G. C. Wu, R. Deshmukh, K. Ndhlukula, T. Radojicic, J. Reilly-Moman, A. Phadke, D. M. Kammen, D. S. Callaway, Strategic siting and regional grid interconnections key to low-carbon futures in african countries, Proceedings of the National Academy of Sciences 114 (15) (2017) E3004–E3012.

[8] R. Prăvălie, C. Patriche, G. Bandoc, Spatial assessment of solar energy potential at global scale. a geographical approach, Journal of Cleaner Production 209 (2019) 692–721. doi:https://doi.org/10.1016/j.jclepro.2018.10.239.

[9] C. Arndt, D. Arent, F. Hartley, B. Merven, A. H. Mondal, Faster than you think: Renewable energy and developing countries, Annual Review of Resource Economics 11 (2019) 149–168.

[10] K. Shiraishi, R. G. Shirley, D. M. Kammen, Geospatial multi-criteria analysis for identifying high priority clean energy investment opportunities: A case study on land-use conflict in bangladesh, Applied Energy 235 (2019) 1457–1467.

[11] R. Deshmukh, G. C. Wu, D. S. Callaway, A. Phadke, Geospatial and techno-economic analysis of wind and solar resources in india, Renewable energy 134 (2019) 947–960. doi:10.1016/j.renene.2018.11.073.

[12] M. Sadeghi, M. Karimi, Gis-based solar and wind turbine site selection using multi-criteria analysis: Case study tehran, iran, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci 42 (2017) 469–476.

[13] A. Gerbo, K. V. Suryabhagavan, T. Kumar Raghuvanshi, Gis-based approach for modeling grid-connected solar power potential sites: a case study of east shewa zone, ethiopia, Geology, Ecology, and Landscapes (2020) 1–15.

[14] P. Windsor, P. Rolfe, Solar and wind energy resource assessment in nepal (swera), Tech. rep., Alternative Energy Promotion Center Government of Nepal Ministry of Environment (2008).

[15] K. R. Adhikari, S. Gurung, B. K. Bhattarai, Solar energy potential in nepal and global context, Journal of the Institute of Engineering 9 (1) (2013) 95–106. doi:10.3126/jie.v9i1.10675.

[16] B. Upreti, A. Shakya, Wind energy potential assessment in nepal (2009).
URL `http://www.wind.arch.t-kougei.ac.jp/APECWW/Report/2009/NEPAL.pdf`

[17] U. Nations, World urbanization prospects 2018 (2018).

[18] C. L. Chidi, Human settlements in high altitude region nepal, Geographical Journal of Nepal 7 (2009) 1–6. doi:10.3126/gjn.v7i0.17436.

[19] A. Warchold, P. Pradhan, J. P. Kropp, Variations in sustainable development goal interactions: Population, regional, and income disaggregation, Sustainable Development.

[20] P. Pradhan, Antagonists to meeting the 2030 agenda, Nature Sustainability 2 (3) (2019) 171–172.

[21] M. P. I. F. Putra, PrajalPradhan, J. P.Kropp, A systematic analysis of water-energy-food security nexus: A south asian case study, Science of The Total Environment (2020) 138451doi:10.1016/j.scitotenv.2020.138451.

[22] IEA, Data and statistics (2020).
URL `https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy\%20supply&indicator=TPESbySource`

[23] MoF, Economic survey: Fiscal year 2018/19, Tech. rep., Ministry of Finance, Kathmandu (2019).

[24] Water, E. C. Secretariat, Electricity demand forecast report(2015-2040), Tech. rep., Nepal Government (Jan 2017).

[25] K. Kandel, A Comprehensive Study on Hydropower Potential of Nepal, Tech. rep., Water and Energy Consultants' Association Nepal (WECAN) (2018).
URL http://www.wecan.org.np/uploaded/HydroPotentialofNepal.pdf

[26] G. Wu, R. Deshmukh, K. Ndhlukula, T. Radojicic, J. Reilly, Renewable energy zones for the africa clean energy corridor, Tech. rep., International Renewable Energy Agency (IRENA) (2015).
URL https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA-LBNL_Africa-RE-_CEC_2015.pdf

[27] J. P. Allebach, 7.1 - image scanning, sampling, and interpolation, in: A. BOVIK (Ed.), Handbook of Image and Video Processing (Second Edition), second edition Edition, Communications, Networking and Multimedia, Academic Press, Burlington, 2005, pp. 895–XXVII. doi:https://doi.org/10.1016/B978-012119792-6/50115-7.

