PERSPECTIVE

100% renewable energy with pumped-hydro-energy storage in Nepal

Sunil Prasad Lohani1,* and Andrew Blakers2

1School of Engineering, Kathmandu University, PO BOX: 6250, Dhulikhel, Kavre, Nepal
2College of Engineering and Computer Science, Australian National University, Canberra, Australia

*Corresponding author. E-mail: splohani@ku.edu.np

Abstract

A radical transformation of the global energy system is underway. Solar photovoltaics and wind now comprise three-quarters of the global net new electricity-generation-capacity additions because they are cheap. The deep renewable electrification of energy services including transport, heating and industry will allow solar and wind to largely eliminate fossil fuels over the next few decades. This paper demonstrates that Nepal will be able to achieve energy self-sufficiency during the twenty-first century. Nepal has good solar and moderate hydroelectric potential but has negligible wind- and fossil-energy resources. The solar potential is about 100 times larger than that required to support a 100% solar-energy system in which all Nepalese citizens enjoy a similar per-person energy consumption to developed countries, without the use of fossil fuels and without the environmental degradation resulting from damming Nepal’s Himalayan rivers. Nepal has vast low-cost off-river pumped hydro-energy-storage potential, thus eliminating the need for on-river hydro storage and moderating the need for large-scale batteries. Solar, with support from hydro and battery storage, is likely to be the primary route for renewable electrification and rapid growth of the Nepalese energy system.

Graphical Abstract

100% Renewable energy in Nepal

2020 status
Electricity consumption: 0.2 MWh/person/year
Hydropower is dominant in electricity, biomass is dominant at home

Energy resources in Nepal
Solar PV: 50,000 TWh/year
Hydro: 500 TWh/year
Bio, wind etc: small

Target for Nepal for 2065:
• 100% renewable energy
• Catch up with developed countries
• 15 MWh per capita per year solar electricity

Nepal target: install 200 Watts of solar per person per year
Australia: installing 250 Watts of solar & wind per person per year

Keywords: solar photovoltaics; pumped-hydro-energy storage; traditional biomass; renewable energy; national energy mix; current scenario; greenhouse gas
Introduction

Energy is an essential commodity. Rapidly increasing populations and economic growth are causing global energy demand to increase, especially in emerging-market economies. Energy supply is interwoven with global warming, local pollution, national and international security, economic growth and the ability to meet basic human needs.

A radical and rapid transformation to a sustainable global energy system is underway. Solar photovoltaics (PV) and wind now comprise three-quarters of the global net new electricity-generation-capacity additions (Fig. 1). Coal, oil, gas, nuclear, hydro and the other renewables comprise the balance [1]. Solar and wind energy are vast, ubiquitous, non-polluting and indefinitely sustainable, and accord well with the United Nations Sustainable Development Agenda for affordable and clean energy.

The deep renewable electrification of energy services allows solar and wind to eliminate fossil fuels, not just from the electricity system. Renewable electrification includes conversion of land transport to electric vehicles; use of electric heat pumps for low-temperature air and water heating; powering of industrial heat with electric furnaces; and, for the chemical industry, replacement of hydrogen from fossil fuels with hydrogen from water splitting.

Many jurisdictions are committing to net-zero emissions by 2050–60 including Japan, the European Union, China, the USA and Korea. Most countries are expected to follow suit in the next few years.

Solar photovoltaics and wind energy are now the cheapest forms of electricity available in regions with good solar and wind resources, respectively, except perhaps for very favourable hydroelectric sites. A dramatic acknowledgement of the rapid pace of change in world energy markets comes from the 2020 World Energy Outlook from the International Energy Agency, which states that ‘[f]or projects with low cost financing that tap high quality resources, solar PV is now the cheapest source of electricity in history’ [2].

Fossil fuels produce three-quarters of global greenhouse gases [3]. According to the Intergovernmental Panel on Climate Change, to limit global warming to 1.5°C, rapid reductions in greenhouse-gas emissions are required [4]. Importantly, developing countries such as Nepal can bypass a fossil-fuel era and transition directly to zero-emission renewables at low cost.

