

RESEARCH ARTICLE

Towards energy efficiency and green network infrastructure deployment in Nepal using software defined IPv6 network paradigm

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Abstract

The use of information and communication technology (ICT) has resulted in significant impacts on social welfare, economic growth, transparency, and good governance in developing countries like Nepal. Due to the diverse geographic and economic situations, ICT network and service expansions throughout Nepal have been becoming quite challenging. Private network operators mostly have confined their services to urban areas. Nepal Telecommunications Authority (NTA) collects 2% royalty form Internet Service Providers (ISPs) and Telecom Operators as Rural Telecommunications Disbursement Fund (RTDF) to enhance ICT services to rural Nepal. Broadband expansion projects initiated by utilizing RTDF to expand ICT infrastructure throughout Nepal are expected to have considerable societal and economical transformations in the rural communities of Nepal. This paper not only presents the current ICT deployment scenario of Nepal but also studies design, analysis, and evaluation of green networking that leverages both software defined networking (SDN), and Internet Protocol version 6 (IPv6)—aka Software Defined IPv6 (SoDIP6)—for energy efficient networking, robust services, and sustainable ICT ecosystem for developing nations like Nepal. We evaluate the SoDIP6 network by considering a typical ISP with end access networks and present benefits and recommendations. Experimental results show that the proposed SoDIP6 network help significantly reduce the energy consumption and carbon footprint leading to overall economic benefits to service providers and the society. Furthermore, energy-saving practices through SoDIP6 networks and some policy directions to the government to focus on green networking considering sensitivity of climate change and global warming impact in the mountainous and developing countries like Nepal are presented.

KEYWORDS

energy, green networking, internet service providers, rural ICT, SoDIP6

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1 | INTRODUCTION

This study is mainly driven by the current status of Nepalese information and communication technology (ICT) infrastructure, and network service and connectivity expansion perspectives towards greening of nationwide network infrastructure for sustainability of both service providers and the society. The overall broadband internet penetration rate of Nepal has crossed 50% (as of August 2018). Particularly, there is less than 1% broadband penetration status in rural Nepal. According to statistical Pocket Book (Central Bureau of Statistics, 2016), more than 80% (43 777 722 out of 5 423 297) households (based on usual type of fuel used for cooking) resides in rural Nepal and less than 1% rural households have internet access. These statistics show tremendous opportunities for service providers to expand their services to rural Nepal. The ICT and Broadband Policy 2015 have proposed some ambitious targets (discussed in Section 2 of this paper) regarding ICT penetration in rural Nepal without focusing on green ICT ecosystem. Increase in ICT accessibility comes with deployment of ICT infrastructure, which leads to increase in energy consumption and demand. The exponential growth of the Internet users and the government's proactive plan to expand ICT infrastructure in the rural Nepal should now consider greening of the ICT and networking infrastructure to optimize the increased energy consumption. Among many governing factors highlighted in Figure 1, the ICT, road network (access network), and energy supply are regarded as the three major pillars of successful development of the nations like Nepal.

For developing nations like Nepal, ICT can play a remarkable role in overall development of the country by providing network services for community development, economic growth, improved education, effective natural resource management, good governance, smart agriculture, smart health, and so on. ICT accessible areas like libraries, tele-centers, cyber-cafes, and service centers offer access to ICT services for underserved populations of rural areas. Based on Nepal Telecommunications Authority (NTA)'s report 2018, NTA has collected more than 18 billion Nepalese rupees at its Rural Telecommunications Disbursement Fund (RTDF). This fund has been used for enhancing rural ICT infrastructure and enhancing backbone network for better rural connectivity and services. With the implementation of the new Constitution for political and administrative transformations of Nepal, the newly established government is missioned with economic and social development via inclusiveness, transparency, good governance, smart agriculture, industrialization, and increase productivity by using ICT ecosystem. It is worth noting that Nepal has tackled the major energy issue that is 12 hours of daily load shading or power outage in the recent past (Central Intelligence Agency, 2014) to no daily load shading or power outage. Similarly, education, innovation, research, and development are the major entities to help complete the mission and address the concerns raised in the Sustainable Development Goals (Griggs et al., 2013). Power outage was one of the major hurdles in addition to the typical geographical distribution of the ISPs and Telcom companies of Nepal to expand their network and services to the rural and far rural areas. In the recent years, the demand-based energy utilization and proper management in the energy industry have finally resolved the issues of regular power outage in Nepal. With the regular power supply, ICT connectivity expansion from urban to rural areas is the major mission of the Nepalese government that helps for the good governance and enhances the overall digital ecosystem of Nepal. Energy optimization and ecofriendly green ICT deployment in underserved rural areas is becoming the one of the next milestones for Nepal.