[28] Q. D. Team, et al., Qgis geographic information system, Open Source Geospatial Foundation Project (2019).

[29] GRASS Development Team, Geographic Resources Analysis Support System (GRASS GIS) Software, Version 7.2, Open Source Geospatial Foundation (2017).
URL http://grass.osgeo.org

[30] ICIMOD, Land cover of Nepal 2010 [Data set] (2013).
URL http://lib.icimod.org/record/30808

[31] A. Jarvis, E. Guevara, H. Reuter, A. Nelson, Hole-filled srtm for the globe : version 4 : data grid, published by CGIAR-CSI on 19 August 2008. (2008).

[32] Y. Charabi, M. B. H. Rhouma, A. Gastli, Siting of pv power plants on inclined terrains, International Journal of Sustainable Energy 35 (9) (2016) 834–843.

[33] T. Y. Khan, M. E. M. Soudagar, M. Kanchan, A. Afzal, N. R. Banapurmath, N. Akram, S. D. Mane, K. Shahapurkar, Optimum location and influence of tilt angle on performance of solar pv panels, Journal of Thermal Analysis and Calorimetry (2019) 1–22doi:10.1007/s10973-019-09089-5.

[34] W. Tian, A. Ozbay, H. Hu, Terrain effects on characteristics of surface wind and wind turbine wakes, Procedia Engineering 126 (2015) 542–548. doi:10.1016/j.proeng.2015.11.302.

[35] D. Mentis, S. Hermann, M. Howells, M. Welsch, S. H. Siyal, Assessing the technical wind energy potential in africa a gis-based approach, Renewable Energy 83 (2015) 110–125. doi:10.1016/j.renene.2015.03.072.

[36] S. M. Baban, T. Parry, Developing and applying a gis-assisted approach to locating wind farms in the uk, Renewable energy 24 (1) (2001) 59–71. doi:10.1016/S0960-1481(00)00169-5.

[37] L.-I. Tegou, H. Polatidis, D. A. Haralambopoulos, Environmental management framework for wind farm siting: Methodology and case study, Journal of environmental management 91 (11) (2010) 2134–2147. doi:10.1016/j.jenvman.2010.05.010.

[38] M. Gautam, K. Acharya, Streamflow trends in nepal, Hydrological sciences journal 57 (2) (2012) 344–357. doi:10.1080/02626667.2011.637042.

[39] A. Georgiou, D. Skarlatos, Optimal site selection for sitting a solar park using multi-criteria decision analysis and geographical information systems, Geoscientific instrumentation, methods and data Systems 5 (2) (2016) 321–332. doi:10.5194/gi-5-321-2016.

[40] Y. Noorollahi, H. Yousefi, M. Mohammadi, Multi-criteria decision support system for wind farm site selection using gis, Sustainable Energy Technologies and Assessments 13 (2016) 38–50. doi:10.1016/j.seta.2015.11.007.

[41] N. S. Department, River network of nepal (Aug 2007).
URL https://rds.icimod.org/home/datadetail?metadataid=852

[42] Solargis, ESMAP, W. B. Group, Photovoltaic power potential nepal, solar resource map (2020).
URL https://solargis.com/maps-and-gis-data/download/nepal

[43] S. Hermann, A. Miketa, N. Fichaux, Estimating the renewable energy potential in africa: a gis-based approach, Tech. rep., The International Renewable Energy Agency (IRENA) (2014).
URL https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_Africa_Resource_Potential_Aug2014.pdf

[44] S. Ong, C. Campbell, P. Denholm, R. Margolis, G. Heath, Land-use requirements for solar power plants in the united states, Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States) (2013).

[45] M. Sengupta, Y. Xie, A. Lopez, A. Habte, G. Maclaurin, J. Shelby, The national solar radiation data base (nsrdb), Renewable and Sustainable Energy Reviews 89 (2018) 51–60. doi:10.1016/j.rser.2018.03.003.

[46] A. P. Dobos, Pvwatts version 5 manual (2014).
URL https://pvwatts.nrel.gov/

[47] Z. Liu, Chapter 2 - clean energy replacement and electricity replacement, in: Global Energy Interconnection, Academic Press, Boston, 2015, pp. 65 – 90. doi:10.1016/B978-0-12-804405-6.00002-6.