Novel themes in this paper are that:

- Nepal can meet all of its energy needs from solar PV by covering 1% of its area with panels, even after (i) Nepal catches up with the developed world in per-capita use of energy and (ii) all energy services are electrified, eliminating fossil fuels entirely (an increase of 70-fold in electricity production).
- Identification of off-river pumped hydro as a vast, low-cost, mature storage opportunity; Nepal has 17 times more off-river pumped-hydro-energy-storage sites than it will ever need even under the zero-fossil-fuel scenario described above, thus eliminating the need for on-river hydro storage. Pumped hydro is much cheaper than batteries for overnight storage.
- Damming of Nepalese Himalayan rivers is unnecessary because PV is competitive with and vastly more available than hydro and can be more readily implemented at both small and large scales.

Section 1 of this paper describes a scenario in which Nepal catches up with developed countries in terms of per-capita energy consumption. Section 2 describes the renewable-energy options for Nepal to meet this consumption and identifies solar PV as by far the most prospective. Section 3 describes methods of balancing high levels of solar PV. Section 4 summarizes policy implications and the conclusion follows.
1 Renewable energy in Nepal

Traditionally, energy from biomass has dominated the domestic energy supply for most people in Nepal and oil was important for motorized transport. However, electricity is becoming increasingly important. In the past, most developing countries followed a path of increasing dependence on fossil fuels as they industrialized and raised living standards for their populations. In the future, most developing countries will transition directly to solar and wind energy, and bypass a fossil-fuel era.

Nepalese people can expect to achieve a high living standard over the course of the twenty-first century. The per-capita electricity consumption in developed countries such as the European Union, Japan, China, the USA, Singapore and Australia is 5–15 megawatt-hours (MWh) per person per year. In developed countries, complete renewable electrification of all energy services and complete elimination of oil, gas and coal allow the avoidance of most greenhouse emissions. To achieve this, electricity production must double or triple to 15–30 MWh per person per year, depending substantially on the degree of participation of the country in the chemical industry [5]. Net-zero emissions in 2050 strictly require such a transformation.

Electricity demand in Nepal is rising because supply is being extended to the whole population, per-capita consumption is increasing and the population is growing. We adopt the following assumptions:

(i) that Nepal with catch up with developed countries in terms of per-capita energy consumption;
(ii) that the energy systems of Nepal are fully electrified, including transport, heating and industry, with zero fossil-fuel use; and
(iii) that the per-capita electricity consumption in the second half of the twenty-first century in Nepal will increase to 15 MWh per person per year for a population of 33 million people.

Thus, Nepal's electricity consumption may reach in the range of 500 terawatt-hours (TWh) per year. This is referred to in this paper as the '500-TWh goal'. Of course, the exact number cannot be reliably predicted, but these assumptions are adopted to illustrate trends as Nepal catches up with developed countries in energy consumption. This 500-TWh goal compares with current consumption of electricity in Nepal of ~7 TWh per year [6].

2 Renewable-energy options for Nepal

2.1 Solar energy

Solar energy is by far the largest and most sustainable energy resource in Nepal. The solar resource is two orders of magnitude larger than Nepal will require to meet the 500-TWh goal.

Very rapid reductions in the price of solar PV over recent years has opened up enormous markets in developed and developing countries alike. The solar resource in Nepal is compatible with production of electricity at a cost of US$40 per MWh once the Nepalese solar industry becomes mature, falling to <US$30/MWh in 2030 [7].

The speed of development of the global solar industry, arising from rapid price reductions, is so fast that previous reports on energy options require updating.

Nepal is located at a latitude of 26–30° north latitude, with the sun shining for >300 days per year. It has relatively high insolation of an average of ~17 megajoules per m² per day (1.7 TWh per km² per year) and national average sunshine hours of 6.8 per day. This makes Nepal a country with moderately high solar potential [8, 9]. All parts of the country are reasonably favourable for solar energy, as shown in Fig. 2.

A solar-energy-system conversion efficiency of 20% (utilizing solar cells with efficiency of 25% [10]) will soon become available, which corresponds to 0.2 gigawatts (GW) per km². This assumes close-packing of solar modules to form a dense array. Nepal has an area of 148 000 km². Thus, if Nepal were covered entirely by solar cells, it could generate 50 000 TWh per year (148 000 km² × 1.7 TWh per km² per year × 20% conversion efficiency). The nominal power capacity would be 30 000 GW.

