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Mitigating the current energy crisis in Nepal with renewable energy sources

RamhariPoudyal[a], Pavel Loskot[a*], RabindraNepal[b1], RanjanParajuli[c] and Shree Krishna Khadka[d]

[a]*College of Engineering, Swansea University, Swansea, SA1 8EN, United Kingdom*
[b]*University of Tasmania, Tasmanian School of Business and Economics, Hobart, TAS 7001, Australia*
[1]*Present address: University of Wollongong, School of Accounting, Economics and Finance, Northfields Ave Wollongong, NSW 2522, Australia*
[c]*Ralph E. Martin Department of Chemical Engineering, University of Arkansas, Fayetteville, AR 72701, USA*
[d]*Centrefor Energy Studies, Institute of Engineering -Pulchwok Campus, Tribhuvan University, Nepal*

Abstract

Nepal has been suffering from a serious energy crisis for decades. It has severely affected its economic, social and political developments. Owing to the continuously evolving energy situation in Nepal, and the recent progress in renewable energy technologies, this study aims to provide an up to date perspective on the current energy crisis in Nepal. In particular, the current energy production and consumption profiles are reviewed, and the main factors contributing to a widening gap between the energy supply and demand are identified. These factors concern delayed and overpriced hydropower projects, outdated and insufficient energy infrastructure, transmission and distribution losses, energy theft, deficient energy management, lack of energy conservation, low efficiency of equipment, unsustainable energy pricing strategies and unsatisfying energy market regulations. Other essential factors worsening the energy crisis can be attributed to specific geographical and geopolitical problems, the strong dependence on energy imports, and inadequate exploitation of the vast amounts of renewable energy resources. The status of existing and planned large hydropower projects is summarized. The recent policies and investment initiatives of the Nepalese government to support green and sustainable energy are discussed. Furthermore, a long-term outlook on the energy situation in Nepal is outlined using the energy modeling software LEAP in order to show how to exploit the tremendous renewable energy resources in Nepal. Our findings suggest that renewable resources are crucial not only for mitigating the present energy crisis, but also to ultimately provide energy independence for Nepal by establishing reliable and secure sources of energy.

Keywords: demand forecast; energy crisis; energy demand; energy policy; Nepal; renewable energy

Word count: approximately 10,000

Abbreviations: ADB, Asian Development Bank; AEPC, Alternative Energy Promotion Centre; BaU, Business as Usual; DoED, Department of Electricity Development; FY, fiscal year; GDP, Gross Domestic Product; GHG, Green House Gas; IEA, International Energy Agency; IPP, Independent Power Producer; LCoE, life cost of energy; LEAP, Long-range Energy Alternatives Planning System; LPG, liquefied petroleum gas; NEA, Nepal Electricity Authority; NOC, Nepal Oil Corporation; NPC, National Planning Commission; NPTA, Nepal Petroleum Transporters Association; NPR, Nepalese Rupees; PPA, Power Purchase Agreement; PV, photovoltaic; RE, renewable energy; SDG, Sustainable Development Goal; T&D, transmission & distribution; toe, ton of oil equivalent; USD, United States Dollars; WECS, Water and Energy Commission Secretariat

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[*]Corresponding author.ipp
E-mail address: p.loskot@swan.ac.uk (P. Loskot).
Tel.: +44 1792 602619; Fax: +44 1792 295676

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1. Introduction

Energy is one of the basic requirements to sustain our civilization, so its supply should be secure and abundant [1]. Electrical energy plays a vital role in the development of industrialized nations in the 21st century [2]. The associated climate change significantly affects the economic systems, ecological structures and social development of many countries [3]. The recently adopted 17 United Nations Sustainable Development Goals (SDGs) [4] aim to end poverty, protect the planet, and ensure the prosperity for all. However, at present, 1.2 billion people in the Least Developed Countries (LDCs) do not have access to electricity, and 2.9 billion people still cook with polluting and inefficient fuels.

Energy consumption accounts for 60% of the total greenhouse gas (GHG) emissions [5]. As our dependency on electricity increases and supply-demand management becomes more challenging, large-scale power outages are more common. This has a direct adverse effect on state economies [7]. Other key factors contributing to the energy crisis are:

- Overconsumption: The overall energy demand is increasing faster with the growing population while energy is not utilized optimally, and its distribution is inefficient.
- Inadequate infrastructure: Infrastructure for power generation and distribution is ageing, and it is too costly to maintain it.
- The imbalance between energy production and consumption: The energy supply does not keep up with the growing energy demands, requiring complex energy management solutions.
- Insufficient exploitation of renewable energy sources: The vast resources of renewable energy in many countries are still underutilized, although the situation is slowly improving.
- Energy wastage: There is generally a low awareness about the importance of conserving energy. A related issue is energy theft which is widespread in some countries.
- Accidents and natural disasters: Pipeline bursts, cyber-attacks, and natural calamities such as floods, earthquakes, and hurricanes damage the power infrastructure, sometime in the long term.
- Wars and civil unrests: Wars and political and public disorders can significantly disrupt the energy supplies.
- Lack of proper energy storage: Energy may need to be stored until it is required whilst the storage capacity has to be continuously increased to match the future demands.

The general causes of energy problems in developing countries are summarized in Figure 1.

The World Energy Outlook 2016 by the International Energy Agency (IEA) interlinks energy, air pollution, and health issues [6]. In order to reduce atmospheric emissions, the IEA recommends avoiding traditional fuels, improving energy efficiency and energy conservation, transitioning towards renewable energy sources, and developing low-carbon and carbon-capture technologies [8]. It is estimated that renewable energy can cover 10% of the total energy consumption in the world and provide 30% of the world population with access to electricity over the next 20 years.

Figure 1 The general causes of energy problems in developing countries.

Despite the tremendous renewable energy resources available worldwide, only about 27% of the world population has access to electricity from clean, renewable energy [9]. Many nations in the Asia Pacific region have potential energy resources in the form of millions of tons of rice husk, waste wood, coconut shells, horticulture and agricultural waste, palm oil waste, organic solids and biogases which can be efficiently utilized in boilers and replace the traditional fossil fuels. Renewable energy has already become an integral part of the national energy policies of many countries post the 1973 oil-shock [10]. However, the development of renewable energy solutions is constrained by numerous technical, economic, and political challenges. In order to improve the reliability of renewable power systems, different types of renewable sources can be combined and utilized together with the energy storage devices and the conventional generators to mitigate potential power outages [11]. Renewable sources naturally support decentralization as they are much more uniformly distributed and accessible also in the remote areas. Off-grid power systems can be used in both rural and urban areas to generate electricity. The economic drivers for exploiting the renewable energy sources are now as important as the previous environmental drivers. However, renewable energy does not reach the energy intensity of conventional fuels, and the former is more challenging to store and transport. In Nepal, the renewable energy investments so far have been mainly in hydropower. The diversification to solar energy such as using solar panels on the roofs can generate new employment opportunities, and provide other benefits. Small scale photovoltaic (PV) electricity generation can save 335.9 kg of CO_2 per MWh [12].

Much of the growing energy demands in the global economy are driven by the emerging economies in China and India. These two countries already account for half of the world demand increases, and their consumption is expected to double by 2030 [13,14]. China announced that it would spend $363 billion USD on expanding its renewable energy capacity by 2020 [15]. The subsidies for the new solar PV panels in China are predicted to drop by 75% in 2025 while solar projects in India will be competitive without any financial support well before 2030 [14].

Comprehensive studies of energy situation exist for many countries including India [16], Pakistan [17], Bangladesh [18], and Nigeria [19]. Although there are many similar studies on the energy crisis in Nepal, these studies are either limited in their scope or now outdated. For instance, the energy studies about Nepal focus only on specific regions, or they do not include the current data on the energy consumption and production [20–26]. It is also crucial to consider the recent rapid developments in the use of renewable energy sources, availability of new data, significant changes in the renewable energy market dynamics, and the renewable energy pricing structures. Therefore, the main aim of our present study is to review the current energy situation in Nepal while focusing specifically on renewable energy developments to assess whether renewable energy sources can meet Nepal's future energy needs. In order to understand the causes of a chaotic energy situation in today's Nepal, our study provides an updated view of the current energy crisis in the country. The potential and utilization of the renewable energy sources in Nepal including the relevant energy policies and trends are outlined. The energy reforms currently underway are discussed. The findings from our study can be used to identify and analyze the critical developmental issues of Nepal which are impacted by the inadequate energy supply.

The rest of this paper is organized as follows. The current energy situation in Nepal is described in Section 2. The renewable energy potential of Nepal is evaluated in Section 3 including the current government initiatives and policies. In Section 4, the LEAP (Long-range Energy Alternatives Planning System) software is used to project the Nepal's energy demands over the next 30 years assuming a business as usual (BaU) scenario. Our findings and observations are summarized in Section 5.

2. The current energy situation in Nepal

Nepal encloses a rectangular area of 147,181 km^2 [27]. The country lies in the subtropical monsoon climate and experiences all four seasons. There are tropical areas in the south, alpine regions in the north, and large topographical variations in between. Nepal's territory contains hundreds of Himalaya fed rivers. Although Nepal's geography is great for hydropower generation, it presents many difficulties for electricity distribution, transportation, and other public services [28]. More importantly, it also poses a natural barrier to its development. The 3-year government plan to increase energy generation capacity and improve energy services is outlined in Table S1 [29].

The Nepalese economy is dominated by agriculture. It provides a livelihood for over 67% of its population and accounts for 33% of its Gross Domestic Product (GDP) [30]. There is generally a strong correlation between the country's energy consumption and the GDP [31]. The energy crisis in Nepal forced the manufacturing sector, the 3rd most significant contributor to its GDP, to operate far below the available capacity estimated presently to be at 58%. The Nepalese government recently formulated a long-term economic vision intending to raise Nepal into a middle-income country by 2030 [29]. The Vision 2030 calls for the transformation of subsistence-based farming into a country with large-scale commercial agriculture production, and to also completely upgrade the currently dismal industrial sector. The planned industrialization of Nepal has been formulated in the Special Economic Zone Act [32]. All these initiatives will create additional energy demands. Meanwhile India and China already made significant investments in Nepal through 898 and 629 energy projects, respectively [9], since Nepal's enormous potential energy sources suit their needs very well [33].

Despite having more than a century-long history of electricity generation, 6.6 million people in Nepal are still without electricity [34], and those who have access to electricity are experiencing long hours of load shedding, especially during dry winter seasons. Only 58% of Nepalese households are connected to the national grid, and another 9% rely on off-grid renewable supplies [9]. Consequently, the Human Development Index (HDI) of Nepal is the 145th among 188 countries in the world [35]. About 80% of Nepal's population lives in remote villages far from the national electricity network. Unfortunately, connecting the remote villages to the national grid is too costly [36]. Even when the national electricity grid is available, natural disasters such as earthquakes, hurricanes, storms, floods and security breaches often lead to subsequent catastrophic power outages.

It is not surprising that Nepal has a low level of electricity consumption of 139 kWh per capita per year compared with the world average of 3,104 kWh per capita annually [39,40]. The total energy consumption in Nepal in 2014/15 was 11,232 toe (tons of oil equivalent) [9]. Nepal relies heavily on the traditional energy sources such as wood as it has no significant deposits of fossil fuels. Traditional fuels represent 78% of total energy consumption, followed by 12% for petroleum products. The use of modern renewable energies and on-grid electricity generation are just 3% each (Figure2). Moreover, the dependency on imported electricity and fossil fuels is continuously growing year by year.

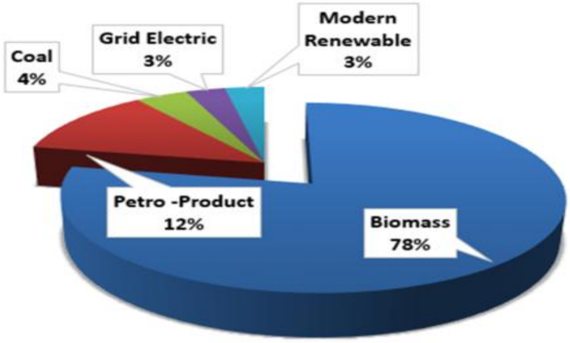


Figure 2 The energy generation mix in Nepal in 2015 [9].

The sector-wise energy consumption in different economic sectors in Nepal is depicted in Figure 3. The residential areas represent 48% of the total consumed energy, and the industrial sector accounts for 38% of consumption. Agriculture is only 2% of the total demand despite being the dominant economic sector in Nepal. The energy consumption in the transport sector is negligible, indicating that this sector is very underdeveloped and hinders the future economic development. Overall, Nepal is mostly dependent on fossil fuels totaling 116.8 billion NPR in 2018. Nepal imports and the consumption of petroleum, oil, and coal has been steadily increasing at an alarming rate of 10% per annum [42,43,44] (Table S2). To meet its energy demands, Nepal spends a large part of its GDP on electricity imports, especially from India, especially to overcome the supply deficits during dry seasons. More importantly, the dependence on imported petroleum products creates a deficit in the trade balance.

The petroleum sector in Nepal is a monopoly. Nepal Oil Corporation (NOC) is a state-owned enterprise in charge of importing, storing and distributing all petroleum products in Nepal. These products and the liquefied petroleum gas (LPG) for cooking are imported from India. Nepal imported 2.07 million kL (kilo-liters) of petroleum in 2017/18, and the demand has been rising at a rate of 13.8% annually [45]. The present storage capacity of 71,622 kL is just enough for 15 days [46]. This greatly contributes to the energy supply uncertainties as the storage capacities in other countries are three months or more.

Petroleum fuels are transported in a two-tier network including the transportation from India to the NOC depots where they are unloaded and stored before being transported further to the dealers' refilling stations. There are almost 1,200 tankers of different sizes operated under the Nepal Petroleum Transporters Association (NPTA). The NPTA does not allow competition among the transporters whilst requiring that NOC accepts the transportation rates. Such practice reduces transportation efficiency and distorts the fuel market [47]. The situation in the supply of petroleum products can be improved by reviewing the competition laws and by enforcing the consumer rights. The reforms in NOC management could improve the transparency of its operations [47]. Moreover, the LPG businesses and gas companies can be directed to expand and upgrade their infrastructure and storage capacity, and the subsidy on LPG should be rectified through price differentiation [48].

Evaporation causes additional losses when the petroleum products are transported to colder places. These so-called technical losses are unavoidable, and NOC used to cover them by supplying extra 0.6% petrol, and 0.4% diesel and kerosene to the dealers. There are also handling losses due to unloading, storage and sale of the petroleum fuels which NOC covered by supplying an extra 0.15% to the dealers. Under the new system, the dealers include 1.6% of technical and handling losses as the extra cost increasing the consumer prices [47].

In 2015, Nepal and India signed a 4.40 billion NPR agreement to invest into a 41km long diesel pipeline to import the petroleum products [48]. The project is currently in its testing phase. The pipeline will reduce the cost of transportation and should mitigate the fuel shortages as pipeline leakages are smaller than the spills from truck tankers.

Electricity is priced at $0.90 USD/kWh for end-users in 2018 which is among the highest in the world. Such high electricity costs in developing countries require financial subsidies. It is mostly the result of poor governance of the state-owned utility companies. Moreover, this situation often promotes corruption, system inefficiencies, overstaffing, poor standards, and as a result, it creates a substantial financial burden to the state.

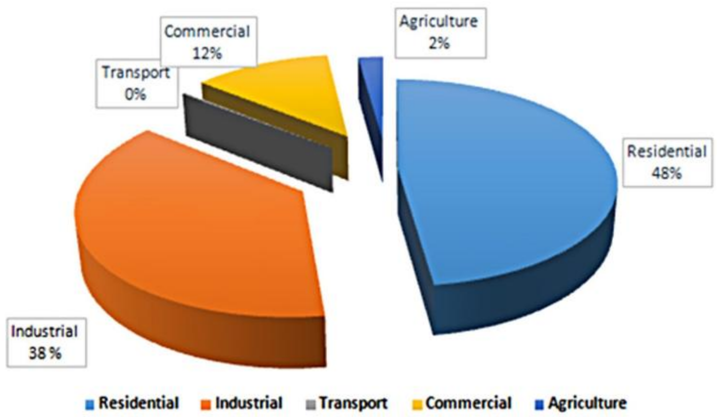


Figure 3 The sector-wise energy consumption in Nepal's economy in 2018 [50].

A detailed view of the current energy situation in Nepal in fiscal year (FY) 2017/18 is provided in Table 1. The data are presented in the following 6 categories: energy available, energy utilized, energy sales, energy revenues, energy expenditures, and energy consumers. The data confirm the trends discussed previously. In particular, over 1/3 of electricity is purchased from India, and most energy is utilized in internal sales with the largest sales of 44% to the households whilst 55% of the expenditures are used for the power purchases. The system losses are significant and amount to 20%. Domestic consumers representing 94% of all consumers generate the largest revenues. The energy trend data are given in Table 2 [44] where it is observed that the energy imports greatly exceed the energy exports, the total energy consumption is on the rise, the domestic energy use is larger than the industrial consumption, and electricity losses are significant. Additional data are given in Table S3 [29].