[48] F. Baumgartner, 5 - photovoltaic (pv) balance of system components: Basics, performance, in: N. Pearsall (Ed.), The Performance of Photovoltaic (PV) Systems, Woodhead Publishing, 2017, pp. 135 – 181. doi:https://doi.org/10.1016/B978-1-78242-336-2.00005-7.

[49] P. Gagnon, R. Margolis, J. Melius, C. Phillips, R. Elmore, Rooftop solar photovoltaic technical potential in the united states. a detailed assessment, Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States) (2016).
URL https://www.nrel.gov/docs/fy16osti/65298.pdf

[50] S. Choice, 1.5 kw solar pv systems: Pricing, outputs and payback (2016). URL https://www.solarchoice.net.au/blog/1-5kw-solar-pv-systems-price-output-payback

[51] C. B. of Statistics, National population and housing census 2011, Tech. rep., Central Bureau of Statistics - National Planning Commission Secretariat, Government of Nepal (2012). URL https://nada.cbs.gov.np/index.php/ddibrowser/54/export/?format=pdf&generate=yes

[52] R. Singh, R. Banerjee, Estimation of rooftop solar photovoltaic potential of a city, Solar Energy 115 (2015) 589–602. doi:10.1016/j.solener.2015.03.016.

[53] M. Gutschner, S. Nowak, D. Ruoss, P. Toggweiler, T. Schoen, Potential for building integrated photovoltaics, Tech. rep., International Energy Agency (IEA) (2002). URL https://iea-pvps.org/wp-content/uploads/2020/01/rep7_04.pdf

[54] D. W. Energy, T. W. Bank, Global wind atlas 3.0 (2020). URL https://globalwindatlas.info/api/gis/country/NPL/power-density/50

[55] R. Laudari, B. K. Sapkota, K. Banskota, Wind farming feasibility assessment in 16 locations of nepal, Journal of the Institute of Engineering 15 (3) (2019) 205–215. doi:10.3126/jie.v15i3.32183.

[56] R. Pletka, D. Djeu, J. Finn, A. Hanna, C. Holmgren, K. Joyce, M. Lock, S. Maki, T. Mason, Renewable energy transmission initiative reti phase 2b, Tech. rep., California Energy Commission (2010). URL http://www.energy.ca.gov/2010publications/RETI-1000-2010-002/RETI-1000-2010-002-F.PDF

[57] M. H. Zhang, Wind resource assessment and micro-siting: science and engineering, John Wiley & Sons, 2015.

[58] C. F. I. E. S. I. N. C.-C. University, I. T. O. S. I.-U. O. Georgia, Global roads open access data set, version 1 (groadsv1), Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC) (2013). doi:10.7927/H4VD6WCT.

[59] RPGCL, Nepal power transmission network map, Tech. rep., Rastriya Prasaran Grid Company Limited (RPGCL) (2018). URL https://moewri.gov.np/storage/listies/May2020/nepal-power-transmission-network-map.pdf

[60] D. Kline, D. Heimiller, S. Cowlin, Gis method for developing wind supply curves, Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States) (2008).

[61] IRENA, Renewable power generation costs in 2018, Tech. rep., International Renewable Energy Agency (IRENA), Abu Dhabi (2019).

[62] IRENA, Renewable power generation costs in 2017, Tech. rep., International Renewable Energy Agency (IRENA), Abu Dhabi (2018).

[63] PGCIL, Report on green energy corridors: Transmission plan for envisaged renewable capacity, Tech. rep., Power Grid Corporation of India Ltd. (PGCIL) (2012).
URL http://www.forumofregulators.gov.in/Data/study/Report-Green-Energy-Tr.-corridor.pdf

[64] J. Lebo, D. Schelling, Design and Appraisal of Rural Transport Infrastructure: Ensuring Basic Access for Rural Communities, no. v. 23-496 in Design and Appraisal of Rural Transport Infrastructure: Ensuring Basic Access for Rural Communities, World Bank, 2001.
URL https://books.google.com.np/books?id=Nme-4f4-DVAC

[65] N. R. Bank, Macroeconomic indicators of nepal (2019).
URL https://www.nrb.org.np/contents/uploads/2019/12/Macroeconomic_Indicators_of_Nepal-2019-11_November_2019-new.pdf

[66] CREC, Cerc (terms and conditions for tariff determination from renewable energy sources) regulations, 2009, Terms and Conditions for Tariff determination from Renewable Energy Sources Regulations (2009).