This approximate calculation shows that Nepal can generate 100 times more solar electricity than would be needed for the 500-TWh goal of high per-capita consumption (similar to developed countries) coupled with the complete electrification of energy services and the elimination of fossil fuels. Equivalently, 1% of Nepal (1500 km²) would need to be covered by solar panels.

Under our assumption of electricity consumption of 15 MWh per person per year, the area of land required for solar collectors is 44 m² per person with a nominal power capacity of ~9 kilowatts (kW).

Large amounts of solar PV can be accommodated on residential, commercial and industrial rooftops, building facades and in other urban areas. The global per-capita leader in rooftop solar, Australia, has 3 million rooftop solar systems with a combined capacity of ~13 GW (550 Watts (W) per person) [11]. Most of this is located on residential buildings, although other sectors are rising quickly. The amount of rooftop solar in Australia may increase to 3.7 kW per person according to the Step Change scenario of the Australian Energy Market Operator [12]. This represents 40% of the 9-kW-per-person target required to meet the 500-TWh goal for Nepal.

Solar PV systems can be located in food-growing areas (Agrivoltaics, APV) whereby widely spaced solar panels shade 10–30% of the crop or pasture but cause only a modest loss of production because the reduction in sunshine is offset by a reduction in wind speeds and evaporation rates [13–22]. Maize, wheat, millet, jute, sugarcane, tea, tobacco, coffee soybeans, beans, lentils, fruit and vegetables may all be suitable for APV in Nepal. However, rice farming appears to be incompatible, since partial shading proportionally reduces rice output. Animal husbandry (cows, buffaloes, goats, sheep, pigs, horses) is also...
compatible with APV. APV offers a second cash crop for farmers. Detailed research will be required to establish the trade-off between agricultural and electricity yields for each crop, and hence to determine the amount of electricity that could be provided through APV. The area of land devoted to agriculture in Nepal is ~41 000 km² [23]. Thus, an average shading of 3.6% of agricultural areas by APV is sufficient to meet the 500-TWh goal for Nepal.

Substantial numbers of panels may be accommodated on non-forested lower slopes of hills and mountains with a southerly aspect. Waste land can become productive through the installation of PV systems, including around the transport infrastructure. For example, the area occupied by roads in an advanced economy is a substantial fraction of the required solar PV area per person (44 m²) to meet the 500-TWh goal. Some solar systems can be floated on lakes and hydroelectric reservoirs, although the area available is small compared with the 1500-km² target. Further work is required to quantify these opportunities.

To reach 9 kW of solar panel per person by 2065, Nepal would need to install 200 W per person per year (~6 GW per year). To put this in perspective, Australia is currently installing 250 W per person per year of new solar- and wind-energy systems (Fig. 3) [1]. This is 10 times faster than the global average and 4 times faster than in the USA, China, Japan and Europe. About one-quarter of Australian electricity is now sourced from solar PV and wind, and this figure is tracking towards 50% in 2025. The state of South Australia sourced 60% of its electricity from solar PV and wind in 2020 [24] and is heading towards 100% by 2025. Plainly, rapid transition to solar and wind energy is feasible.

As the price of solar-energy systems continues to fall, solar energy becomes ever more affordable. The price of utility-scale solar systems (tens to hundreds of megawatts) in countries that have large-scale annual deployment (and have thereby achieved critical mass of people and capability) is ~US$0.7 per Watt and is likely to decline to <US$0.4 per Watt in 2030 [10]. These prices are affordable in most countries, including Nepal. However, prices for infrequent construction within a country can be much higher due to immature supply chains.

Solar PV is unique among energy technologies in that small-scale (kilowatts) and large-scale (gigawatts) installations are built using the same basic unit (a solar panel) and have similar energy costs. A roof-mounted system has low land, engineering, approval and financing costs while a large-scale system has low panel and deployment costs. Electrification can proceed both by grid extension and through house- and village-scale small solar systems with battery storage.

Small-scale solar systems for individual households or villages provide major benefits for lighting,
telecommunications, water pumping, grain grinding and refrigeration. When many people in a village deploy household solar, then microgrids can form, comprising distributed solar panels and battery storage, which can gradually increase in scale and power by interconnection with other microgrids, eventually leading to widespread interconnection [25, 26]. Larger-scale systems can power cooking, heating, industry and transport, particularly in combination with extension of the electricity grid to most citizens.