About 78% of the total energy demand in Nepal is supplied by fuel-wood and 12% by agricultural residues and animal dung [9] (Table 3). Thus, the reliance on traditional biomass as well as the consumption of kerosene and LPG in households continues to be very high (Table S4) [41]. Burning low-quality fuels and fossil fuels has severe adverse impacts on the health of people, especially in rural areas, leading to the death of more than 7,500 women and children each year due to the indoor air pollution [51]. Children are also forced to spend plenty of their time to collect the energy resources such as wood, so they are deprived of education. Depletion of the forest areas has prompted the environmentalist and the energy planners to address the underlying energy problems collaboratively.

Nepal consumes 1.4 million tons of LPG every year according to NOC. A substantial part of this amount ends up in hotels and restaurants which typically consume several gas cylinders every day. The majority of households maintain a stock of two or three gas cylinders. Although urban families can still afford to pay the market prices for gas, more impoverished communities in the valleys and across all nooks and corners of the country must rely on kerosene or the fuel-wood instead. Energy consumption for cooking has grown significantly in the Kathmandu valley. It is estimated to amount to 200 MW annually and is expected to rise even further in the future [50]. For every 10 LPG cylinders delivered to Nepal, 6 are used in the Kathmandu valley alone. The overall energy demand of the Kathmandu valley in 2014/15 stood at 1,300 GWh, and it has been increasing at the rate of more than 10% each year. The price trends of petroleum products in Nepal over the past two decades including prices of petrol, diesel, kerosene, aviation fuel and LPG are listed in Table S5[53]. These data indicate that the cost of kerosene has increased almost 6-fold while the price of LPG increased nearly 3-fold.

Table 1 The energy data from NEA in 2017/18 [9].

A. Availability of energy	
Purchase from India	36.6%
Hydro	32.7%
Purchase in Nepal	30.7%
Thermal	0.0%

B. Energy utilisation	
Internal sales	78.7%
System loss	20.5%
Self-consumption	0.8%
Export	0.1%

C. Energy sales	
Domestic	43.5%
Industrial	37.4%
Others	8.4%
Commercial	7.4%
Non-commercial	3.1%
Export	0.1%

D. Energy revenue	
Domestic	41.6%
Industrial	36.0%
Commercial	10.7%
Others	6.9%
Non-commercial	4.7%
Export	0.1%

E. Energy expenditures	
Power purchase	55.6%
Depreciation	13.3%
Ops. & maintenance	9.3%
Interest	7.6%
Others	5.2%
Royalty	1.9%

F. Energy consumers	
Domestic	93.8%
Others	3.6%
Industrial	1.4%
Commercial	0.6%
Non-commercial	0.6%

Table 2 The evolving energy situation in Nepal (in mil. kWh) over the past 7 years [9].

FY	Domestic	Industrial	Commercial	Other	Consum. total	Electr. loss	Gener. & import	Energy trade	
								Import	Export
10/11	1143.2	1012.9	204.9	294.9	2687.0	1071.4	3758.4	94.1	31.1
11/12	1311.1	1192.1	227.1	384.5	3164.7	953.7	4119.0	800.0	50
12/13	1397.5	1141.1	237.9	379.6	3156.0	756.0	4220.2	790.1	0
13/14	1526.8	1246.7	285.2	385.6	3444.3	853.8	4681.1	1070.5	0
14/15	1688.5	1362.6	302.6	415.8	3772.6	1194.0	4966.7	1367.7	3.2
15/16	1799.6	1206.7	286.5	430.7	3789.0	1358.2	5077.2	1782.9	3.2
16/17	2150.2	1235.1	352.4	536.2	4776.5	966.5	5743.1	2175.0	2.7
17/18*	1397.6	1127.8	229.0	348.5	3104.7	511.3	3616.0	1413.8	1.75

*the first 8 months

Table 3 The breakdown of energy consumption (in %) [52].

	2013/14	**2014/15**	**2015/16**	**2016/17**	**2017/18**
Traditional	77.6	78.4	72.4	74.5	68.9
Firewood	70.5	71.2	65.8	67.6	62.5
Agricultural residues	3.5	3.5	3.2	3.3	31
Cow dung	3.7	3.7	3.4	3.5	3.3
Coal	4	4.6	5.2	4	27.9
Petroleum products	12.5	10.8	16.2	13.8	18.7
Electricity	3.4	3.7	3.9	4.1	4
Renewables	2.5	2.5	2.3	3.5	3.2
100% total (in Mtoe)	11728	11768	12866	8257	9019

2.1 Ongoing energy crisis

The ongoing energy crisis in Nepal has become a major public concern after the Nepalese government declared the state of emergency due to the acute energy shortage in early 2008. The energy crisis threatens to undermine the social foundations of the country. The energy crisis did not appear suddenly, but it is a direct consequence of chaotic energy policies over past decades. It disrupts everyday lives of individuals and businesses through frequent power outages. Some Nepalese citizens are facing 12–14 hours of load shedding every day, especially during the winter months. The present solution is to employ diesel generators during the shedding hours. Many hospitals and healthcare clinics use such generators regularly. It creates substantial environmental pollution also indoors. According to the Environmental Performance Index, Nepal remains the 149th among 180 countries in terms of air quality [54]. More generally, Nepal ranks the 130th out of 190 nations in terms of its infrastructure availability which is the worst in South Asia. More than 2/3 of Nepalese firms perceive electricity as a critical issue. Due to frequent power outages, companies must rely on expensive diesel generators to substitute as much as 40% of their electricity use. It increases the production costs and reduces their competitiveness [30].

The unplanned power outages severely impact the national economy. The economic losses in the industrial sector due to power outages amount to $24.69 million USD a year which is about 4% of the total GDP produced by the whole industrial sector [55]. Service-oriented industries cut their office hours to keep uniformity with other market participants. Manufacturing units are compelled to use diesel generators to maintain the production which increases the cost of finished products by a whopping 25–40%. This has constrained many companies to either permanently shut down their operation, or they transformed into trading more basic goods and products. The use of diesel generators is also encouraged by the deferred investments in the electricity infrastructure. Manufacturers processing glass, textiles, chemicals, plastics, cement and other similar materials cannot tolerate even a short electricity disruption, since it may take several hours to resume the production after the outage. The adverse impacts of load shedding on the delivery of different services are quantified in Figure 4 as the percentages of time the normal services are being disrupted. The economic costs of electricity disruptions are enumerated in Table S6 [55]. The most negative effects are felt in provisioning education and water supply services whereas the financial losses due to load shedding are the largest in materials processing industries and food production.

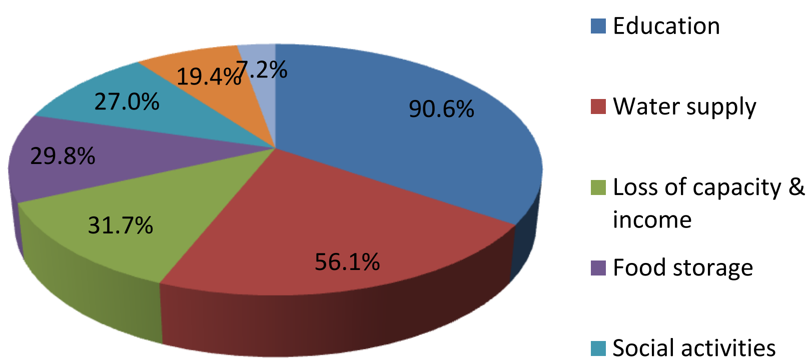


Figure 4 The impacts of load shedding [56].

To understand the severity of energy problems in today's Nepal, it is sufficient to compare the overall electricity demand and supply in the country, as shown in Figure 5 and Table S3 [52]. Current attempts to close the supply-demand gap are not successful. A typical daily power load profile in Nepal in 2018 is depicted in Figure S1 [50]. It shows that energy demand is continuously decreasing overnight from midnight until about 4 pm the next day when the demand starts to rise abruptly. The peak demand occurs daily between 4 pm and 7 pm. Peak demand is expected to increase from the current value of 1,500 MW to 3,200 MW in 10 years [57]. More importantly, the peak demand of 1,500 MW is mostly driven by households. The peak demand cannot be satisfied as only 1,045 MW of electricity including the imports is available. The data in Table S7 [52] illustrate the extents of the current electricity and petroleum product imports and their distribution among the provinces. Thus, hydropower-rich Nepal ironically imports 34% (up from 27% only a year earlier) or 345 MW of its electricity from India [50]. In 2015/16, Nepal paid India 16 billion NPR for 2,175 GWh of electricity, 109 billion NPR for 1.3 million tons of refined fuels, and 17 billion NPR for 1.4 million tons of LPG [53]. Such large trade deficits have severe negative impacts on the Nepalese economy, and the situation is worsening over years [26]. The trend of the electricity imports from India is contrasted with the volumes of the electricity generation in Figure S2 [50].

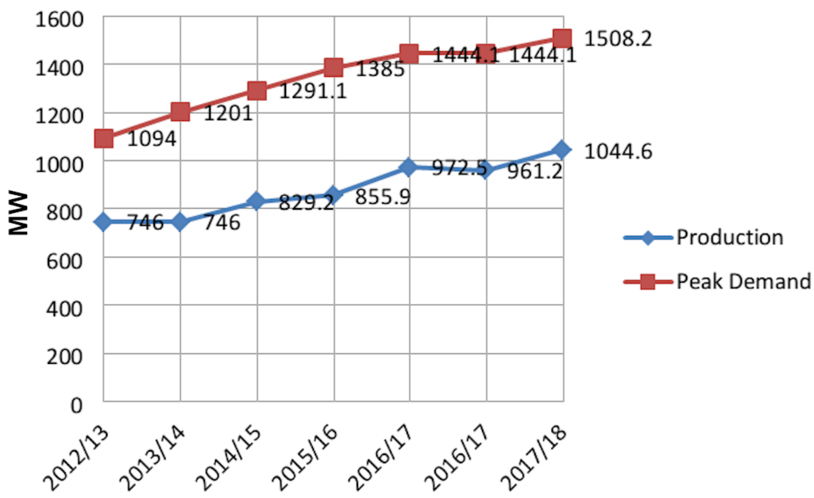


Figure 5 The electricity production and peak demand in Nepal over the past 5 years [52].

The entire length of the existing power transmission lines is 3,496km, and about the same length is under construction. More importantly, Nepal is blessed with a huge theoretical hydropower potential of 83,000 MW out of which 45,000 MW is considered to be techno-economically feasible [58]. Nepal has almost 6,000 rivers with the total annual discharge of 174 billion m^3 of water. However, until today, only 1,044.6 MW of hydropower is supplied to the peak load system representing only 2% of the total energy supply [59]. The excessive reliance on hydropower means that the energy situation in Nepal rapidly deteriorates in dry seasons lasting from November to April each year while the water level in many rivers is significantly reduced. Fortunately, the situation improves during wet seasons lasting from April to November each year. The data on demand and supply balance during wet and dry seasons projected over the next 5 years are shown in Table 4. The actual data on energy use for years 2005 – 2015 as well as the predicted data for years 2020 – 2030 are provided in Table 5 (Tables S11 and S12). The electricity demand forecast report of NEA for years 2015 – 2040 predicts similar future electricity demands [60].

These data imply that the Nepalese government expects the country's energy consumption will substantially increase over the next decade. At the same time, the utilization of renewable resources is projected to increase from today's 12% to over 20% in the next 10 years while the dependency on imported electricity is expected to rise to 34% which will negatively affect the country's economic independence. Some experts argue that Nepal's dependence on energy imports may not affect its energy security too much as long as the foreign suppliers are reliable [61]. However, the energy consumption data in Figure S2 and the energy projections in Tables 5, S11 and S12 indicate that Nepal's energy vulnerability is likely to worsen. The volatile nature of the international energy markets aggravates the situation and makes the energy crisis more severe and more persistent [62,63].

2.2 Approaches to mitigating the energy crisis

The initial strategy for mitigating the present energy crisis is concerned with identifying and reducing the transmission losses and improving the efficiency of energy systems and processes. This is achievable without requiring any radical changes. In addition, the load/demand profile diagram and the projected energy use can be utilized to devise efficient power management strategies and to obtain a good understanding of the power supply-demand economics. The load profiles can be obtained for monthly, daily, and hourly time-scales depending on the analysis and the goals considered. An example of the hourly daily demand curve is shown in Figure S1.

Table 4 The current and predicted electricity demand and supply (in MW) in wet (April – November) and dry (November – April) seasons [52].

	FY	Demand	Supply	Balance
Wet seasons	2018/19	1841.13	2283.45	441.32
	2019/20	2225.65	2856.97	631.32
	2020/21	2638.29	3584.44	946.15
	2021/22	3062.87	3963.87	901
	2022/23	3365.97	4046.14	670.17
Dry seasons	2018/19	1841.13	1470	-372
	2019/20	2225.65	1686	-539
	2020/21	2638.29	1928	-709
	2021/22	3062.87	2055	-1007
	2022/23	3365.97	2079	-1283

Table 5 The current and predicted future energy use in Nepal [64].

Index	2005	2010	2015	2020	2025	2030
Per capita energy (GJ)	15	16	16	17	19	23
Per capita electricity (kWh)	67	80	124	231	496	1070
Household electricity use (%)	1	2	4	7	13	17
Energy per household (GJ)	76	79	78	78	13	17
Non-carbon elect. share (%)	1.7	1.9	2.8	4.8	9.3	16.5
Share of renewable (%)	11.7	11.9	11.2	12.3	15.4	22.1
Imported electricity (%)	10.6	13.4	18	23.4	29.9	34.8
Per capita GHG production (kg)	474	459	420	392	508	672

The lack of proper governance to overcome widespread inefficiencies in energy systems is one of the key factors contributing to the energy crisis. For instance, the transmission and distribution (T&D) losses exceed 34% compared to the world average of only 8% while the largest T&D losses are observed in the South Asian region [65]. The low-quality equipment and poor maintenance practices directly contribute to these losses. Furthermore, energy theft is estimated to account for 10% of the overall losses and is expected to reach more than 200 MW of electricity used in Nepal or $75.47 USD million annually.

Inadequate planning and investment in electricity generation, transmission, and distribution networks due to lack of adequate legal and regulatory frameworks constitute a major issue. About half a dozen of transmission line projects were put on hold due to lack of the proper energy policies. For instance, NEA is unable to secure the rights of way from private landowners to pass the transmission lines over their land [66]. The rights of way and forest clearance processes hamper the development of the critical energy infrastructure [21]. Appropriate regulatory policies can address most of these issues.

Government regulations and policies involving various financial and investment issues in the energy sector is an effective strategy for mitigating the energy crisis. For instance, the Nepalese government drafted the 10 and 20 year hydropower development programs along with the supporting policies. The premise of these programs is to enlarge the generation capacity in order to satisfy the expected demands. It has been projected that until 2030 additional 20,354 MW of electricity generation capacity will be added to the Integrated Nepal Power System (INPS) excluding the already planned large hydropower projects [67]. Moreover, anticipated climate change has been reflected in several national energy policies. For example, Nepal's first energy policy statement appeared in its 5-Year Plan 1975 – 1980 [68] emphasizing the need for increased utilization of renewable energy sources while reducing the dependence on traditional energy sources and the petroleum imports. However, despite many of these energy policies adopted by the Nepalese government, their practical implementation is often lacking. The situation is further exacerbated by a high level of corruption which leads to widespread institutional and governance failures [69].

The average cost of generating 1kW of electricity in Nepal has doubled from $1,000 USD in the early 1980's to above $2,000 USD in the late 1990's [70]. The study [71] expects that the average cost will further rise to $2,500 USD per kW shortly, despite a wider adoption of renewable energy sources, and the associated economies of scale [26]. This is reflected in energy policies concerned with setting the energy pricing levels. Unfortunately, electricity prices in Nepal now represent one of the costliest tariffs in South Asia, even though the same pricing level was maintained for more than a decade. The 20% price increase in August 2012 and the additional 18% increase in July 2016 were adopted following the guidance of the Tariff Fixation Committee of Nepal. On the other hand, the study [72] argues that the electricity prices in Nepal are too low to cover all the real costs, and the current rates are not based on the market principles, but rather on the vested interests and political motives. The electricity is then supplied to end-users at highly subsidized prices distorting the market dynamics. This could be one of the main reasons why NEA has suffered substantial financial losses, so it cannot afford to invest the required sums of money into the infrastructure and the needed hydropower projects. However, under the new NEA leadership, many transmission lines have been completed and are now operational. The hydropower plants Chameliya and Kulekhani III which were in chronic troubles for many years are also moving ahead. NEA succeeded to make Kathmandu and Pokhara regions to be almost load shedding free since FY 2016/17 while the power cuts in other areas were substantially reduced [50,73].

Another strategy for mitigating the energy crisis in Nepal is to optimize the mix of the energy sources used in different regions of the country. The immense hydropower potential of Nepal is not yet exploited to satisfy the energy demands. Nepal has been also facing uncertainties regarding the supply of petroleum products from India from time to time. Nepal's geographical location, its small size and economic dependency on other countries leaves Nepal vulnerable, especially at times of geopolitical crises [74–76]. For instance, after the Nepalese parliament passed the new constitution in 2015, it prompted India to halt its trucks carrying cooking LPG, gasoline, salt and other essential products at the borders to Nepal [77,78]. This trade blockade lasting for 2 months caused acute shortages of gasoline, cooking gas and medical supplies. It is likely that the whole economy of Nepal can be transformed by utilizing its enormous renewable energy sources with the right energy mix. Nepal has enough renewable resources to generate sufficient amount of electricity to satisfy not only its own needs, but to even sell excess electricity to the entire SAARC (South Asian Association for Regional Cooperation) region. The key challenge is to make these opportunities commercially, economically and politically viable. Even small scale renewable energy sources including hydro, solar, wind and biomass can be utilized to immediately mitigate the acute energy crisis. The Nepalese government set the goal of increasing the share of renewables in the country from today's less than 1% to at least 10%, and to improve access to electricity from alternative sources from 10% to 30% within the next 20 years. The Nepalese government plans to invest $1,076 million USD into the renewables by 2020, targeting primarily the hydropower, solar and biogas technologies [79,80].