[67] Protected areas and ecosystems (2018).
URL https://ntnc.org.np/thematic-area/protected-areas-and-ecosystems

[68] IUCN, UNEP, The world database on protected areas (wdpa) (2013).
URL https://www.iucn.org/theme/protected-areas/our-work/quality-and-effectiveness/world-database-protected-areas-wdpa

[69] B. R. Poudel, S. Shrestha, S. Kandel, K. Das, Solar pico pv market potential in nepal: Current trend and future perspective, Tech. rep., Patan, Nepal: SNV Neatherlands Development Organisation (2014).
URL https://sun-connect-news.org/fileadmin/DATEIEN/Dateien/New/Solar_Pico_PV_Market_Potential_in_Nepal.pdf

[70] K. C. Surendra, S. Kumar, P. Shrestha, B. Lamsal, Current status of renewable energy in nepal: Opportunities and challenges, Renewable and Sustainable Energy Review 15 (8) (2011) 4107–4117. doi:10.1016/j.rser.2011.07.022.

[71] J. Henryson, T. Haakansson, Solar home systems in nepal, Tech. rep., Department of Heat and Power Engineering, Lund Institute of Technology, P.O. BOX 118, SE-221 00 Lund Sweden (1999).
URL https://www.osti.gov/etdeweb/servlets/purl/10149650

[72] AEPC, Annual progress report 2067/68 (2010/11), Tech. rep., Lalitpur, Nepal: Alternative Energy Promotion Center (AEPC) (2012).
URL aepc.gov.np/old/files/20131029070523_2067-2068.pdf

[73] CES, Profile: Introduction (June 2020).
URL http://ces.ioe.edu.np/?page_id=110

[74] SEMEN, Introduction (June 2020).
URL https://www.semannepal.org.np/introduction

[75] AEPC, Nepal photovoltaic quality assurance (nepqa) 2015.rev1, Tech. rep., Lalitpur, Nepal: Alternative Energy Promotion Center (AEPC) (2016).
URL https://www.retsnepal.org/downloads/file?id=39

[76] WECS, , Tech. rep., Kathmandu, Nepal: Water and Energy Commission Secretariat (WECS), Government of Nepal (2013).
URL https://policy.asiapacificenergy.org/sites/default/files/National%20Energy%20Strategy%20of%20Nepal%202013%20%28EN%29.pdf

[77] R. Bhandari, I. Stadler, Electrification using solar photovoltaic systems in nepal, Applied Energy 88 (2) (2011) 458–465. doi:10.1016/j.apenergy.2009.11.029.

[78] J. N. Shrestha, Application of building integrated photovoltaic electric system: its contribution in reduction of load shedding hours in nepal, Journal of the Institute of Engineering 7 (1) (2009) 1–5. doi:10.3126/jie.v7i1.2056.

[79] AEPC, Urban solar energy system and soft loan operation manual, Tech. rep., Lalitpur, Nepal: Alternative Energy Promotion Center (AEPC) (2015).

[80] DOED, Construction licencse:: Solar (June 2020).
URL https://www.doed.gov.np/license/23

[81] NEA, A year in review–fiscal year 2019/20, Tech. rep., Nepal Electricity Authority (NEA) (2020).
URL https://www.nea.org.np/admin/assets/uploads/supportive_docs/Annual_book_2077.pdf

[82] M. Republica, Solar plant construction in nuwakot in final stages (Mar 2020).
URL https://myrepublica.nagariknetwork.com/news/solar-plant-construction-in-nuwakot-in-final-stag

[83] Investopaper, Butwal solar power project (8.5 mw) connected to national transmission line (October 2020).
URL https://www.investopaper.com/news/butwal-solar-power-project/

[84] S. Nepali, S. Ghale, K. Hachhethu, Federal Nepal: the Provinces Socio-Cultural Profiles of the Seven Provinces, Governance Facility, 2018.
URL https://www.lahurnip.org/uploads/resource/file/federal-nepal-the-provinces-socio-cultural-pro
pdf

[85] NEA, Nepal electricity authority report, Tech. rep., Nepal Electricity Authority (2018).
URL https://www.nea.org.np/admin/assets/uploads/supportive_docs/annual_report_2076.pdf

[86] B. R. Gautam, F. Li, G. Ru, Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in nepal, Energy and Buildings 86 (2015) 735 – 744. doi:https://doi.org/10.1016/j.enbuild.2014.10.038.