Nepal's currently installed solar capacity is ~60 MW (2 W per person) [27]. Much of this is in the form of 1.1 million small home systems that are not grid-connected. Institutional solar PV systems up to a capacity of 2 kW have been installed in thousands of institutions such as schools, health posts and homestays. More than 10,000 solar streetlights have been installed [28, 29].

The construction of Nepal’s largest solar-energy plant with an installed capacity of 25 MW began in April 2018 in the Nuwakot district and is now in the early stage of producing electricity [30].

An important advantage of solar is that millions of individuals can acquire and own their own rooftop solar system. These systems can connect to a battery or the grid, or both. This sidesteps institutional barriers at the national level.

To put this in perspective, Australia has a population of 25 million, only a little less than Nepal. Most people live in south-east coastal cities where the annual solar resource is similar to that of Nepal. According to the government's Clean Energy Regulator, Australia is installing 3 GW per year of new rooftop solar systems and there is now a total of 3 million rooftop solar systems with a combined capacity of >13 GW [11]. Individuals install these systems because they compete with retail prices, which are much higher than wholesale prices.

2.2 Hydropower

Hydropower is one of the two sources of energy in Nepal that can play an important role in Nepal’s future economy. However, the hydro potential is a tiny fraction of the solar PV potential. Table 1 represents the annual energy estimate and power potential of four major river basins: Narayani, Saptakoshi, Karnali and Mahakali of Nepal. Though Saptakoshi is the largest river basin of Nepal, the Narayani river basin has the largest annual energy production of ~113 TWh and power potential of ~18 GW [31].

Presently, hydropower plants with a combined capacity of 1.2 GW have been installed in Nepal. Most are run-of-river with output varying according to rainfall and provide little storage [32].

Approximately 50% of the total hydropower assets are owned by the Nepal Electricity Authority, a government agency, and the rest is owned by independent power producers. An important achievement in 2018 was the commissioning of a new Dhalkebar Muzaffarpur cross-country transmission line between Nepal and India, giving an additional boost to Nepal’s energy-trading system [33].

It is important to understand the environmental destruction usually associated with large-scale hydropower projects, particularly if they include energy storage in large reservoirs. These include displacement of people, flooding of farmland, destruction of river ecosystems, forest clearance and methane release due to the decay of a large number of plants and organic residues.

Importantly, the cost of solar energy has fallen below all but the most favourable hydropower systems.

2.3 Wind energy

Nepal has a low potential for the large-scale utilization of wind energy (Fig. 4) [34]. Typical expected capacity factors...
are <20% except on the high ridges of the Himalayas, which are largely inaccessible for wind turbines. This means that wind energy will be much more expensive than solar energy.

There is potential for small turbines in some favourable locations. Various government and private organizations are taking initiatives to promote small-scale wind energy in Nepal [35]. At present, there is no ongoing wind-turbine-installation project that uses wind energy alone [36]. The Energy Sector Management Assistance Program of the World Bank has had a project since 2015 for the ground-based measurement of wind potential at 10 sites (Mustang (2); Morang; Siraha; Panchthar; Dang (2); Jumla; Ramechhap; Banke) [37, 38]. This has allowed reliable wind-power estimation that can be used by potential wind-power developers in Nepal.

### 2.4 Biomass

Biomass in various forms, including wood, agricultural residue, animal dung and biogas, is an important small-scale energy source for millions of people in Nepal. However, biomass can never be a large-scale source of energy. The primary reason is that the conversion of solar energy into biomass and then into useful energy occurs with very low efficiency—orders of magnitude lower than via solar PV. This means that a great deal of land is required to supply energy services, and this competes directly with food and timber production and with environmental values.

Electricity can readily replace biomass and fossil fuels for heating, cooking and lighting. Importantly, electricity eliminates indoor air pollution. Use of biomass may decline over the next several decades, as has occurred in most other countries as their economies have developed.