3. Renewable energy potential of Nepal

The seasonal nature of renewable energy sources is one of the main challenges hindering their efficient utilization [81,82]. A better understanding of such barriers is required to support their wider adoption. In particular, the renewable power plants do not always operate at their full generation capacity mainly due to the varying weather conditions. In order to provide reliable renewable power sources with the good quality and stable output, the energy storage devices and the conventional generators should be used to mitigate supply outages. The data on adoption of renewable energy sources in Nepal since FY 2012/13 are given in Table 6.

Table 6 Adoption of the alternative energy sources in Nepal [52].

Electricity generation	2012/13	2013/14	2014/15	2015/16	2016/17	2016/17	2017/18
Small and micro-hydro (kW)	3366	3288	3346	1910	1245	957	939.5
# household solar systems	96495	87038	103161	56770	16084	9291	16572
# solar pumps	140	202	30	11	0	5	14
# bio-gas plants	17635	31512	30078	16706	20536	15707	8346
# improved cook stoves	120364	140662	310281	51211	60555	34767	10018

Another strategy is to combine the output of several renewable energy sources [83]. The micro-grids can be formed by interconnecting the hydropower sources with wind turbines or PV systems [84]. The study [81] pointed out that despite good support from the international community, the funding for small-scale renewable energy projects is usually rather limited. Unfortunately, most funds are allocated primarily to large-scale energy projects, so the energy needs of the poorest are neglected. The ongoing energy crisis forced the policymakers to consider various energy models in order to balance environmental and economic benefits. The estimated energy potential from different renewable energy sources in Nepal is presented in Table 7. These data indicate that Nepal can exploit immense amounts of hydropower, solar energy, wind and biofuels.

Nepal is among the top 20 countries with the highest rates of electricity access to the off-grid solar supply [86]. Provided that the super-efficient appliances are used with off-grid solar power systems, the total cost of providing off-grid electricity can be reduced by as much as 50% [87]. However, in 2018, only 12% of Nepalese citizens had access to electricity from renewable energy sources with 23 MW attributed to micro-hydro plants, 12 MW to solar PV systems, and 12 MW came from the windmills. For large part of rural population consuming low amounts of electricity, there is no other viable alternative to solar electricity to achieve the electrification. The operational and maintenance costs of diesel generators are too high, and biogas technology does not work satisfactorily in the cold environment at high altitudes in the mountains whilst it would be also too difficult to realize with the roving herds of cattle [85]. Small hydro turbines need specific topographical conditions which are usually found only near small number of dwellings. However, although the solar power is a good option in many locations, it cannot fully solve the rural electrification problem.

Solar power limitations can be overcome with proper planning and by integrating with other types of renewable sources. Hybrid and distributed generation systems can be the best choice for supplying electricity in all areas of Nepal [88]. The hybrid plant in the village of Bhorleni in Makawanpur District of Nepal combines 15 kW solar and 10 kW wind generation. This 13 million NPR project funded by the local government has electrified 131 local households requiring $1.40 USD a month per household [88]. Another 12 kW solar-wind hybrid plant was funded by the Asian Development Bank (ADB) in the village of Dhaubadi in the Nawalparasi district. It is charging $2.80 USD a month per household [89].

Off-grid technologies can becreated by using local mini-grids based on solar and micro-hydro, or by expanding the household energy technologies such as the solar home systems. About 45% of electricity supplied to residential areas comes from the main grid. In the past, this was almost entirely supplied from the domestic hydropower plants. However, due to a seasonal generation disparity and the increasing demands, power shortages worsened over time. The renewable sources can bridge this electricity supply and demand gap by utilizing the mini-grids across the country [91]. In addition, the study [21] argues that off-grid electricity consumption is strongly dependent on the rural population and the electrification ratio of the country, since increasing the energy access is largely driven by the expansion of mini-grids. The potential benefits from the expansion of mini-grids and renewable energy sources in Nepal have been observed mainly to support the improved access to energy services for the poor and in remote areas [90].

Table 7 The estimated renewable energy potential of Nepal [92].

Technology	Potential	Comment
Mini/micro hydro	>100 MW	Possible in 55 districts of Nepal
Domestic biogas	1.1 million plants	For existing livestock population
Solar energy	2,100 MW	4.5KWh/m^2/day radiation and 2% country area
Improved cooking stoves	>2.5 million	Assuming 75% of households eligible
Improved water mill	25 – 30,000 MW	
Wind	3,000 MW	Assuming 10% area with more than 300W/m^2
Biofuel	100,000 tons	

3.1 Hydropower

Water resources in Nepal are estimated at 225 billion m^3/km^2/year which is 4 times higher than the world average [93]. Hydropower is often promoted as the most viable option for Nepal and its future economic developments [94]. However, despite such colossal potential, Nepal is currently utilizing only 2% of this resource [50,95] whilst other renewable resources are largely ignored. Presently, there are 88 hydropower plants in operation in Nepal with the total generating capacity of 967.85 MW; 60 of those plants belong to the Independent Power Producers (IPP), and they contribute 441 MW. There are another 113 hydropower plants in the construction stage with total generating capacity of 3,090 MW. The key hydropower projects are listed in Table 8. Most of the existing hydropower stations are a run-of-river type, so any reduction in water flow during the rainless months is immediately reflected in the falling production. The total generation capacity of the 30 largest hydropower projects is 12,766 MW representing only 15% of the total hydropower potential of the country. Only Kulekhani I and II hydropower plants with combined 92 MW of generating capacity have water reservoirs, so that they can sustain fluctuations of the river flows. During dry seasons, overall production is reduced by as much as 35% while domestic hydropower electricity generation plunges by more than 30%.

Table 8 The key hydropower projects in Nepal and their capacity (in MW) [96,97].

A. Completed projects	
Upper Mai C	5.1
Dhunge Jiri	0.6
SabhaKhola	4.0
PuwaKhola	4.0
FawaKhola	5.0
ThapaKhola	13.6
SardiKhola	4.0
ChakeKhola	2.8
MidimKhola	3.0
SyouriBhumi	0.02
Chameliya	30.0
Total	72.1

B. Largest projects	
WestSeti	750
BudhiGandaki	1200
Kali Gandaki	600
Arun	643
Karnali	1380
Pancheswor	6480
Dudh Koshi	30
AndhiKhola	180
Langtang	218
UpperTamakoshi	309

C. Projects under construction		
Kulekhani 3rd	14	2018/19
Upper Tamakoshi	456	2018/19
Upper Trishuli 3A	60	2019/20
Rahughat	40	2020/21
Tanahun	140	2022/23
Total	710	

Large hydropower projects often have significant environmental, social, cultural, technical, financial, and economic impacts. Without any mitigating measures, these impacts are unevenly distributed, and are facing the prospect of high rewards as well as risks [49]. The World Commission on Dams developed a set of guidelines to address many of the social and environmental impacts of dams on the natural habitats and the livelihoods of people [98]. Unfortunately, the electricity production from large hydropower projects is very sluggish as most of these projects are experiencing large cost and time overruns (Table S8) [44]. The investments required for the hydropower plant development are behemoth. It costs as much as $2 million USD per MW to build a hydropower plant. Other reasons behind the overruns are the NEA's centralized and prolonged procurement processes, the NEA's weak project management capacity, and the existence of ghost contractors [99]. The start of some hydropower projects is often deliberately postponed with the intention to build "water grab" dams. More than 400 hydroelectric schemes are planned in the mountain regions which can be a disaster for the environment [100]. Both India and China funded several large hydropower projects (Table 9). Furthermore, political instability, labor actions, and power outages are the main obstacles for foreign companies to do business in Nepal according to the Enterprise Surveys for Nepal [102]. The "Water Resources and Public Investment" policy has been formulated to enable participation of the general public and the Nepalese communities abroad [50].

Small scale hydropower generation is becoming very popular for the off-grid power supply in remote places [9]. According to the World Bank, over 400 micro-hydro power plants were built between 2007 and 2014 in Nepal, providing 150,000 rural households with access to reliable and clean power. Nepal generated 1,095 kW of electricity from the micro and small hydroelectricity plants in 2015 with 15 MW from the mini-hydro projects. In 2016, 308 improved water mills were installed in Nepal [50]. The combined generation capacity of the existing domestic hydropower plants already reached 961.2 MW [104]. However, the current generation capacity of these plants is down to 617MW [105].

Table 9 The hydropower projects in Nepal funded by India and China [103].

Project	Power (MW)	Funder	Originated	Comments
Arun 3	900	India	November 2014	Just started Financial management problems.
Dudhkoshi 2	240	India	April 2015	Applied for the license.
Dudhkoshi 4	350	India	April 2015	Undecided.
Upper Karnali	900	India	September 2014	Land acquisition and compensation problems. Financial management problems.
Bheri 3 Storage	480	India	October 2012	Survey stage.
Western Seti	750	China	February 2012	PPA, Investment style not fixed yet.
Upper Marsyandi 2	600	India	2011	Equity and free electricity put on hold.
Upper Trisuli	102	China	May 2015	Applied for the license.
PancheshworTrishuli	6720	India	1995	DPR not yet read.

3.2 Solar

The cumulative PV solar generation globally has grown from 3 GW in 2003 to 219 GW in 2015, and reached 430 GW in 2018 [104]. Using the PV modules with 12% efficiency, and assuming the sunshine of 4.5 hours a day as the national average, the total energy produced by these PV modules is, $0.12\times4.5\times147{,}181\times10^6$ = 80,000 GWh/day = 17.7 TW [58]. If only 0.25% of Nepal was covered with the solar panels having 20% efficiency, enough electricity would be generated to satisfy all of Nepal's demands [50]. The overall commercial potential of solar energy for the on-grid utilization in Nepal is estimated to be 2,100 MW according to the 2008 report on the Solar and Wind Energy Resource Assessment by the Alternative Energy Promotion Centre (AEPC) of the Nepalese government. Nepal also received a credit from the World Bank toward the cost of the Grid Solar Energy and the Energy Efficiency Project (GSEEP) totaling $130 million USD [107].

The cost of solar PV panels is now half of what they used to be only seven years ago, and the prices are likely to fall by another 60% over the next decade [108]. Solar PV panels are now viable without financial support even in the regions with abundant fossil fuel resources [109]. At the same time, the prices of batteries and other electricity storage technologies have fallen as much as 80% since 2010 [85]. A sample calculation of the solar panel yield and the expected financial returns for a typical household in Kathmandu is provided in Table S9. The solar energy in Nepal has been used mainly for lighting in the communities not connected to the main grid, but it is now spreading also to urban households and the medium-sized businesses. For instance, the small PV systems which are used widely for lighting in remote places can provide 10–20 W of power with 7–20 Ah batteries [110]. Harnessing solar power helped several hospitals and medical clinics in rural Nepal to replace diesel generators [111]. Nepal has on average 300 sunny days a year, reaching about 3.6 to 6.2 kWh/m^2/day of the solar irradiance [112]. There are 6.8 sunshine hours per day on average, i.e. 2,482 sunshine hours per year with the intensity of the solar insolation 3.9–5.1 KWh/m^2/day [112]. This makes solar energy to be a very promising energy source for Nepal. The solar map of Nepal showing the average solar radiation intensities is in Figure S3 [113].

The Department of Electricity Development (DoED) classifies solar power generation as domestic producers (500 W to 10 kW), and organizational producers (10 kW to 500 kW). The solar power plants with capacity of more than 1 MW require a survey license. However, all the producers will need permission from the DoED to be allowed to connect to the main national grid.

3.3 Windpower

Wind power is one of the most widely used renewable energy resources in the world [114]. Nepal's tall and windy mountains are very suitable for deploying wind turbines. Wind turbines are relatively quick to install, and they take much less space than solar arrays. For instance, a 100MW wind farm can be erected within 6 months. Larger wind turbines yield cheaper cost of electricity generation, but the primary concern is the road access for their installation. The utilization of wind energy is growing faster than solar PV generation with the annual increases in the capacity of around 20%, growing from 39 GW in 2003 to 318 GW in 2013, and reaching 600 GW in 2018 [115]. However, wind electricity generation has to be backed by the conventional generation capacity due to wind intermittency [107]. Assuming onshore wind turbines, China has the lowest weighted average levelized cost of electricity (LCOE) between 50 USD/MW to $72 USD/MW whereas, in the Middle East and Africa, the LCOE is about $95USD/MW [116]. The LCOE values of different renewable energy sources are compared in Figure S4 [116]. Thus, solar PV generation shows the most significant decrease in the LCOE over the past 5 years while hydropower remains the cheapest source.

The wind power potential of Nepal is estimated to be 3,000 MW according to the World Bank. However, the current utilization of wind power in Nepal is negligible as the focus is almost exclusively on hydropower. As of 2018, the wind turbines installed in Nepal have the total generation capacity of 113.6 kW comprising of the 65 kW wind turbines provided by the AEPC while 3.5 kW are due to Practical Action, and the private sector financed 45.1 kW wind turbines. A draft of the National Wind Policy for Nepal has been prepared by the National Wind Task Force (NWTF). On-grid wind power purchases agreement provision was presented in the Nepal's Energy Crisis Alleviation 10-Year Development Plan in February 2016. The South Asia Sub-regional Economic Cooperation (SASEC) project is funded by the ADB. This project aims to review tariff regulations and norms including designing tariff plans for the remote mini-grid connections. More importantly, all wind turbine projects in Nepal are tax-exempt.

Until now, no comprehensive wind mapping study of Nepal has been conducted, although a relevant project is ongoing with the help of the Technical University of Denmark (DTU) aiming at producing a 80–100 meter wind resolution map for the 10 selected sites. The output of this 3-year project will be the Wind Atlas of Nepal [117]. A low-resolution wind map of Nepal which is, however, insufficient for planning the wind turbine deployment is shown in Figure S5 [118]. The wind mapping initiative of Nepal is also part of the Energy Sector Management Assistance Program (ESMAP) and part of the Nepal Energy Sector Development Platform. In addition, the World Bank designed a capacity development program for educating the policymakers, financiers, developers, and technical experts in developing countries [119].

3.4 Biomass

Since Nepal is mostly agricultural country, livestock and farming activities produce massive amounts of biomass. However, the traditional use of biomass creates the indoor air pollution [120]. According to the World Health Organization [121], over 4 million people a year die worldwide due to illnesses caused by the household air pollution from cooking with the solid fuels such as wood, crops and animal dung. In 2014, a conservative forecast by the Winrock International predicted that the remaining technical potential of biogas is about 0.9–1.3 million plants [122] (Tables 6 and 7). Although there is no estimate how many of these plants can become large commercial systems, at present, there are 365,000 household biogas systems, 10 community systems and 370 institutional larger biogas systems in the operation worldwide according to the World Bank.

3.5 Policies for the adoption of renewable energy

In order to regulate the energy projects and industries in Nepal, the government formulated and issued a number of relevant acts, rules, regulations, and policies. The policymakers in Nepal are presently exploring mixed energy models. It has been shown that including solar power into the energy mix can make a noticeable difference [123]. The energy mix with suitable energy storage solutions can be beneficial to cope with the daily as well as seasonal demand fluctuations [124]. Unfortunately, the adoption of renewable energy sources in Nepal has been very slow so far. The new measures to boost utilization of renewables are necessary, for example, by introducing the licensing arrangements for the private sector, deciding on tariffs, and defining the renewable energy market rules. As long as Nepal can start implementing its energy policies and other energy measures effectively, it will likely satisfy all its current as well as future electricity demands [124]. More specifically, the following key energy policies and acts were issued by the Government of Nepal: Hydropower Development Policy (1992) [125] and (2001) [126], Water Resource Act (1992) [127], Electricity Act (1992) [128], Forest Sector Policies and Forest Act (1993) [129], Water Resource Strategy (2002) [130], National Water Plan (2005) [130], Rural Energy Policy (2006) [131], National Electricity Crisis Resolution Action Plan (2008), the 10 Years Hydro Power Development (2009), the Energy Sector Synopsis Report (2010) [79], the Scaling up Renewable Energy Program (2011) [132], and the National Energy Strategy of Nepal (2013) [133].

The Rural Energy Policy (2006) [135] focuses on opportunities for improving the living standards in rural communities by developing and exploiting sustainable, i.e., renewable energy sources. The main objectives of this policy are: (i) reduce the dependency on traditional energy sources and conserve the environment by increasing the access to clean and cost-effective energy in rural areas, (ii) increase the employment and productivity through the development of rural energy resources, and (iii) improve the living standards for rural populations by integrating the energy extraction with the social and economic benefits. The more recent renewable energy policies and visions of the Nepalese government which are in effect from 2016 include: Renewable Energy Subsidy Policy (2013) [136], Renewable Energy Subsidy Delivery Mechanism (2013) [137], National Energy Crisis Mitigation and Energy Development Decade (2016) [138], and Renewable Energy Capacity Needs Assessment for Nepal (2016) [139].