[87] N. E. Authority, Nea board decisions on the power purchase rates and associated rules for ppa of ror/pror/storage projects (2017).
URL https://www.nea.org.np/admin/assets/uploads/supportive_docs/99343289.pdf

[88] Solar Pico PV Market Potential in Nepal Current Trend and Future Perspective, Netherlands Development Organisation (SNV).
URL https://energypedia.info/images/a/a5/Solar_Pico_PV_Market_Potential_in_Nepal.pdf

[89] Progress at a Glance: A year in Review, FY (2018/2019), AEPC, Ministry of Energy, Water Resources and Irrigation, 2019.
URL https://www.aepc.gov.np/uploads/docs/progress-at-glance-a-year-in-review-fy-207576-201819-157
pdf

[90] Universalizing Clean Energy in Nepal, A plan for Sustainable Distributed Generation and Grid Access to All by 2022, National Planning Commission, Government of Nepal, 2018.
URL https://www.npc.gov.np/images/category/SUDIGGAA_final_version.pdf

[91] P. L. Joskow, Comparing the costs of intermittent and dispatchable electricity generating technologies, American Economic Review 101 (3) (2011) 238–41.

[92] A. Mills, R. Wiser, Changes in the economic value of variable generation at high penetration levels: a pilot case study of california, Tech. rep., Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States) (2012).

[93] D. of Roads, Statistics of strategic road network 2017-18 (2017-2018).
URL https://dor.gov.np/home/publication/statistics-of-strategic-road-network-2-17-18

[94] RPGCL, Transmission System Development Plan of Nepal, Rastriya Prasaran Grid Company Limited, 2018.
URL https://rpgcl.com/images/category/TSMPN_RPGCL_GoN.pdf

[95] W. B. Group, Measuring rural access: Using new technologies, World Bank, 2016.

[96] K. Gyanwali, R. Komiyama, Y. Fujii, Representing hydropower in the dynamic power sector model and assessing clean energy deployment in the power generation mix of nepal, Energy (2020) 117795doi:10.1016/j.energy.2020.117795.

[97] B. R. Tiwari, N. Bhattarai, A. K. Jha, Performance analysis of a 100 kwp grid connected solar photovoltaic power plant in kharipati, bhaktapur, nepal, in: Proceedings of the IOE Graduate Conference, Patan, Nepal, Vol. 5, 2017.

[98] K. N. Pondyal, B. K. Bhattarai, B. Sapkota, B. Kjeldstad, Solar radiation potential at four sites of nepal, Journal of the Institute of Engineering 8 (3) (2011) 189–197.

[99] J. Zheng, F. Wen, M. Zhou, L. Hu, Q. Xu, Z. Lan, Transmission planning with renewable generation and energy storage, APSCOM 2015 (2015). doi:10.1049/ic.2015.0224.

[100] Present Situation and Future Road-map of Energy, Water Resources and Irrigation (Whitepaper), Ministry of Energy, Water Resources and Irrigation, Kathmandu, Nepal, 2018. URL https://moewri.gov.np/storage/listies/May2020/white-paper-2075-with-annex02.pdf

[101] P. Pradhan, D. R. Subedi, D. Khatiwada, K. K. Joshi, S. Kafle, R. P. Chhetri, S. Dhakal, A. P. Gautam, P. P. Khatiwada, J. Mainaly, et al., The covid-19 pandemic not only poses challenges, but also opens opportunities for sustainable transformation, Earth's Future 9 (2021) e2021EF001996. doi:https://doi.org/10.1029/2021EF001996.

[102] M. Dhimish, S. Silvestre, Estimating the impact of azimuth-angle variations on photovoltaic annual energy production, Clean Energy 3 (1) (2019) 47–58.

[103] M. of Health, P. MOHP/Nepal, N. ERA/Nepal, I. C. F. International, Nepal demographic and health survey 2011, Tech. rep., Kathmandu, Nepal (2012). URL http://dhsprogram.com/pubs/pdf/FR257/FR257.pdf