Nepal produces a large amount of organic solid waste, manure and sewage sludge along with various types of organic industrial waste. This waste needs to be managed properly to protect the environment. Landfilling is not an environmentally friendly option. Anaerobic digestion of these wastes is an environmentally beneficial and energy-efficient waste-management option to recover biogas (about 60% methane) and digestate sludge as a by-product that is used as an organic fertilizer. This helps Nepal to replace chemical fertilizer and biogas can be used for cooking, heating and industrial applications.

| River basins | Annual energy estimate (TWh) | Power potential (GW) |
|--------------|-------------------------------|---------------------|
| Narayani     | 113                           | 18                  |
| Saptakoshi   | 109                           | 17                  |
| Karnali      | 102                           | 16                  |
| Mahakali     | 150                           | 2                   |
| Solar PV potential | 50 000          | 30 000              |

![Fig. 4: Wind-capacity factors in Nepal (redder is better) [34]](https://academic.oup.com/ce/article/5/2/243/6275217)
3 Balancing high levels of solar electricity

Balancing high levels of variable solar energy over every hour of every year is straightforward. Storage via batteries and pumped hydro allows the daily solar cycle to be accommodated. Sharing power over large areas via high-power-transmission lines spanning Nepal from east to west allows the smoothing-out of local weather and demand variability.

Australia is installing variable solar and wind faster per capita than any other country. Australia only derives ~6% of its electricity from hydro, and hence lacks the smoothing ability of hydroelectric generation backed by large dams. In response, Australia is deploying multiple gigawatts of new off-river pumped hydro, gigawatt-scale batteries and new gigawatt-scale transmission [39]. Large-scale demand management is also being deployed through pricing structures to encourage the transference of consumption to times of excess renewable-energy availability.

3.1 Pumped-hydro-energy storage (PHES)

PHES entails pumping water from a lower to an upper reservoir when excess solar energy is available and allowing the water to run down through a turbine at a later time to recover the energy [40]. Typical round-trip efficiency is 80%.

PHES comprises ~95% of global electricity-storage power (~170 GW) and a higher fraction of storage energy [41]. Most existing pumped-hydro systems are associated with river-based hydroelectric projects with large reservoirs. This generally entails flooding large areas of land.

PHES systems can be located away from rivers. Since most of the land surface of Earth is not adjacent to a river, a vastly larger number of potential sites are available for off-river (closed-loop) PHES compared with river-based PHES. Off-river PHES comprises a pair of reservoirs (20–500 hectares (Ha)), separated by a few kilometres, but at different altitudes (200–1200 m altitude difference or ‘head’) and connected by a pipe or tunnel (Fig. 5). Water is pumped uphill on sunny/windy days and energy is recovered by allowing the stored water to flow back through the turbine. The water oscillates indefinitely between the two reservoirs.

For example, a pair of 100-Ha reservoirs with a head of 600 m, an average depth of 20 m, a usable fraction of water of 90% and a round-trip efficiency of 80% (accounting for losses) can store 18 gigalitres of water with an energy potential of 24 GWh, which means that it could operate at a power of 1 GW for 24 hours. These reservoirs are very small compared with river-based hydros. Water requirements (initial fill and evaporation minus rainfall) are very small compared with a comparable coal-fired power station (cooling tower). It amounts to a few square metres of land per person for the 500-TWh goal, which is much less than the land needed for the associated solar PV systems and very much less than the land alienated by an equivalent river-based system.

Nepal has enormous potential for off-river PHES. The Global Pumped Hydro Storage Atlas [42, 43] identifies ~2800 good sites in Nepal with combined storage capacity of 50 TWh (Fig. 6). To put this in perspective, the amount of storage typically required to balance 100% renewable energy in an advanced economy is ~1 day of energy use [44]. For the 500-TWh goal, this amounts to ~1.5 TWh.

Seasonal variation in solar-energy supply in Nepal is moderate, fluctuating from 75% of the mean in winter to 125% in spring [9]. This means that significant seasonal storage may be required. A simple analysis of data in [9] suggests an upper bound in seasonal storage of 50 TWh, which could be accommodated with off-river pumped-hydro storage [40]. In practice, far lower storage would be needed.

The amount of storage needed is a trade-off between the cost of the storage and the cost of providing additional solar generation to cover winter. The latter implies substantial excess solar electricity in summer. Because the cost of solar-energy systems continues to fall, the economic optimum is likely to favour the overbuilding of solar rather than the deployment of large amounts of seasonal storage.