In addition to these policies, the Ministry of Water Resources, the Ministry of Energy, Water and Energy Commission, the Department of Electricity Development, and NEA have the right to formulate different policies, administer the development of hydropower projects, and enter into the power purchase agreements (PPAs). The assessments of climate and carbon activity impacts have been published in different governmental reports [140]. Nepal is also a signatory country of many bilateral and multilateral agreements. However, these pacts are typically more ceremonial than actionable, so they are of limited value [52].

Moreover, Nepal is currently undergoing a significant transition of governance into a federal system with 7 newly elected federal governments. This creates the opportunity to restructure energy systems and address the energy crisis in each state individually. However, due to Nepal's diverse geography and developments, there are large inequalities among the federal states at the level of their energy infrastructure development. The National Planning Commission (NPC) of Nepal drafted a proposal to produce 383MW of electricity from 277 hydropower plants dispersed among all 7 provinces with the generation capacity between 500 and 1,000 kW as indicated in Table S10 [52]. This proposal also counts on the local exploitations of solar, wind and biogas resources. The number of certificates and licenses issued for the hydropower projects is summarized in Table S11 [141–143]. In January earlier this year, the Nepalese government requested that NEA starts promoting the use of renewables so that utilization of alternative energy sources can reach at least 10% of the total installed capacity in near future. In addition, the Ministry of Energy issued the guidelines in February 2018 for connecting alternative energy sources to the national grid.

4. Long term prognosis of energy demand in Nepal

Addressing the present energy crisis is essential, but not sufficient. It is equally important to understand how the energy demands are going to evolve in the years to come. Hence, the likely energy demands in Nepal were projected over the next 30 years using large-scale energy modeling in the LEAP. Such analysis is vital for formulating the long-term integrated energy policies, and for planning the expansion of energy generation and distribution systems and other infrastructure to fulfill the demands, and most importantly, to tackle the energy crisis [144]. The LEAP modeling shows that a massive scale adoption of renewable energy sources must become an integral part of any future energy planning policies.

As discussed previously, the largest energy consumers in Nepal are in the industrial, commercial and agricultural sectors. Our prediction methodology extrapolates the energy consumption data available for FYs 2011/12 until 2016/17. The energy forecast assumes an optimistic BaU scenario, since other scenarios may require more detailed long-term analysis of the anticipated societal, economical and upcoming technology changes which is beyond the scope of this paper. For instance, future energy systems will involve increasing electrification and the share of variable renewable sources. Representing the short-term variability in the long-term studies and incorporating the effects of climate change to ensure openness and transparency in the modeling is difficult [146]. The energy demand extrapolation is numerically carried out in the commercial LEAP software. This software can incorporate many assumptions including anticipated modernization of agriculture, ongoing industrialization, diversification and internationalization of the national economy, and any other factors contributing to the energy consumption. The LEAP software was developed in the Stockholm Environment Institute at Boston, and quickly became a widespread professional tool for large-scale energy system modeling at the national, state and regional levels. It can be also used for assessment of the national energy policies [145], and for evaluating the emission reduction projections submitted to the United Nations Framework Convention on Climate Change (UNFCCC) [145]. More importantly, the accounting-based energy modeling used in the LEAP software is the most suitable modeling approach for the scenarios in developing countries where often only the limited data are available [144].

4.1 Energy demand modeling for Nepal

The LEAP adopts a bottom-up accounting framework which is used in all the energy modeling and forecasting scenarios [146]. The energy model accounts for all sources of the GHG emissions, and it also enables to assess the air pollutants and air pollution. The main advantage of using the LEAP is its low requirements for supplying the input data since the energy models follow relatively simple accounting principles while many other modeling aspects are optional. Most energy studies described in literature generally include a historical period known as the current accounts where the model can be tested to be able to replicate known data, and one or more forward-looking periods depending on the scenarios considered. The LEAP allows the policymakers to assess the marginal effects of each policy and to identify the interactions which occur when multiple strategies are combined.

Our task is to evaluate the energy demands in different economic sectors assuming FY 2011/12 as the base year. The BaU scenario requires knowledge about the existing energy production and supply systems which may occasionally incorporate also the renewable energy sources. The LEAP energy model contains various modules with different assumptions about the energy resources, demands and transformations. The key assumptions module is used to define main parameters of the prediction such as national GDP, GDP growth, total population, population growth and other. Future energy demands are then estimated, assuming the following model settings:

1. General system parameters: standard energy unit (GJ), standard currency unit (USD), base year (2011), baseline reference years (2011–2017), and the end year of the forecast (2041).
2. Options for the energy demand analysis: energy-consuming sectors (residential, industrial, transport, agriculture, and commercial), and fuel type (fuel-wood, agricultural residues, animal dung, coal, electricity, and petroleum).
3. Model options: model type (bottom-up), and the technologies, policies, and alternatives considered.
4. Current accounts: current year inputs, including the end-use energy intensity and activity data.
5. Reference scenario: business as usual.

The model data including the anticipated growth rates in all economic sectors are mostly obtained from various annual reports and other literature. In particular, we assume the national population growth rate to be

1.35% annually, and the national GDP to optimistically grow at 4.3% each year. The primary energy demand of Nepal is expected to grow at the rate of 2.73% per year along with the electrical energy demands to grow by 8.8% per year [6]. Global primary energy demand is projected to increase on average by 1.46% per year between 2009 and 2035 [132]. The same demographic characteristics are assumed throughout the whole evaluation period. The base year demographics and the energy data were obtained from the reports by the Water and Energy Commission Secretariat (WECS) [147], the National Planning Commission [147], the Central Bureau of Statistics of Nepal [148], the National Population and Housing Census (2011) [149], the Economic Survey by the Ministry of Energy [150], and the data from the Ministry of Finance [151], Nepal Oil Corporation [44] and NEA [50].

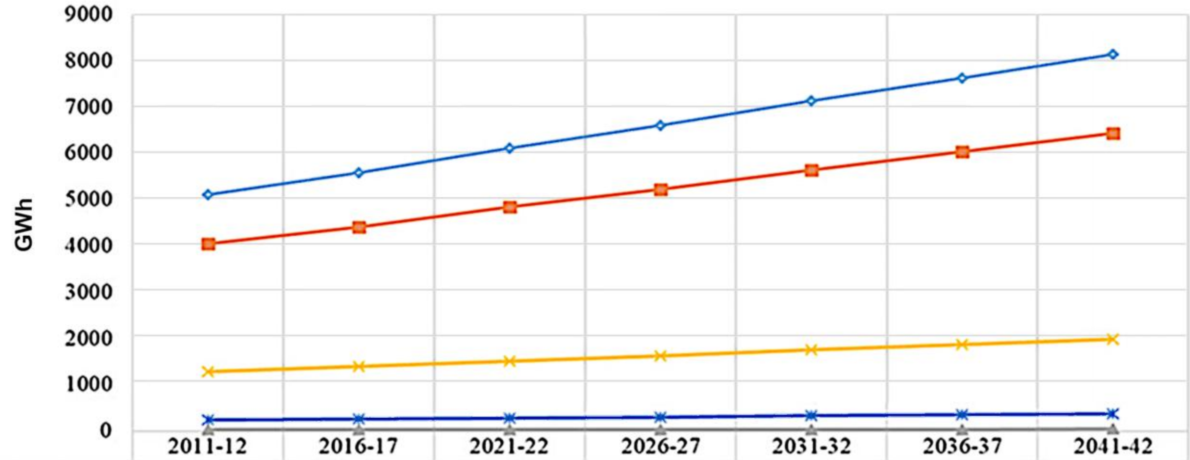
The results of the projected energy demand up to FY 2041/42 are presented in Figures S6–S10 and also summarized in Figure 6. The residential sector is the dominant electricity consumer under the BaU scenario. This sector consumes 48% of the total electricity produced. At the end of the reference year 2017, the residential energy consumption was calculated to be 5.6 million GWh which is then projected up to 8.14 million GWh at the end of the year 2041. The industrial sector comes second with 38% of the overall electricity consumption. It requires about 4.04 million GWh during 2014 while the demand in 2017 is 6.5 million GWh which is projected to increase to 5.6 million GWh by 2030. The power motive runs are the most energy-intensive processes in the industry, but the industrial heating and cooling follow similar trends. The overall electricity demand in the agricultural sector is projected up to 0.4 million GWh in 2041, up from 0.25 million GWh in 2017. In case of transportation, cable cars are still the primary means of transport in Nepal. Although they are electricity demanding, they will reach only 0.04 million GWh in 2041. The commercial sector incorporates large electric appliances, so it contributes 12% to the overall electricity consumption. The baseline consumption was found to be between 1.3 and 1.4 million GWh between 2011 and 2017 which is projected to increase to 2.0 million GWh in 2041.

The energy demand projection in Figure 6 can be validated by considering other related forecasts in the literature. In particular, Figure S11 shows the forecast by WECS [60], and Figure S12 shows the forecast by NEA [59]. The curves in Figure S11 are parameterized by 3 different GDP growth rates, since it is one of the key factors affecting the future energy demand. Comparing our forecasts in Figure 6 for the GDP growth rate 4.3% with the forecasts in Figure S11 and S12 shows that our energy demand forecast is somewhat optimistic. One reason is that our assumed GDP value is smaller, and our forecast is for a benign BaU scenario.

It should be noted that the data used to set up the LEAP model came from different sources. Thefore, these data were obtained using different measurement campaigns and procedures with different assumptions. More careful analysis and pre-processing of the data which are used as the input to the LEAP model would be required, since comparing different energy models is only possible by assuming some common economic model or another common reference.

5. The way forward

The long-term impacts of energy supplies on the economic performance and the country's developments are severe. Recently, the state-controlled NEA started to improve the dismal energy situation by adopting series policy and technological measures. The previously poor performance of NEA contributed to the rise of the IPPs which altered the energy markets in the country. The power supplied by the IPPs reached 80% of electricity levels imported from India annually. The current problems in Nepal's energy sector are summarized in Figure 7. Diversification and increasing electricity production are two crucial conditions for improving the country's socio-economic development. There are many great opportunities to invest in the development and deployment of renewable energy technologies in Nepal. However, it is essential to understand how these investments in small and large renewable energy projects would affect the energy-dependent economy of Nepal, and how to establish the right mix of different renewable energy sources in order to satisfy the needs of industry and the society. Locally, smaller-scale renewable energy sources can be utilized to promote economic activity and the lifestyle of communities in remote areas. At the same time, large hydro projects are necessary to safeguard industrial and agricultural production in the long run.



	2011-12	2016-17	2021-22	2026-27	2031-32	2036-37	2041-42
Residential	5116.500	5578.400	6119.600	6607.933	7131.511	7631.593	8147.338
Industrial	4046.160	4411.460	4839.410	5225.593	5639.621	6035.086	6442.926
Transport	23.360	25.830	28.600	31.170	33.873	36.488	39.161
Commercial	1283.940	1390.440	1515.720	1628.480	1749.587	1865.129	1984.381
Agriculture	232.480	254.140	278.220	300.687	324.229	347.054	370.357
Total	**10702.44**	**11660.27**	**12781.55**	**13793.863**	**14878.82**	**15915.36**	**16984.16**

Figure 6 The sector-wise projected electricity demands until FY 2041/42 using the LEAP software energy modeling.

The current level of energy consumption in Nepal with poor harnessing of its renewable resources and increasing dependence on imported fossil fuels is unsustainable. The electrification rate of Nepal remains to be one of the lowest among the developing countries. Since the development of power grids and power stations is hugely capitally intensive, substantial funding and the proper technical expertise from both the private and public sectors are required. This may require to dramatically restructure the public investment programs, intensify the level of competition in domestic markets especially in transport, logistics, and telecommunication sectors, and reduce the cost of doing business while opening and steadily integrating the national economy into the global markets [28]. Large investments are also needed to modernize the electricity infrastructure, mitigate the T&D losses, monitor and improve energy efficiency, and to raise the overall industrial production. The plans for tackling Nepal's energy problems are summarized in Figure 8. Other short-term and long-term economic policies to stimulate economic development in developing countries are discussed in [101] and summarized in Table S12. Nepal can be considered under all 4 scenarios outlined in Table S12.

Nepal is preparing for a major socio-economic transformation towards the sustainable development. The transformation success and economic activities are critically dependent on providing sufficient energy supply. The renewable energy sources abundantly present in Nepal are naturally the key potential solution to the present energy crisis. However, creating the right energy mix for Nepal is still subject to debate. It is clear that hydropower plants will likely remain the dominant source of electricity. The existing run-of-river hydropower systems may be improved by also considering the peak-run-of-river and the reservoir type plants. The use of PV rooftop panels and wind turbines is economical, provided that the required load is less than 75 kWh/day, and the load point is more than 50 km away from the national grid. Pumped hydro storage systems can be a good solution for the peak-hour load management and for leveling the electricity demand more evenly over the course of the day. The development of hydropower-based electricity storage systems can significantly reduce the seasonal dependency for the flow-of-river type hydropower plants. It is imperative that energy consumption and energy efficiency are monitored at different scales, preferably in real-time to minimize the currently massive energy losses. It would be also instrumental to periodically report the energy-related data which can be subjected to international auditing.

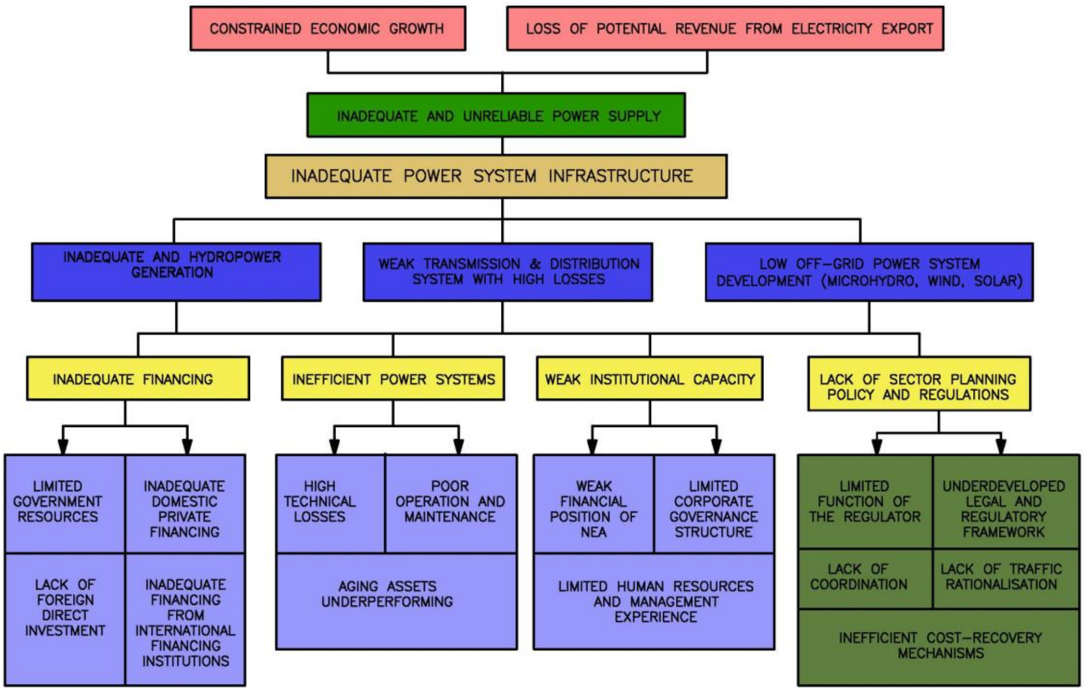


Figure 7 The summary of challenges in the energy sector of today's Nepal [152].

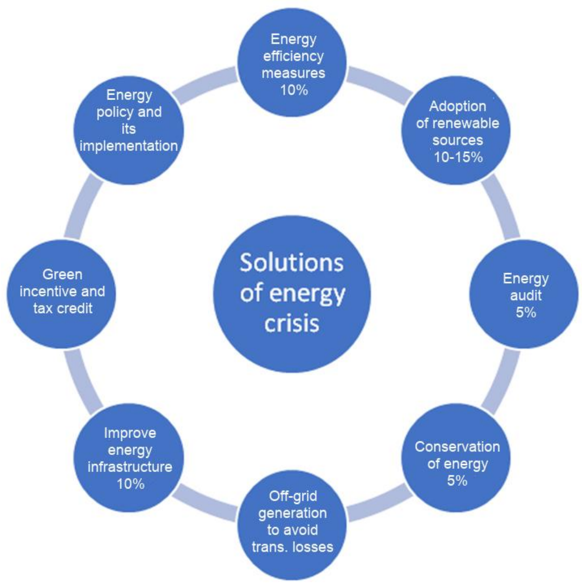


Figure 8 General strategies for solving the energy crisis in developing countries.

Our study was motivated by the lack of comprehensive reports on the current energy situation in Nepal involving up-to-date data about the energy consumption and production and energy pricing trends which would account for the significant recent developments in the development of renewable energy technologies. Understanding the current energy situation in Nepal is the first key step towards tackling its energy crisis. However, the ultimate goal is to eradicate, not just mitigate the energy crisis. It is only when the energy demands are met that substantial economic and social developments in Nepal can be expected. At present, there seem to be no signs of relief while the national economy is also suffering from other issues including political instability, corruption, and a large trade deficit. Nepal has to stimulate the deployment of advanced technologies for exploiting its immense renewable energy resources, in addition to adopting the relevant energy policies. There is an urgent need to increase the generation and distribution capacity and to improve energy utilization to reduce the dependency on the energy imports. Introducing the energy efficiency measures in industries and upgrading the production infrastructure can assist in curtailing the huge system-level energy losses. Nepal should follow the international trend of creating the energy mix to build up its power systems rather than focusing only on large hydropower projects as is happening at present. In order to meet the required level of investments, various innovative policies have to be adopted to stimulate also involvement of the private sector. Such investment policies in energy may involve tax exemptions, and other risk-mitigating measures including elimination of administrative hurdles. The central bank of Nepal has political and economic power to encourage the domestic and foreign investments into the energy infrastructure. Another viable strategy is to promote closer collaboration with other countries in the South-East Asian region to jointly develop systemic solutions which are not limited by the national borders. The energy demand forecasting is mandatory for developing the informed and forward-looking solutions. Our energy demand projection over 30 years was based on the somewhat optimistic BaU scenario, so it likely underestimates the actual energy demands in the future. Considering alternative economic scenarios can provide more reliable forecasts. As more relevant data become available, more sophisticated energy models and predictive tools can be implemented which is the avenue for our future research.

Acknowledgement

Figure 7 was reused from the Asian Development Bank. 2013. Country Partnership Strategy, Nepal 2013-2017. Manila: ADB. © ADB. https://www.adb.org/sites/default/files/publication/356466/nepal-energy-assessment-road-map.pdf CC-BY 3.0 IGO.

References

[1] Zafar R, Mahmood A, Razzaq S, Ali W, Naeem U, Shehzad K.Prosumer based energy management and sharing in smart grid. Renew Sustain Energy Rev 2018;82:1675–84. doi:10.1016/J.RSER.2017.07.018

[2] The World Bank. Annual Report. 2013. Washington, DC: World Bank. doi: 10.1596/978-0-8213-9937-8

[3] Harris JM, Roach B, Codur AM. The Economics of Global Climate Change. Global Development and Environment Institute, Tufts University 2017; 70 pp.

[4] UN General Assembly, Transforming our world: the 2030 Agenda for Sustainable Development, 21 October 2015, A/RES/70/1, available at https://www.refworld.org/docid/57b6e3e44.html [accessed 18 November 2018].

[5] United Nations Department of Economic and Social Affairs. UNDESA. SDGs & Topics. Sustainable Development Knowledge Platform. United Nations Dep Econ Soc Aff 2015. https://sustainabledevelopment.un.org/topics/; 2015 [accessed 18 November 2018].

[6] International Energy Agency and OECD. OECD Green Growth Studies: Energy. 2011; 106 pp.

[7] McLeish E. Energy Crisis (World Issues): A look at the way the world is today. London: Franklin Watts Publishing; 2006.

[8] International Energy Agency. Energy and Air Pollution.World Energy Outlook 2016. Special Report. 2016; 266 pp.

[9] Government of Nepal. Ministry of Finance. Economic Survey. Kathmandu, Nepal. 2015.

[10] Nepal R, Jamasb T. Reforming small electricity systems under political instability: The case of Nepal. Energy Policy 2012;40:242–51. doi:10.1016/j.enpol.2011.09.062

[11] Bhandari B, Lee KT, Lee CS, Song CK, Maskey RK, Ahn SH. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl Energy 2014;133:236–42.

doi:10.1016/j.apenergy.2014.07.033

[12] Tillett A, Locke J, Mencias J. National Energy Policy Framework, "Energy By the People … For the People". Report for Government of Belize 2012; 368 pp.

[13] British Petroleum Plc. BP Energy Outlook. 2017; 104 pp.

[14] International Energy Agency. World Energy Outlook 2016.

15] International Energy Agency. Energy Efficiency Market Report 2016.

[16] Pattanayak P, Panigrahy N, Mishra S. Overcome of energy crisis using hybrid renewable energy sources in India: HOMER application. Proc. IEEE 9th Int. Conf. Intell. Syst. Control, ISCO 2015.

[17] Awan AB, Khan ZA. Recent progress in renewable energy - Remedy of energy crisis in Pakistan. Renew Sustain Energy Rev 2014;33:236–53. doi:10.1016/j.rser.2014.01.089

[18] Ahmed S, Islam MT, Karim MA, Karim NM. Exploitation of renewable energy for sustainable development and overcoming power crisis in Bangladesh. Renew Energy 2014;72:223–35. doi:10.1016/j.renene.2014.07.003

[19] Aliyu AS, Dada JO, Adam IK. Current status and future prospects of renewable energy in Nigeria. Renew Sustain Energy Rev 2015;48:336–46. doi:10.1016/j.rser.2015.03.098

[20] Gurung A, Ghimeray KA, Hassan SHA. The prospects of renewable energy technologies for rural electrification: A review from Nepal 2011. doi:10.1016/j.enpol.2011.10.022

[21] Parajuli R, Østergaard PA, Dalgaard T, Pokharel GR. Energy consumption projection of Nepal: An econometric approach. Renew Energy 2014;63:432–44. doi:10.1016/j.renene.2013.09.048

[22] Surendra KC, Khanal SK, Shrestha P, Lamsal B. Current status of renewable energy in Nepal: Opportunities and challenges. Renew Sustain Energy Rev 2011;15:4107–17. doi:10.1016/J.RSER.2011.07.022

[23] Chauhan A, Saini RP. A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. Renew Sustain Energy Rev 2014;38:99–120. doi:10.1016/j.rser.2014.05.079

[24] Jha DK, Shrestha R. Measuring Efficiency of Hydropower Plants in Nepal Using Data Envelopment Analysis. IEEE Trans Power Syst 2006;21:1502–11. doi:10.1109/TPWRS.2006.881152

[25] Poudel RC. Quantitative decision parameters of rural electrification planning: A review based on a pilot project in rural Nepal. Renew Sustain Energy Rev 2013;25:291–300. doi:10.1016/j.rser.2013.04.032

[26] Nepal R. The roles and potentials of renewable energy in less-developed economies. Renew Sustain Energy Rev 2012;16:2200–2206. doi:10.1016/j.rser.2012.01.047

[27] Government of Nepal. Study of climate and climatic variation over Nepal. Nepal Hydrological and Meteorological Research Centre and Consultancy Pvt. Ltd. 2015; 41 pp.

[28] Cosic, D., Dahal, S., and M. Kitzmuller. 2017. Climbing Higher: Toward a Middle-Income Nepal. Country Economic Memorandum. Washington, DC: World Bank.

[29] Government of Nepal. Ministry of Finance. Economic Survey. Kathmandu, Nepal. 2016.

[30] World Bank. 2018. Nepal - Systematic country diagnostic (English). Washington, D.C.: World Bank Group.

[31] IEA Atlas of Energy 2016. International Energy Agency, http://energyatlas.iea.org/#!/tellmap/-1118783123/1 [accessed 18 November 2018].

[32] Government of Nepal. Ministry of Industry, Commerce & Supplies. Special Economic Zone Authority, https://www.seznepal.gov.np/; 2013 [accessed 18 November 2018].

[33] Alam F, Alam Q, Reza S, Khurshid-Ul-Alam SM, Saleque K, Chowdhury H. A Review of Hydropower Projects in Nepal. Energy Procedia 2017;110:581-5. doi:10.1016/j.egypro.2017.03.188

[34] Central Intelligence Agency. The World Fact Book, https://www.cia.gov/library/publications/resources/the-

world-factbook/geos/ma.html; 2011 [accessed 18 November 2018].

[35] United Nation Development Programme. Human Development Report 2015: Work for human development, 2015; 288 pp.

[36] Alex Z, McKay Kimber H, Komp R. Renewable Energy Village Power Systems for Remote and Impoverished Himalayan Villages in Nepal. Proc Int Conf Renew Energy Dev Countries 2006:34.

[37] United Nations Development Programme. Nepal Country Report. Global Assessment of Risk. 2009; 210 pp.

[38] Sharma RD. Nepal needs Rs73b for flood recovery. The Kathmandu Post, https://kathmandupost.com/money/2017/11/12/nepal-needs-rs73b-for-flood-recovery/; 2017 [accessed 18 November 2018].

[39] The World Bank. World Development Indicators, http://data.worldbank.org/data-catalog/world-development-indicators/; 2016 [accessed 18 November 2018].

[40] The World Bank. Electric power consumption (kWh per capita), http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC; 2014 [accessed 25 August 2017].

[41] Nakarmi AM. Current energy consumption trends & future energy scenarios of Nepal. IPPAN Seminar, Hotel Yak &Yeti, 2016.

[42] Karki NR, Jha DK, Verma AK. Rural energy security utilizing renewable energy sources: Challenges and opportunities. Proc. IEEE TENCON; 2010, p. 551–6.

[43] Nepal Oil Corporation, http://www.nepaloil.com.np/; 2018 [accessed 18 November 2018].

[44] Government of Nepal. Ministry of Finance. Nepal Portfolio Performance Review (NPPR). 2015; 115 pp.

[45] Khanal R. Storage tanks, pipelines estimated to cost Rs 41b. The Kathmandu Post, https://tankterminals.com/news/storage-tanks-pipelines-estimated-to-cost-rs-41b/; 29 April 2019 [accessed 20 July 2019].

[46] Nepal Oil Corporation Limited. Nepal Monetary Solutions, https://nepalmonetarysolutions.blogspot.com/2015/09/nepal-oil-corporation-limited-noc.html; 2018 [accessed 18 November 2018].

[47] Sharma, MM; Shrestha S. Anti-Competitive Practices in Nepal’s Petroleum Sector. South Asia Watch on Trade, Economic and Environment; 2007.

[48] Timilsina P. Prioritise smooth supply of petroleum products. The Himalayan Times, https://thehimalayantimes.com/business/perspectives/prioritise-smooth-supply-petroleum-products/; 21 May 2017 [accessed 20 July 2019].

[49] Ljung P. Energy Sector Reform: Strategies for Growth, Equity and Sustainability.Sida studies no. 20, 2007; 192 pp.

[50] Nepal Electricity Authority. Annual Report. A Year in Review, Fiscal Year 2016/17, August 2017; 176 pp.

[51] Centre for Rural Technology, Nepal (CRT/N). Annual Report 2016/17, 2017; 40 pp.

[52] Government of Nepal. Economic Survey. Ministry of Finance. Kathmandu, Nepal. 2017.

[53] Nepal Oil Corporation Limited. Selling Price Archive, http://www.nepaloil.com.np/selling-price-archive-16.html; 2017 [accessed 24 November 2017].

[54] Yale Environmental Performance Index, University of Yale, https://epi.envirocenter.yale.edu/; 2018. [accessed 18 November 2018].

[55] United States Agency for International Development.USAID-SARI/Energy Program. Economic Impact of Poor Power Quality on Industry, Nepal, 2003; 64 pp.

[56] United States Agency for International Development.USAID-SARI/Energy Integration Program, Nepal, Energy

Sector Overview, https://sari-energy.org/oldsite/PageFiles/Countries/Nepal_Energy_detail.html; 2016 [accessed 20 October 2017].

[57] Nepal Electricity Authority. System Planning Department, Load Forecast Report, 2015; 17 pp.

[58] Government of Nepal. Water and Energy Commission Secretariat. Energy Sector Sypnosis Report, July 2010; 116 pp.

[59] Nepal Electricity Authority. Annual Report. A Year in Review, Fiscal Year 2015/16, August 2016.

[60] Government of Nepal. Water and Energy Commission Secretariat. Electricity Demand Forecast Report (2015-2040), 2017; 23pp.

[61] Williams JL, Alhajji AF. The coming energy crisis. Oil Gas J 2003:1–8.

[62] Stiftung KA. Energy and Environmental Security, A Cooperative Approach in South Asia, Institute of Conflict and Piece Studies, 2010; 8 pp.

[63] Krishna, KS, Kumar, KS. A review of hybrid renewable energy systems. Renew Sustain Energy Rev 2015;52:907–16. doi:10.1016/j.rser.2015.07.187

[64] Government of Nepal. Department of Electricity Development, Ministry of Energy. Guidelines for Power System Optimization of Hydropower Projects, December 2015; 328 pp.

[65] The World Bank. Electric power transmission and distribution losses (% of output), http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS; 2014. [accessed 25 August, 2017].

[66] Nepal Energy Forum. Ministry of Energy to Involve Private Sector in Transmission Lines Project. http://www.nepalenergyforum.com/ministry-of-energy-to-involve-private-sector-in-transmission-lines-project/; 1 September 2017 [accessed 18 November 2018].

[67] Joshi S, Shrestha R. Performance Evaluation of Runoff River Type Hydropower Plants Operating in Nepal: A Case Study of Nepal Electricity Authority. J Inst Eng 2014;10:104–20.

[68] Government, Nepal. Nepal the Fifth Plan (1975-80) in Brief. National Planning Commission, 1975; 68 pp.

[69] Transparency International. Corruption in 2017. http://www.transparency.org.uk/corruption-in-2017/; 20 December 2016 [accessed 11 October 2017].

[70] Nepal R. Roles and potentials of renewable energy in less-developed economies: The case of Nepal. Renew Sustain Energy Rev 2012;16:2200–6. doi:10.1016/j.rser.2012.01.047

[71] Mainali B, Silveira S. Financing off-grid rural electrification: Country case Nepal. Energy 2011;36:2194–201. doi:10.1016/j.energy.2010.07.004

[72] Nepal R, Jamasb T. Reforming Small Power Systems under Political Volatility: The Case of Nepal 2012;40:242-1. doi:10.1016/j.enpol.2011.09.062

[73] International Economy and Development. NEA Transforms Power Sector, http://www.jineeen.com/nea-transforms-power-sector/; 8 November 2017 [accessed 18 November 2018].

[74] Basu N. What the India-China Doklam Standoff Means for Nepal. The Diplomat, https://thediplomat.com/2017/07/what-the-india-china-doklam-standoff-means-for-nepal/; 19 July 2017 [accessed 18 November 2018].

[75] Crow B, Singh N. The Management of International Rivers as Demands Grow and Supplies Tighten: India, China, Nepal, Pakistan, Bangladesh. India Rev 2009;8:306–39. doi:10.1080/14736480903116826

[76] Pandey P. Trilateral Naval Exercise Concludes Amid India-China Standoff. The Diplomat, https://thediplomat.com/2017/07/malabar-2017-trilateral-naval-exercise-concludes-amid-india-china-standoff/; 19 July 2017 [accessed 18 November 2018].

[77] Lakshmi R. Nepal is angry with India, so it turns off the TV. The Washington Post,

https://www.washingtonpost.com/news/worldviews/wp/2015/09/29/nepal-is-angry-with-india-so-it-turns-off-the-tv/; 29 September 2015 [accessed 18 November 2018].

[78] Acharya M, Phuyal S, Dhakal S. Nepal blockade: Six ways it affects the country. BBC News,https://www.bbc.com/news/world-asia-35041366/; 12 December 2015 [accessed 18 November 2018].

[79] Bhusal BK, Scaling-Up Renewable Energy Program (SREP) Investment Plan for Nepal. Case Study, Green Growth. March 2013; 3 pp.

[80] Government of Nepal. Office of the Investment Board. Nepal Investment Guide, 2018, 2018; 44 pp.

[81] Bhattacharyya, SC. Financing energy access and off-grid electrification: A review of status, options and challenges. Renew Sustain Energy Rev 2013;20. doi:10.1016/j.rser.2012.12.008

[82] Chang MK, Eichman JD, Mueller F, Samuelsen S. Buffering intermittent renewable power with hydroelectric generation: A case study in California. Appl Energy 2013;112:1–11. doi:10.1016/j.apenergy.2013.04.092

[83] Bhandari B, Lee KT, Lee CS, Song CK, Maskey RK, Ahn SH. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl Energy 2014;133:236–42. doi:10.1016/j.apenergy.2014.07.033

[84] Jha SK, Stoa P, Uhlen K. Microgrid: Prospects and challenges in Nepal. Proc. IEEE Power and Energy Systems: Towards Sustainable Energy, 2014; p. 1–6.

[85] Proietti S, Sdringola P, Castellani F, Astolfi D, Vuillermoz E. On the contribution of renewable energies for feeding a high altitude Smart Mini-Grid. Appl Energy 2017. doi:10.1016/j.apenergy.2015.12.056

[86] Phadke A, Jacobson A, Park WY, Lee GR, Alstone P, Khare A. Powering a Home with Just 25 Watts of Solar PV: Super-Efficient Appliances Can Enable Expanded Off-Grid Energy Service Using Small Solar Power Systems. EO Lawrence Berkeley National Laboratory, April 2015; 26 pp.

[87] Yadoo A, Cruickshank H. The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. Energy Policy, 2012. doi:10.1016/j.enpol.2011.12.029

[88] International Renewable Energy Agency. Policies and Regulations for Private Sector Renewable Energy Mini-grids. September 2016; 112 pp.

[89] Nepal Policy Research Network, http://www.nepalpolicynet.com/; 2016 [accessed 18 November 2018].

[90] Rai N et al. Policies to spur energy access: volume 2. Case studies of public-private models to finance decentralized electricity access. Technical Report NREL/TP-7A40-64460 2015;107 pp.