Interconnection with neighbouring countries to the north and south, where large wind-energy resources are located, could substantially reduce the need for seasonal storage. Excess summer solar generation can be used for underground seasonal thermal storage and can be exported to neighbouring countries.

3.2 Batteries

Batteries have a typical round-trip efficiency of ~90% for battery chemistries based on lithium [45]. Batteries are being deployed at the gigawatt scale around the world to support rising levels of wind and solar. For storage-time periods of seconds to hours, batteries have an economic advantage. For several hours, overnight and seasonal storage, pumped hydro is much cheaper. Batteries and pumped hydro are complementary storage technologies.

3.3 Hydrogen

Hydrogen production in Nepal is unlikely to be significant. Hydrogen or hydrogen-rich chemicals such as ammonia could be used to store and transport energy in Nepal. However, this is unlikely to occur because the efficiency is very low compared with those of batteries, pumped hydro and thermal storage, which unavoidably translates into high costs.

Hydrogen can be sustainably produced using renewable electricity to electrolyse water. Hydrogen is difficult to store. Options include liquefaction at very low temperatures and conversion to a more tractable chemical such
as ammonia. Conversion of hydrogen energy to a useful form such as electricity or motive power is a low-efficiency process. Typically, the round-trip efficiency of electricity–hydrogen–electricity is 20–30% \[46\] compared with 80–90% for batteries or pumped hydro. Basic physical constraints mean that hydrogen storage can never have a high round-trip efficiency. This is a large economic barrier to the use of hydrogen as an energy-storage medium.

It is difficult to see how hydrogen could compete with batteries for short-term storage because batteries react in milliseconds to grid disturbances and have a 90% round-trip efficiency. It is difficult to see how hydrogen could compete with pumped-hydro storage for overnight and longer storage because pumped-hydro storage has an 80% round-trip efficiency and is mature and already low-cost.

Electric vehicles are being produced at the multi-million scale per year. In contrast, hydrogen-powered vehicles have a miniscule market share. The enormous advantage of incumbency means that electric vehicles are likely to dominate land transport in the future, which eliminates...
the automotive market for hydrogen. This includes heavy vehicles and long-distance transport. For example, the Tesla electric semi with a 35-tonne load has an expected range of ≤800 km (similar to the width of Nepal) [47].

Hydrogen is needed in the chemical industry for the synthesis of materials such as fertilizers, explosives, plastics, synthetic jet fuels and the reduction of iron oxide. Nepal is unlikely to play a significant part in the international hydrogen chemical industry because other countries have far better wind and solar resources and land availability, and will be able to produce hydrogen much more cheaply.

4 Government policy

Government energy roadmaps in many countries are being overtaken and rendered obsolete by a sustained rapid decline in the cost of solar energy and sustained rapid growth in solar-energy deployment. New solar-energy-generation capacity is being deployed about twice as fast as the net new coal-, gas-, oil-, nuclear- and hydro-generation capacity combined. In leading countries such as Australia, solar and wind comprise 99% of the new generation capacity [1].

The demonstrated pathway to high levels of solar deployment in countries with leading per-capita deployment rates such as Australia and Germany is two-fold: deployment of millions of small residential rooftop solar systems of a few kilowatts each and the parallel development of multiple 10- to 500-MW solar farms. The experience gained is synergistic, since there is much in common between the markets.

Early deployment is relatively expensive because of the initial lack of skill and supply chains coupled with the perceived risk due to inexperience with solar technology. However, it is important to look beyond the initial high prices to understand the low and falling cost of solar energy in a mature market that has gained critical mass.

Government and international support for a few hundred megawatts of rooftop solar and solar farms in Nepal will help to overcome the initial hurdle, leading to rapidly increasing solar infrastructure and deployment skill, and a rapidly declining solar-electricity price.

Government can leave the development of solar farms and solar rooftop systems to the private sector. However, there is an important government role in facilitating adequate transmission and storage. In particular, government has an important role in selecting and facilitating the construction of several off-river PHES systems as and when they become necessary.

The federal, provincial and local governments of Nepal have been working for some time in coordination with energy-sector stakeholders of Nepal to promote clean and sustainable energy. The Ministry of Energy, Water Resources and Irrigation is the line ministry having the primary jurisdiction and authority to plan, develop and implement national energy policy and strategy. To ensure the promotion and development of sustainable energy, Nepal joined the UN Secretary General’s Sustainable Energy for All (SE4ALL) initiative in 2012, targeting the provision of clean energy to all by 2030.