[91] Dhakal S, Srivastava L, Sharma B, Palit D, Mainali B, Nepal R, et al. Meeting Future Energy Needs in the Hindu Kush Himalaya. Hindu Kush Himalaya Assess., Cham: Springer International Publishing; 2019, p. 167–207. doi:10.1007/978-3-319-92288-1_6

[92] Sangroula, DP. Hydropower Development and Its Sustainability Concerning Sedimentation in Nepal. J Inst Eng 2009;7:1–9. doi:10.3126/jie.v7i1.2063

[93] The World Bank. Alternative Energy Promotion Centre. Renewable Energy Capacity Needs Assessment - Nepal. Final Report. 2016.

[94] Surendra KC, Khanal SK, Shrestha P, Lamsal B. Current status of renewable energy in Nepal: Opportunities and challenges. Renew Sustain Energy Rev 2011;15:4107–17. doi:10.1016/j.rser.2011.07.022

[95] Government of Nepal. Ministry of Finance. Economic Survey 2017. doi:10.1016/B978-1-4160-5198-5.00016-2

[96] Kumar D, Katoch SS. Environmental sustainability of run of the river hydropower projects: A study from the western Himalayan region of India. Renew Energy 2016;93:599–607. doi:10.1016/j.renene.2016.03.032

[97] Baños R, Manzano-Agugliaro F, Montoya FG, Gil C, Alcayde A, Gómez J. Optimization methods applied to

renewable and sustainable energy: A review. Renew Sustain Energy Rev 2011;15:1753–66. doi:10.1016/j.rser.2010.12.008.

[98] Poudyal R, Khadka SK, Loskot P. Understanding Energy Crisis in Nepal: Assessment of the country's Energy Demand and Supply. In Proc. International Electrical Engineering Congress (iEECON), 2017; p. 1-6.

[99] Vidal J. China and India "water grab" dams put ecology of Himalayas in danger. The Guardian, https://www.theguardian.com/global-development/2013/aug/10/china-india-water-grab-dams-himalayas-danger; 2013 [accessed 18 November 2018].

[100] Poudyal R. Balance of power. The Kathmandu Post, https://kathmandupost.com/opinion/2016/03/13/balance-of-power; 13 March 2016 [accessed 18 November 2018].

[101] The World Bank. A Vision for Nepal - Policy Notes for the Government, https://www.worldbank.org/en/news/feature/2014/09/01/a-vision-for-nepal-policy-notes-for-the-government/; 1 September 2014 [accessed 18 November 2018].

[102] Government of Nepal. Ministry of Energy. Sustainable energy - Honorable Minister's (Minister of Energy) translated speech for the Regional Meeting, http://unohrlls.org/custom-content/uploads/2017/03/Minister_speech-Translation.pdf; 22 March 2017 [accessed 18 November 2018].

[103] Mainali B, Silveira S. Alternative pathways for providing access to electricity in developing countries. Renew Energy 2013;57:299–310. doi:10.1016/j.renene.2013.01.057

[104] Subedi B. Power output takes hit as rivers shrink; down 35pc. The Kathmandu Post, https://kathmandupost.com/printedition/news/2017-12-13/power-output-takes-hit-as-rivers-shrink-down-35pc.html; 2017 [accessed 1 December 2017]

[105] The European Commission Directorate. General For Energy. World Energy Scenarios. 2013.

[106] Mohanty S, Patra PK, Sahoo SS, Mohanty A. Forecasting of solar energy with the application for a growing economy like India: Survey and implication. Renew Sustain Energy Rev 2017;78:539–53. doi:10.1016/j.rser.2017.04.107

[107] Panos E, Densing M, Volkart K. Access to electricity in the World Energy Council's global energy scenarios: An outlook for developing regions until 2030. Energy Strategy Rev 2016. doi:10.1016/j.esr.2015.11.003

[108] International Renewable Energy Agency, REthinking Energy 2017: Accelerating the global energy transformation. International Renewable Energy Agency, Abu Dhabi, 2017; 130 pp.

[109] Fu R, Feldman D, Margolis R. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72399, 2018; 63 pp.

[110] Gray J. SunFarmer - Power reliable healthcare with solar energy in rural Nepal, https://www.indiegogo.com/projects/sunfarmer-power-reliable-healthcare-with-solar-energy-in-rural-nepal/; 2016 [accessed 14 December 2017].

[111] Adhikari KR, Bhattarai BK, Gurung S. Estimation of Global Solar Radiation for Four Selected Sites in Nepal Using Sunshine Hours, Temperature and Relative Humidity. J Power Energy Eng 2013;1:1–9. doi:10.4236/jpee.2013.13003

[112] Shrestha JN. Application of Clean Energy in Nepal : Prospects and Problems Geography of Nepal 2014.

[113] Nepal R. Roles and potentials of renewable energy in less-developed economies: The case of Nepal. Renew Sustain Energy Rev 2012;16:2200–6. doi:10.1016/j.rser.2012.01.047.

[114] Eltigani D, Masri S. Challenges of integrating renewable energy sources to smart grids: A review. Renew Sustain Energy Rev 2015;52:770–80. doi:10.1016/j.rser.2015.07.140.

[115] World Nuclear Association. Renewable Energy and Electricity, http://www.world-nuclear.org/information-

library/energy-and-the-environment/renewable-energy-and-electricity.aspx; 2018; [accessed 18 November 2018].

[116] International Renewable Energy Agency. Renewable Energy Capacity Statistics 2017.

[117] The World Bank. Global Wind Atlas2019, https://globalwindatlas.info/;2019 [accessed 17 July 2019].

[118] Rai K. Renewable Energy Capacity Needs Assessment- Nepal. Final Report. 2016.

[119] Reddy KN, Bloom D, Kaniz A, Zaidi M. Energy and Social Issues. Energy 2000:40–60. doi:92-1-126126-0.

[120] World Health Organisation. Household air pollution and health. WHO 2018. https://www.who.int/en/news-room/fact-sheets/detail/household-air-pollution-and-health (accessed April 7, 2019).

[121] Amigun B, Von Blottnitz H. Capacity-cost and location-cost analyses for biogas plants in Africa. Resour Conserv Recycl 2010;55:63–73. doi:10.1016/j.resconrec.2010.07.004

[122] Nepal R, Jamasb T, Sen A, Cram L. Small Systems, Big Targets: Power Sector Reforms and Renewable Energy Development in Small Electricity Systems, 2017. https://doi.org/10.17863/CAM.12935

[123] Gautam BR, Li F, Ru G. Assessment of urban roof top solar photovoltaic potential to solve the power shortage problem in Nepal. Energy Build 2015;86:735–44. doi:10.1016/j.enbuild.2014.10.038

[124] Shrestha JN. Application of Clean Energy in Nepal:Prospects and Problems, SAR/StANCE Meeting, Kathmandu, Nepal, 10 November 2014.

[125] Government of Nepal. Hydro-power development policy 2058 (2001), 2001; 35 pp.

[126] Government of Nepal. Ministry of Energy, Water Resources and Irrigation, http://www.moewri.gov.np/en/category/act_and_regulations/; 2018 [accessed 18 November 2018]

[127] Government of Nepal. Water Resources Act 2049 (1992), 1992; 11 pp.

[128] Yasami Y, Dahal GR, Khanal D, Pokharel P. Forest tenure policies in Nepal: Status, gaps and way forward. Food and Agriculture Organization of the UN, 2016; 8 pp.

[129] Government of Nepal. Water and Energy Commission Secretariat 2002.

[130] Government of Nepal. National Water Plan 2005.

[131] Government of Nepal. Water and Energy Commission Secretariat. Energy Sector Synopsis Report, July 2010; 116 pp.

[132] Government of Nepal. Water and Energy Commission Secretariat. Nepal's Energy Sector Vision 2050 A.D., Final Report, November 2013; 149 pp.

[133] Government of Nepal. Water and Energy Commission Secretariat. National Energy Strategy of Nepal 2013. WECS Rep 2013.

[134] Government of Nepal. Ministry of Environment. Rural Energy Policy 2006, November 2006; 11 pp.

[135] Government of Nepal. Ministry of Science, Technology and Environment. Subsidy Policy for Renewable Energy 2069 BS, February 2013; 13 pp.

[136] Government of Nepal. Ministry of Science, Technology and Environment. Alternative Energy Promotion Centre. Renewable Energy Subsidy Delivery Mechanism 2013, June 2013; 55 pp.

[137] Government of Nepal Ministry of Energy. National Energy Crisis Mitigation and Energy Development Decade 2016.

[138] Rai K. Renewable Energy Capacity Needs Assessment- Nepal Conducted for: Alternative Energy Promotion Centre Supported by: The World Bank Final Report. 2016.

[139] Government of Nepal. Sustainable Energy and Technology Management. Publications, http://setmnepal.org/publications.html/; 2015 [accessed 18 November 2018].

[140] Poudyal R. Struggle for power. The Kathmandu Post, http://kathmandupost.ekantipur.com/news/2017-12-07/struggle-for-power.html; 7 December 2017 [accessed 2 January 2018].

[141] Liu Y, Yu S, Zhu Y, Wang D, Liu J. Modeling, planning, application and management of energy systems for isolated areas: A review. Renew Sustain Energy Rev 2018;82:460–70. doi:10.1016/J.RSER.2017.09.063

[142] Zeng YR, Zeng Y, Choi B, Wang L. Multifactor-influenced energy consumption forecasting using an enhanced back-propagation neural network. Energy 2017;127:381–96. doi:10.1016/j.energy.2017.03.094

[143] Sapkota A, Lu Z, Yang H, Wang J. Role of renewable energy technologies in rural communities' adaptation to climate change in Nepal. Renew Energy 2014;68:793–800. doi:10.1016/j.renene.2014.03.003

[144] Suganthi L, Samuel AA. Energy models for demand forecasting - A review. Renew Sustain Energy Rev 2012;16:1223–40. doi:10.1016/j.rser.2011.08.014

[145] Heaps, CG. An introduction to LEAP: Long-range Energy Alternatives Planning System. Stock Environ Inst 2008:16 pp.

[146] Bhattacharyya SC, Timilsina GR. Modelling energy demand of developing countries: Are the specific features adequately captured? Energy Policy 2010;38:1979–90. doi:10.1016/j.enpol.2009.11.079

[147] Government of Nepal. Central Bureau of Statistics. National Population and Housing Census 2011 (National Report), November 2012; 270 pp.

[148] Government of Nepal. Central Bureau of Statistics, http://www.cbs.gov.np/; 2018 [accessed 18 November 2018].

[149] Government of Nepal. Ministry of Energy, http://www.moen.gov.np/; 2018 [accessed 18 November 2018].

[150] Government of Nepal. Ministry of Finance, http://www.mof.gov.np/; 2018 [accessed 18 November 2018].

[151] Government of Nepal. Nepal Oil Corporation. 2017. http://nepaloil.com.np/ (accessed December 14, 2017).

[152] Asian Development Bank. Nepal energy sector assessment, strategy, and road map. 2017;88pp. doi:10.22617/TCS178936-2

Supplementary Figures

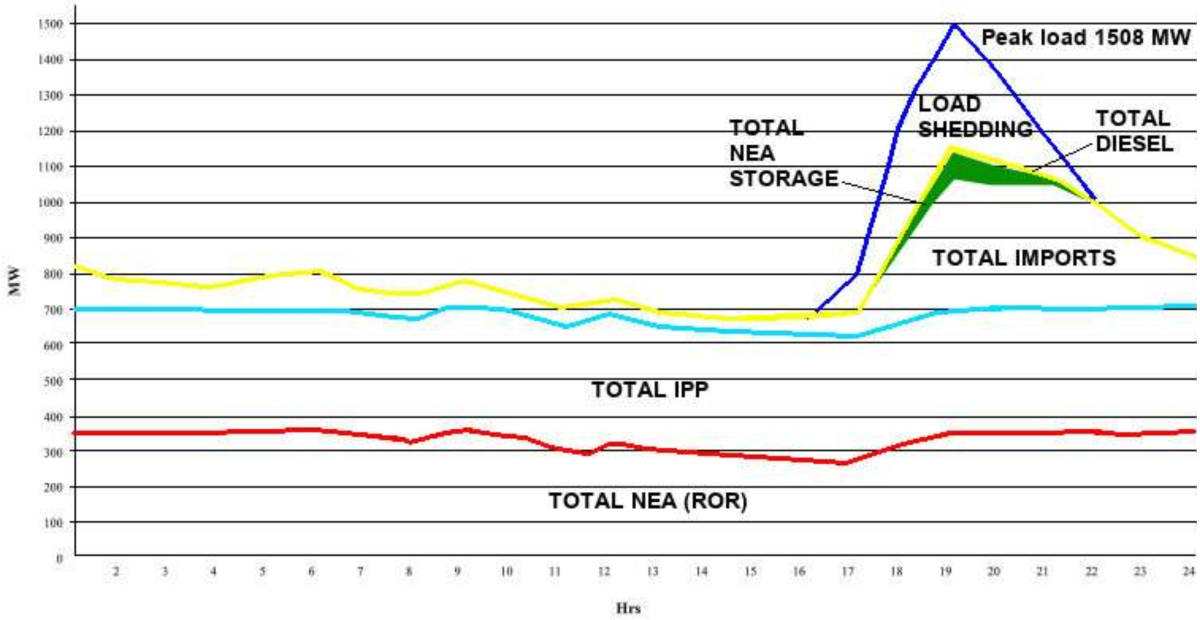


Figure S1 Typical daily power load profile in Nepal with the current peak load of 1,508 MW in 2018 [46]. NEA: Nepal Electricity Authority, IPP: Independent Power Producers, ROR: Rate of Return

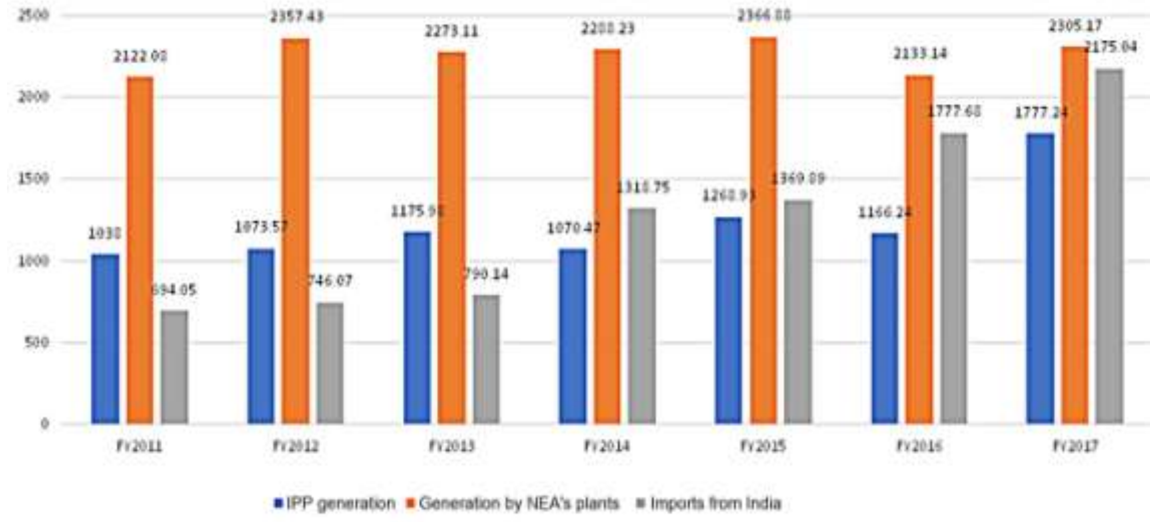


Figure S2 The trend of electricity generation and imports in Nepal over the years 2011 – 2017 (in millions of kWh) [46].

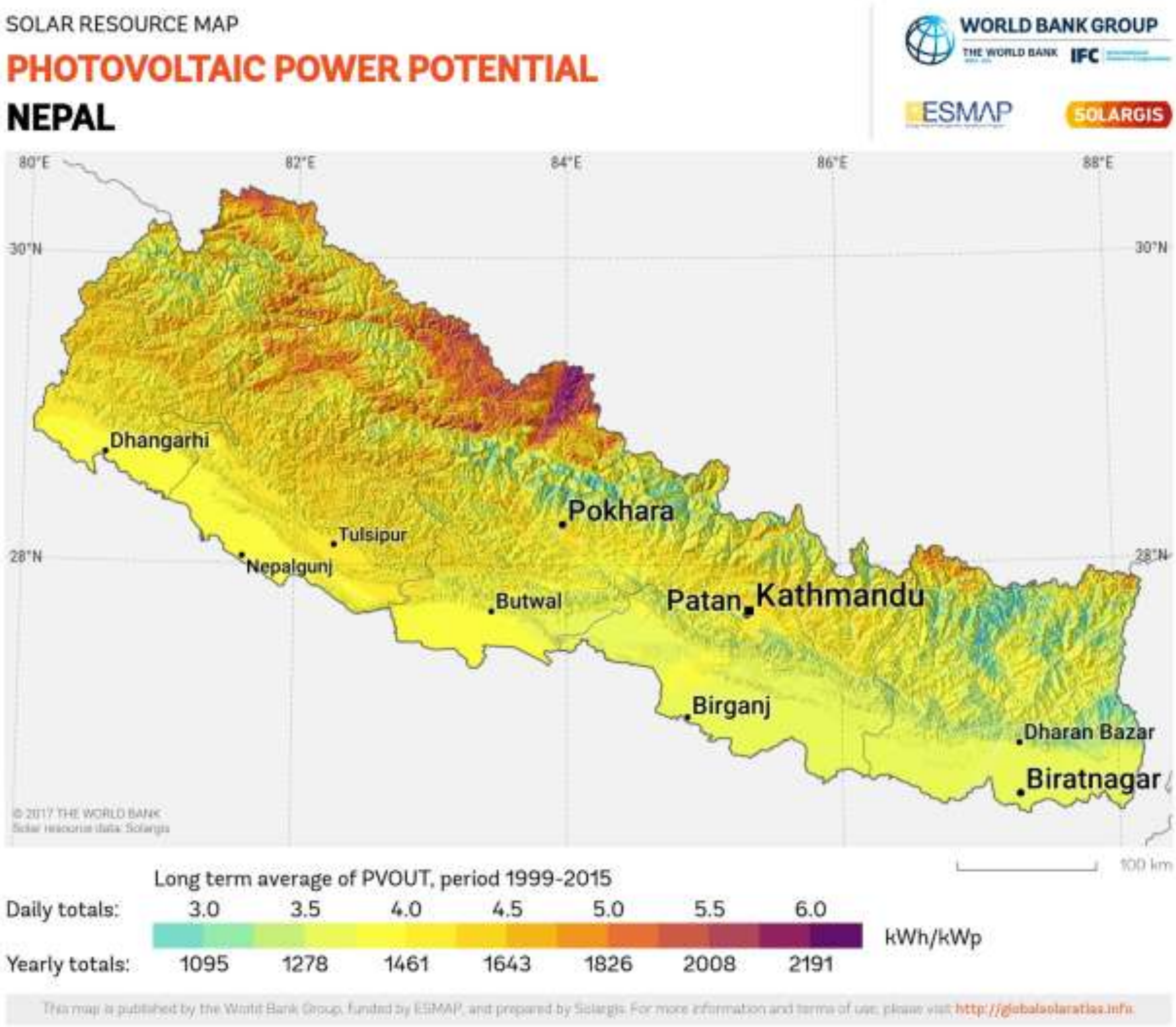


Figure S3 The solar map of Nepal [106].

Acknowledgement: Solar resource data obtained from the Global Solar Atlas, owned by the World Bank Group and provided by Solargis.

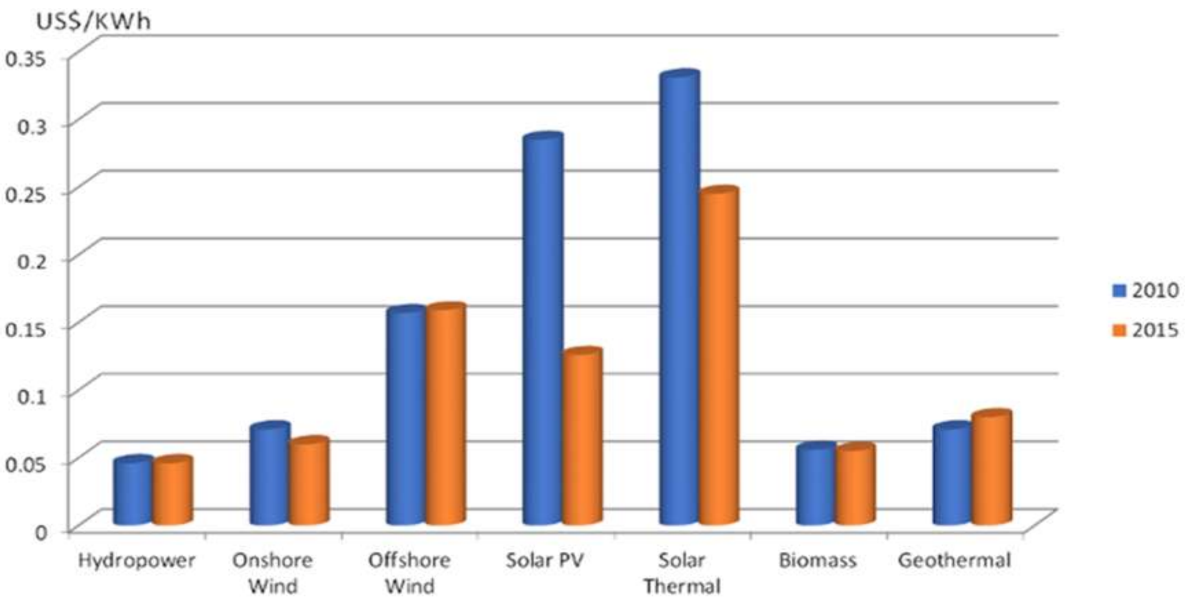


Figure S4 Comparison of the levelized electricity costs from the renewables in 2010 and 2015 [109].

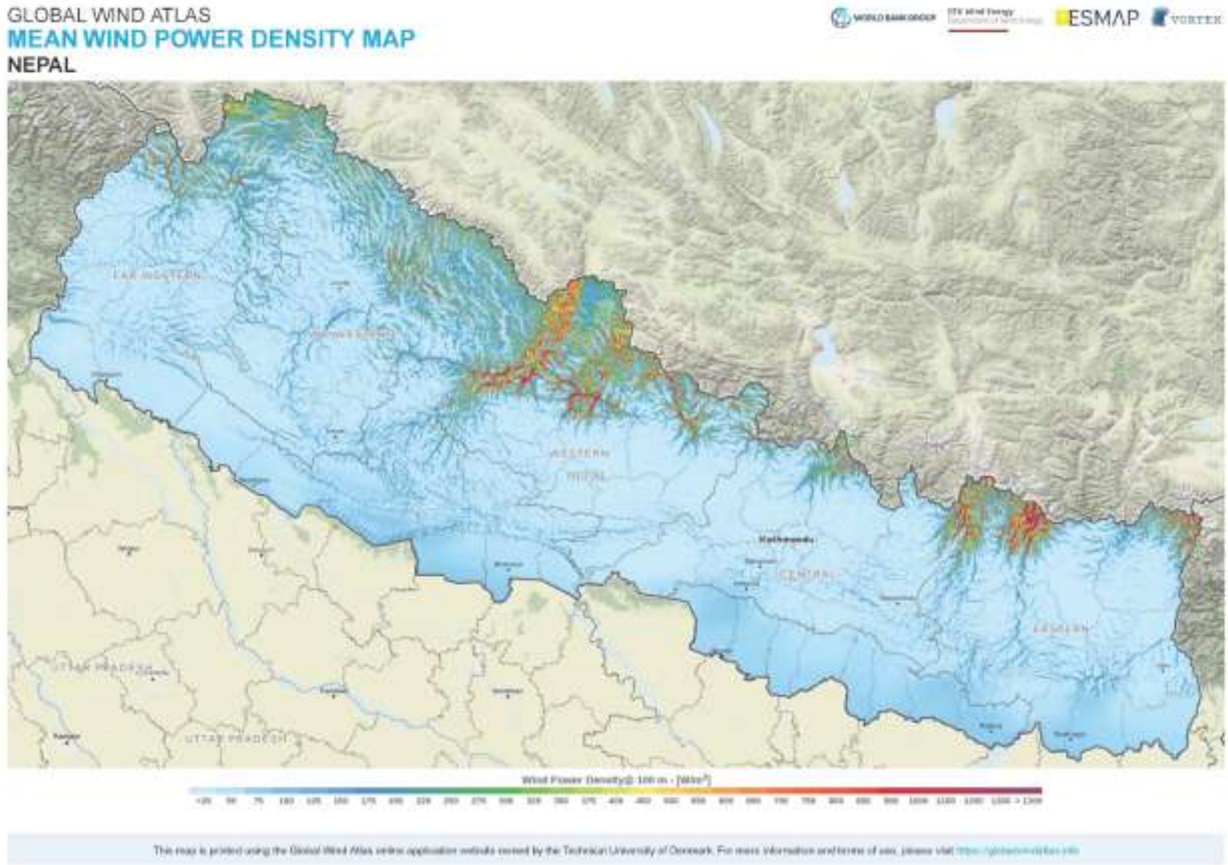
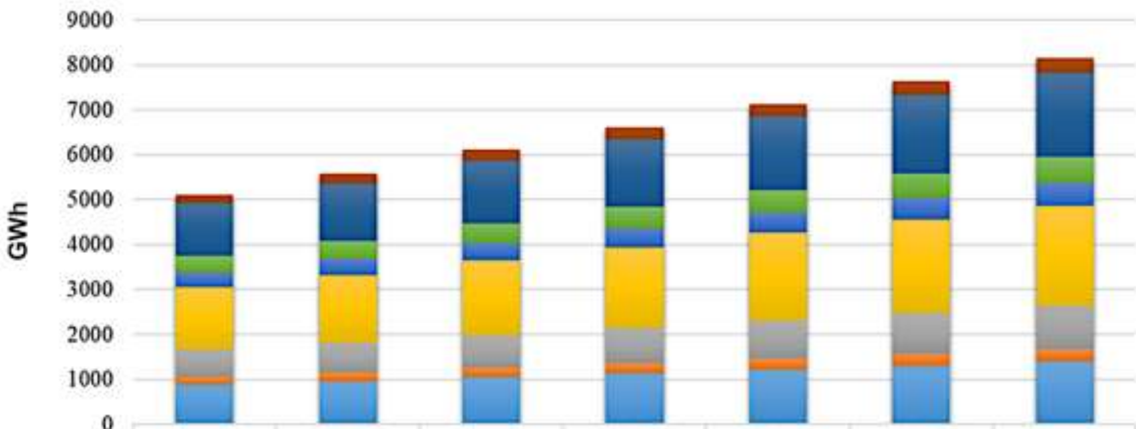


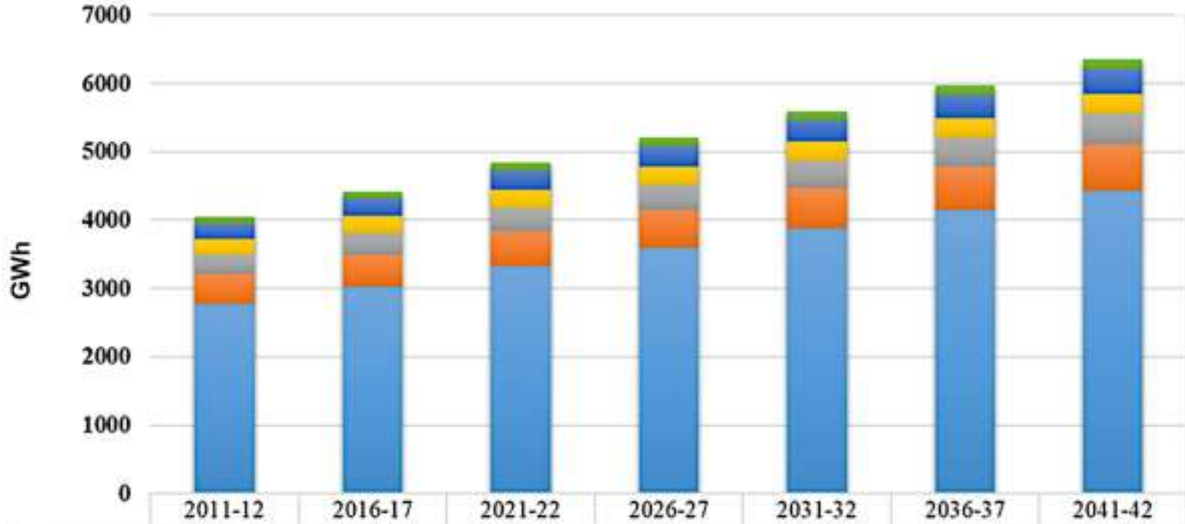
Figure S5 The wind map of Nepal [111].

Acknowledgment: Wind map was obtained from Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info.



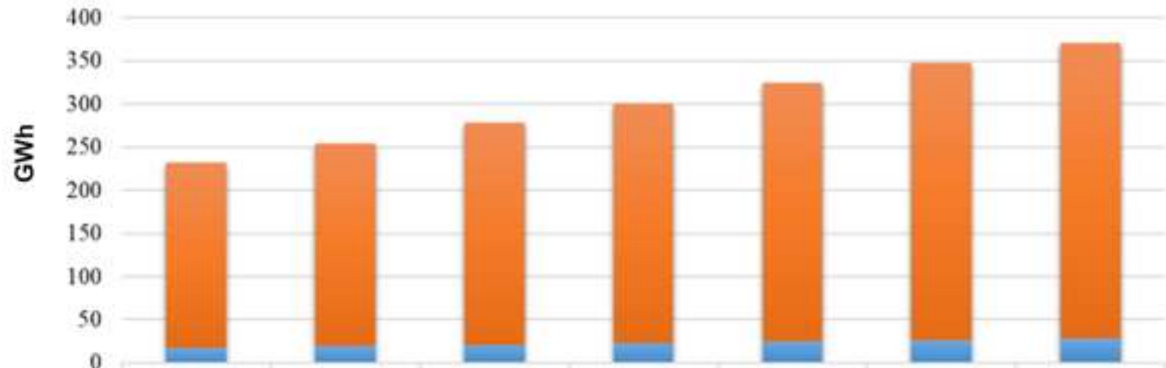
	2011-12	2016-17	2021-22	2026-27	2031-32	2036-37	2041-42
Other Uses	199.200	217.100	238.200	257.167	277.556	296.996	317.069
Electric Appliances	1173.100	1279.100	1403.200	1515.233	1635.311	1750.026	1868.316
Water Pumping	365.000	397.900	436.500	471.300	508.633	544.278	581.048
Water Boiling	326.500	355.900	390.500	421.633	455.078	486.981	519.912
Lighting	1390.700	1516.200	1663.300	1796.000	1938.300	2074.200	2214.367
Cooling	609.400	664.400	728.900	787.067	849.456	909.030	970.480
Heating	174.200	190.000	208.400	225.067	242.889	259.941	277.506
Cooking	878.500	957.800	1050.700	1134.533	1224.411	1310.259	1398.794

Figure S6 The electricity consumption and demand in the residential sector.



	2011-12	2016-17	2021-22	2026-27	2031-32	2036-37	2041-42
Others	91.890	100.190	109.910	118.683	128.088	137.071	146.336
Lighting	232.380	253.360	277.930	300.107	323.879	346.587	370.005
Boiler	228.080	248.670	272.790	272.202	276.320	275.535	276.352
Process Cooling	282.280	307.760	337.620	364.560	393.447	421.036	449.490
Process Heating	432.130	471.150	516.850	558.097	602.312	644.549	688.104
Power Motives	2779.410	3030.340	3324.310	3589.587	3873.992	4145.645	4425.800

Figure S7 The electricity consumption and demand in the industrial sector.



	2011-12	2016-17	2021-22	2026-27	2031-32	2036-37	2041-42
Water Pump	214.630	234.650	256.900	277.663	299.418	320.511	342.046
Thresher	17.850	19.490	21.320	23.023	24.811	26.543	28.312

Figure S8 The electricity consumption and demand in the agriculture sector.

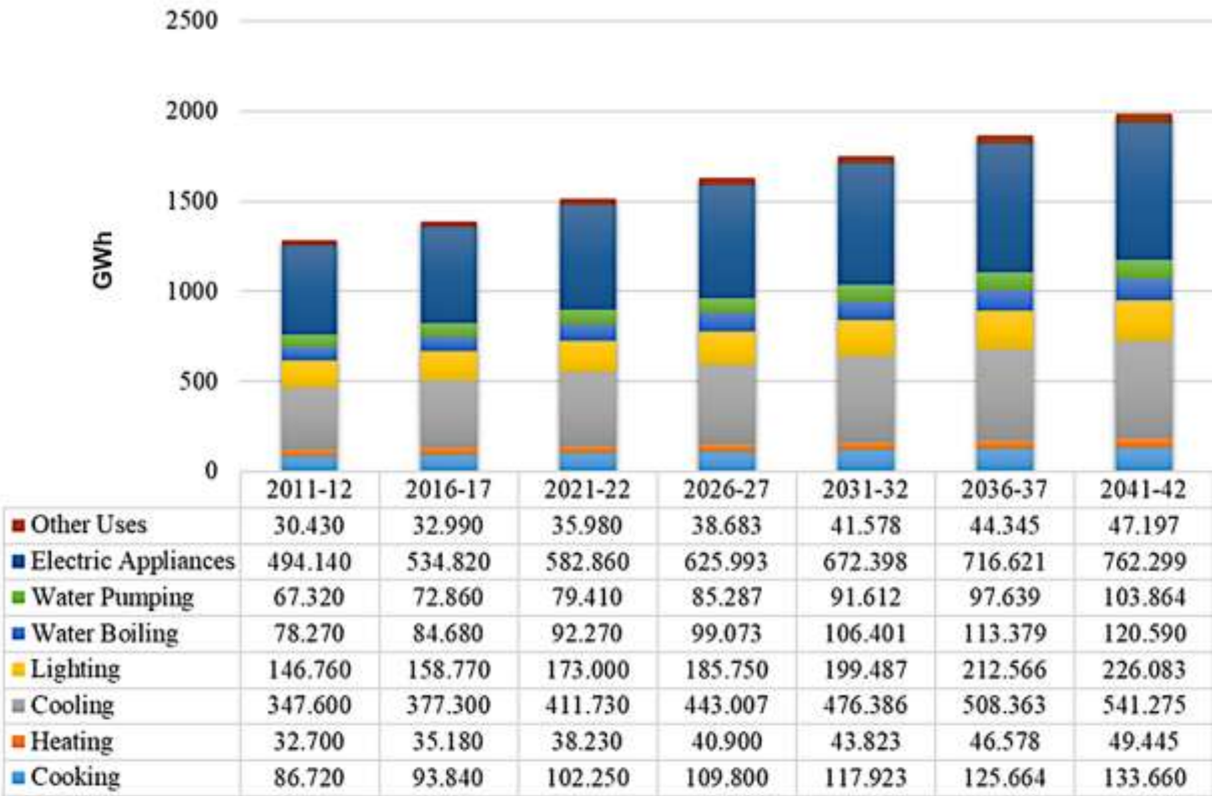


Figure S9 The electricity consumption and demand in the commercial sector.