Concerning legislation, Part 4 of Article 51 of the Constitution of Nepal (2015) states that the government will adopt policies regarding the protection, promotion and use of natural resources to guarantee appropriate, affordable and sustainable energy to citizens. Nepal has established various relevant strategies and guidelines for the promotion and development of renewable energy. Some of these relevant to large-scale renewable-energy promotion include the White Paper on Energy, Water and Irrigation: Present Situation and Future Prospect 2018 and the Guidelines for Development of Alternative Electricity Connected to Grid 2018. These have elements that seek to support the large-scale promotion of renewable-energy technologies in Nepal. More specifically:

- The White Paper on Energy, Water, and Irrigation: Present Situation and Future Prospect, released by the Ministry of Energy and Water Resources and Irrigation in 2018, sets targets of increasing household electricity usage to 700 kWh within 5 years and 1500 kWh within 10 years, and to have electric cookstoves in all households by 2030. It also aims to promote a renewable-energy mix from solar, wind and biomass to reduce dependence on a single energy source and to improve energy security.
- As per the Guidelines for Development of Alternative Electricity Connected to Grid 2018, published on 8 February, people can feed electricity generated from solar, wind and biogas plants into the national grid and get paid a fixed amount of money per kilowatt hour of energy. The generation licence will have a validity of 25 years and the Nepal Electricity Authority will pay producers US$62/MWh (1 USD = NRs 116 (exchange rate in February 2021)) [48].

This is an attractive price once the solar PV industry is mature enough to enable low costs. These policies and responses will require extensive modification once the low prices available from a mature solar industry in Nepal become available.

5 Conclusion

Nepal has good solar resources by world standards and moderate hydro resources, but negligible wind- and fossil-energy resources. The solar-energy resource is two orders of magnitude larger than the hydro resource. Solar energy is likely to be competitive with new hydro in Nepal. Government energy roadmaps made earlier than 2020 are largely outdated by the rapid progression of solar.

Solar collectors equivalent to ~1% of Nepal’s land area are required to allow Nepalese citizens to have the same per-capita energy consumption as those in developed
countries and with zero fossil-fuel utilization. This includes the electrification of transport, heating and industry. These panels can be accommodated on rooftops, in conjunction with agriculture and on lakes and unproductive land.

Since most existing Nepalese hydro is run-of-river, substantial new storage is required to support a solar-based energy system. Nepal has enormous potential for the deployment of off-river PHES systems, which have a much lower environmental and social impact than river-based hydro storage.

The economic advantage of solar PV over fossil and hydro energy in a mature and competitive market is compelling. However, several factors can impede the rapid deployment of solar PV. Perhaps the most important is the relatively high cost of solar until the critical mass of skilled people and supply chains is obtained—then costs will fall rapidly towards international norms. Another important barrier can be unnecessary regulatory constraints on private citizens and companies feeding solar electricity into the grid, often based on spurious and thoroughly outdated technical arguments.

The government of Nepal can unlock the potential of solar PV by providing support for several tens of thousands of rooftop solar systems and several 10- to 100-MW solar farms in order to establish supply chains and a critical mass of knowledge. This support can be in the form of advantageous feed-in tariffs to unlock private capital. International experience shows that, once a private market is well established, prices for solar electricity fall rapidly. The main ongoing role for government is to facilitate the provision of adequate transmission and storage capacity. The private sector could provide the capital for this infrastructure through a regulated return-on-capital investment.

This study is at a ‘bird’s-eye’ level and does not delve into the detail of the best way to establish a vibrant solar market in Nepal. Future studies could identify the amount of solar electricity that could be harvested from Nepal’s rooftops; undertake analysis of the best sites for solar farms, off-river pumped-hydro sites and transmission corridors; conduct hour-by-hour studies over many years to determine the amount of storage needed to support high levels of solar electricity; investigate agriphotovoltaics in Nepal in detail; and identify social, regulatory and economic factors that will enhance or impede the rapid deployment of solar energy in Nepal.

Conflict of Interest
None declared.

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