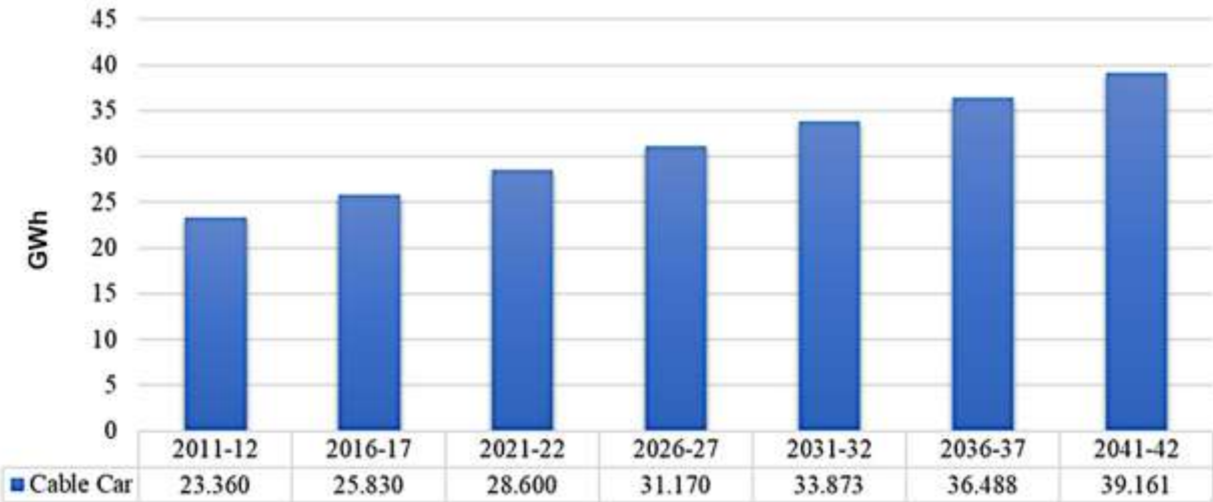


Figure S10 The electricity consumption and demand in the transportation sector.

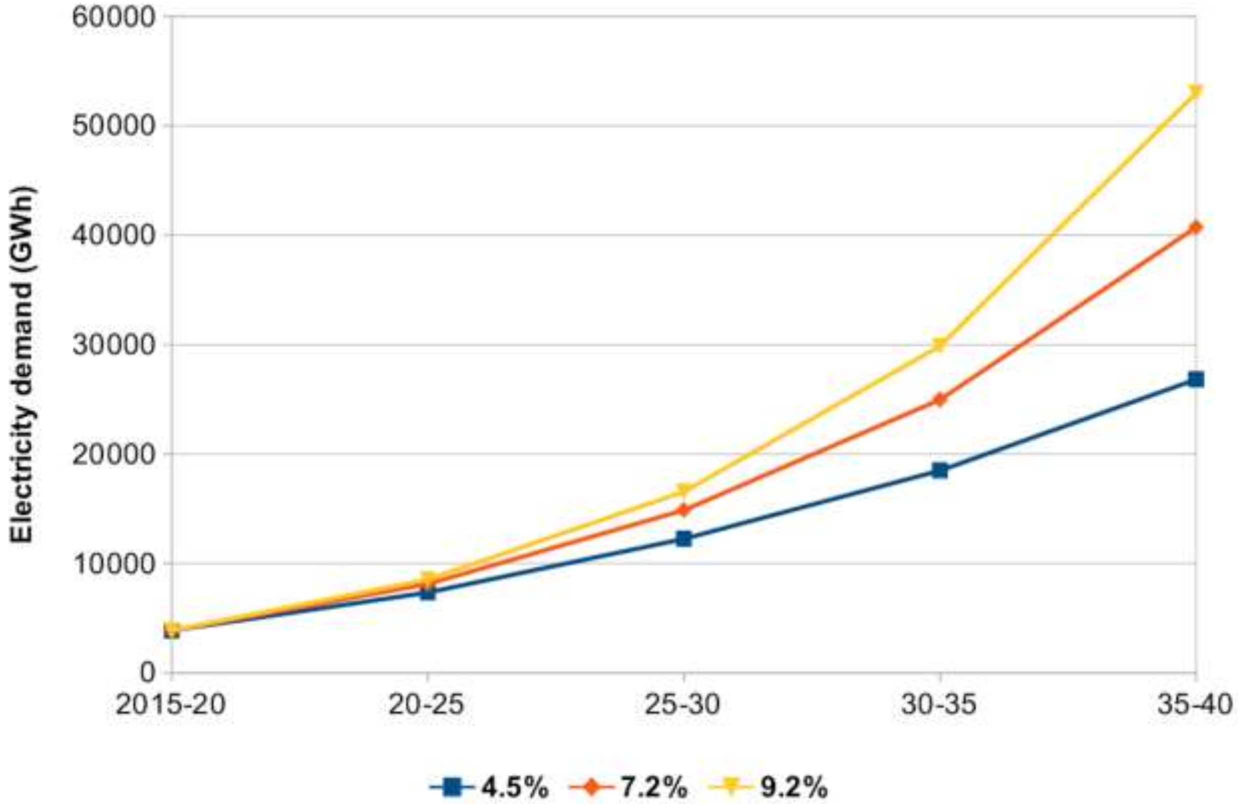


Figure S11 The overall projected electricity demand in Nepal by WECS assuming 3 different GDP growth models [57].

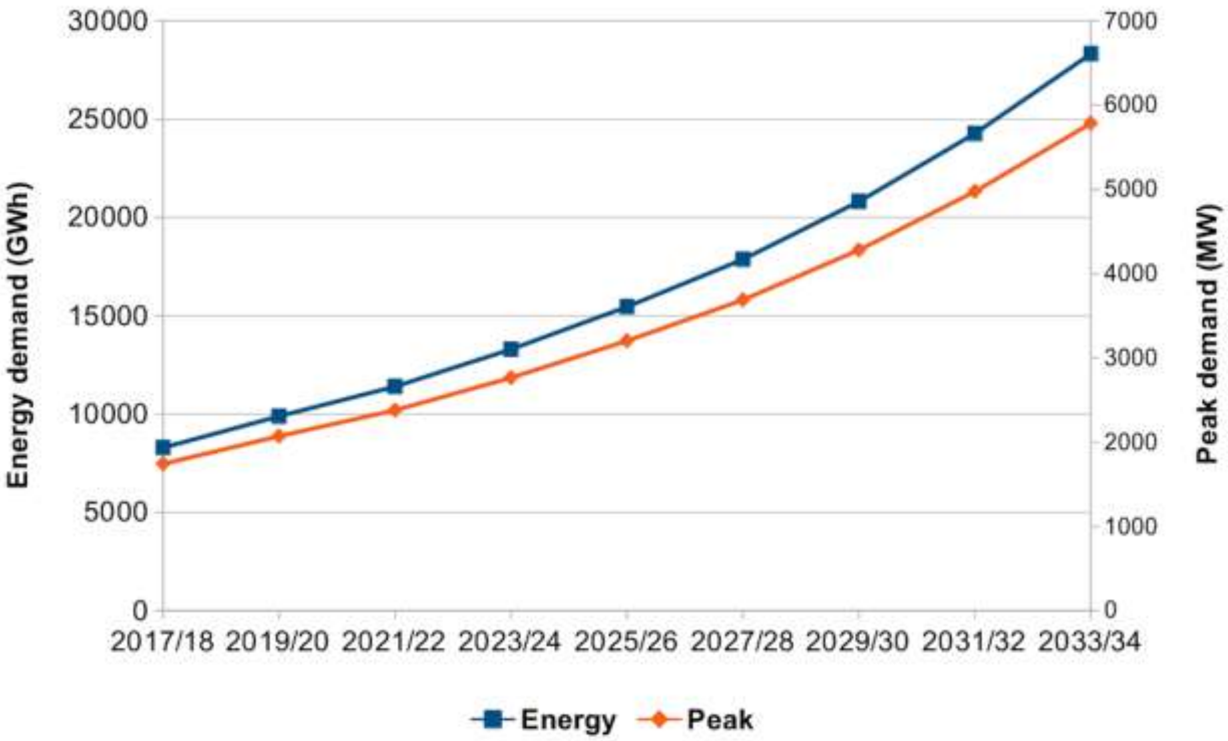


Figure S12 The long-term projected energy and peak demands in Nepal by NEA [56].

Supplementary Tables

Table S1 The13th government plan to increase the energy generation in Nepal [29].

	end 2015	13th Plan targets
Per capita electricity (kWh)	132.65	140
Generation (MW)	829	1,358
Electricity access (%)	61.94	67
Houses (millions)	2.868	3.115
Villages	2,892	3,000
33 kV distribution lines (km)	4,011	4,000
11 kV distribution lines (km)	28,824	25,500
Distribution lines >66 kV (km)	2,848.86	2,958.86

Table S2 The average daily and monthly imports of petroleum products [41].

Product (kt)	2014/15		2015/16	
	Daily Avg.	Monthly Avg.	Daily Avg.	Monthly Avg.
Petrol	794.09	23,822.22	410.08	12,302.50
Diesel	2,553.00	76,590.08	1,270.80	38,124.00
Kerosene	55.01	1,650.42	23.75	712.58
Aviat. fuel	394.82	11,644.67	131.94	3,958.17
Total (excl. LPG)	3,796.92	113,708.00	1,836.57	55,097.25
LPG (Mt)	717.42	21,522.63	365.63	10,960.58

Table S3 The developments of electricity generation and transmission systems in Nepal over the past 5 years [29].

	2012/13	2013/14	2014/15	2015/16	2016/17	2016/17	2017/18
Generation (MW)	746.0	746	829.2	855.9	972.5	961.2	1044.6
Transmission lines (km)	1987.4	1987.4	2848.9	3006	2848.9	3204	3496
Consumers	2,599,152	2,713,804	2,872,015	2,969,576	2,922,041	3,121,902	3,592,187
Distribution lines (km)	114,160.4	116,066.6	123,827.8	124,115	123,827.8	124,976	134,851
Total available (GWh)	4,260.5	3,92.5	4,966.7	5,077.2	4,966.7	3,964.2	4508.9
Peak demand (MW)	1094	1201	1291.1	1385	1291.1	1444.1	1508.2
India imports (GWh)	790.14	1318.75	1369.89	1782.86	2179	1171.4	1814
Demand-supply gap (MW)	348	455	461.9	529.1	461.9	482.9	463.6

Source Ministry of Energy, Water Resources and Irrigation

Table S4 Monthly cooking costs in urban households in Nepal (in NPR) [47].

Year	Kerosene	LPG	Electricity
1997	180	350	605
2000	270	410	680
2003	340	510	790
2012	1640	1030 (with subsidy)	940

Table S5 The development of petroleum product prices in Nepal since 2000 [50].

Year	Petrol NPR/Liter	Diesel NPR/Liter	Kerosene NPR/Liter	Aviat.fuel USD/KL	LPG NPR/Cyl
2000	40	23	13	360	465
2001	46	26.5	17	360	550
2002	52	26.5	17	360	650
2003	54	31	24	360	700
2004	56	35	28	609.27	750
2005	67	46	39	660.12	900
2006	67.25	53.15	47.65	931.83	900
2007	80	56.25	51.2	1180	1100
2008	80.5	68.5	68.5	945	1325
2009	77.5	58	58	750	1125
2010	88	68.5	68.5	945	1325
2011	105	76	76	1215	1325
2012	125	99	99	1250	1470
2013	130	103	103	1300	1470
2014	140	109	109	1400	1470
2015	113.50	90	90	1400	1470
2016	101.50	77.50	77.50	750	1325
2017	100	76	76	750	1350
Rise (%)	250	330.43	584.61	208.33	290.32

Table S6 The economic costs of electricity disruptions as 90% confidence intervals (in US$/KWh) [52].

Industry	Planneddisruptions	Unplanneddisruptions
Food, beverages, and tobacco	(0.00, 0.15)	(0.44, 1.13)
Chemical, petroleum, rubber	(0.00, 0.47)	(0.12, 0.73)
Textile and leather	(0.00, 0.74)	(0.71, 2.78)
Iron and steel	(0.00, 0.24)	(0.46, 2.31)
Hotels	(0.00, 0.24)	(0.00, 0.11)
Non–metallic and minerals	(0.00, 0.16)	(0.00, 0.05)
Miscellaneous	(0.00, 0.16)	(0.10, 0.38)
Industry sectors average	(0.03, 0.25)	(0.35, 0.62)

Table S7 The storage capacity and sales volume of petroleum products in FY 2017/18 [49].

Province	Storage (%)	Sales (%)
1	16.7	16.2
2	32.7	28.1
3	31.9	27.1
4	4.8	4.4
5	10	19.1
6	0.2	0.9
7	3.7	4.2
100% total (in kL)	71,707	1,712,477

Source: Economic survey 2017/18

Table S8 The time and cost overruns of the hydropower and transmission line projects [87].

Project	Capacity	Due	Time overrun (months)	Cost overrun
Kulekhani I	60 MW		21	68– 123.6 mil.US$
Marsyangdi	69 MW		7	17mil.US$
Kali Gandaki – A	144 MW		18	100mil.US$
Middle Marsyangdi	70 MW		48	130mil.US$
Chameliya	30 MW	2011	72	8.5 to 15.6 bil. NPR
Raughat	40 MW	2014	84	827.4 mil. NPR
Upper Trisuli 3 A	60 MW	2013	72	125.8mil. US$
Upper Tamakoshi	456 MW	2017	18	
Khimti – Dhalkebar	220 kV	2015	>120	
Dhalkebar – Muzaffarpur	400 kV		6	

Trisuli 3 A	37MW		26	
Kulekhani III	14 MW	2011	72	4.63 bil. NPR
Chilime	22.1 MW		60	

Table S9 A rooftop solar panel model for a typical household in Kathmandu.

Size of feasible solar plant	3 kWp
Annual values of units generated	4077 KWh
Annual values of solar radiation	5 $KWh/m^2/day$
Capacity utilisation factor	16%
Total cost	330,000 NPR
Cost of electricity saved	4,080 NPR/month
Total payback period of	6 years
Total loan	231,000 NPR @ 10% over 9 years
Calculated returns	5,043 NPR/month

Table S10 The planned hydropower plants and their capacity (in MW) in different provinces of Nepal [90]**.**

Province	In operation	Under construction w/ financial closure	Different stages w/o financial closure	Public-private partnerships (PPP)	Total
1	16 , 97.47	24 , 406.11	24 , 406.11	45 , 1442.23	101, 2132.31
2	-	install solar 3.285	-	18, 61, biomass 21.5	-
3	28, 202.06	35, 1210.16	21, 842.47	32, 607.77	116, 2861.46
4	19, 151.21	26, 362.85	17, 256.22	63, 2603.53	125, 3373.81
5	4, 20.15	4, 9.37	2, 1.56	5, 5.68	15, 36.76
6	1, 3.75	2, 6.35	3, 19.55	4, 613	10, 642.65
7	1, 8.5	6, 76.82	3, 11.23	8, 152.1	18, 248.65
Total	69, 483.14	97, 2,099.94	67, 1537.14	159, 5,524.81	385, 7,163.33

Table S11 The current status of hydropower project certificates and licenses [133–135].

Project type	Number	Capacity(MW)
Running projects with production certificates	84	973.8
Projects under construction with production certificates	168	4620.1
Applying for production license	35	3451.7
Survey licenses issued	288	14370.5
Applying for survey license	16	1531.5
Total	591	24947.6

Table S12 The recommended investment incentives and policies [145].

Scenario	Short – term policy	Long – term policy
Countries with weak investment climate	Investment incentives are ineffective and the waste of tax revenues. The revenues should instead be used to provide public goods. Reforms should be introduced to streamline the taxes.	Such countries should reduce barriers to investment, for example, by simplifying investment procedures
Countries facing tax competition	Incentives can be used in the short term to ensure that the country is not a disadvantage relative to its neighbours.	Such countries should work on regional pacts to stop tax competition and promote their substantive differences (labour skills, infrastructure, and so on).
Countries seeking to diversify their economy	Such countries can use incentives linked to investment growth (investment allowances, accelerated depreciation), but for a limited period based on clear prioritisation of sectors in line with FDI competitiveness.	Broader industrial policy strategies have to be followed, including a focus on sector targeting and promotion to attract investments.
Countries with unique advantage (natural beauty, natural resources)	General investment incentives to attract investments that exploit such advantages waste revenue unless they can start investments.	Barriers should be lowered for investments designed to exploit natural resources, e.g. by improving access to land.