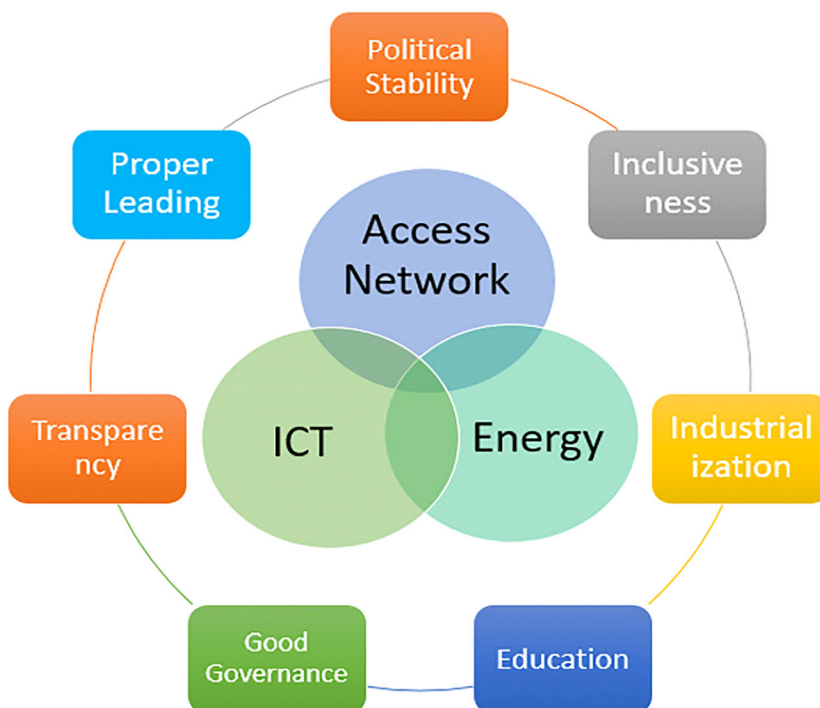


FIGURE 1 Pillars of social development

Green networking mainly deals with the design, development, and deployment of ecofriendly ICT infrastructure that help reduce greenhouse gas (GHG) emission by using energy efficient technologies to power the networking devices, designing energy efficient networks, deploying energy efficient devices (also called green devices), and deploying green routing and switching. Recent studies have identified that adaptive link rate, proxy and caching services, energy-aware ICT infrastructure, and energy-aware applications are the major dimensions of green networking by which energy saving can be achieved (Bianzino, Chaudet, Rossi, & Rougier, 2012). Our research is in the context of network expansion that focuses on the energy-aware ICT infrastructure such as switches and routers, and energy efficient ICT services such as communication links, routing, and switching.

It is estimated that the volume of carbon dioxide (CO₂) emission produced by ICT sector will be at least 2% of total world carbon footprint in 2020 (Maaloul, Chaari, & Cousin, 2018). The total energy consumption ratio by the ICT sector in 2012 was 4.7% of the total worldwide energy consumption (Gelenbe & Caseau, 2015). This is about 530 Mt of CO₂ and about 1.7% of worldwide total amount. The GHG emission as contributed by ICT is forecasted to be 1.3 Gt in 2020. Being a mountainous country, the global warming and climate change effect like rapidly retreating glaciers (average retreat rate of more than 30 M/year), erratic rainfalls and frequent flooding, and severe drought that leads to alarming situations for developing country, Nepal (Karki, Mool, & Shrestha, 2009). Energy consumption in ICT sector represents a significant portion of CO₂ emission and is expected to increase rapidly if no greening techniques are adopted in the ICT services and network expansion. With the increasing expansion of ICT infrastructure, energy consumption increases, which leads to increase in CO₂ that creates adverse change in climate for Nepal.

In this paper, we present analysis, design, and deployment of green ICT ecosystem that leverages emerging networking technologies such as SDN and IPv6 networks, jointly known as Software Defined IPv6 (SoDIP6) network. The proposed networking approach, SoDIP6, is compatible with IPv6 and managed by SDN controllers (Dawadi, Rawat, & Joshi, 2018). We present not only better approaches for energy saving in ICT ecosystem for sustainable future network design and implementation but also recommendations to stakeholders for creating ecofriendly environment in Nepal. This study addresses the following research questions. (a) What are the policy initiatives and the current broadband deployment trend in Nepal? (b) Does the SDN enabled IPv6 (SoDIP6) network contribute to green ICT and service provider sustainability? (c) What are energy-saving approaches with SoDIP6 network implementation? (d) What are the challenges and recommendations for developing countries like Nepal?

The rest of this paper is organized as follows. Section 2 highlights the policy recommendations regarding the rural connectivity with ICT enhancement of Nepal and the initiatives taken by NTA as a regulator to implement the policy actions by utilizing RTDF. In Section 3, we review the literature in the recent trend of energy utilization via ICT and explored the relevant technologies advancement carried out in the field of energy aware and energy efficient future networking design, operation, and management with respect to Internet Protocol Version 6 (IPv6) and the Software Defined Network (SDN) as an enabler of green networking technologies. Possible energy forwards and plan of government for rural Nepal are presented in Section 4. Section 5 presents the overview of research design and data collections from concerned stakeholders of Nepal including experimental design to evaluate energy consumptions by switches and links with SoDIP6 network. Section 6 presents the results of qualitative analysis from survey as well as results of simulation study. In Section 7, we discuss and recommend the energy saving approaches through SoDIP6 network as well as present challenges and a way forward for Nepal, followed by the conclusion in Section 8.

2 | BACKGROUND AND THE CONTEXT OF ICT EXPANSION OF NEPAL

2.1 | Nepalese ICT status and policy initiatives for nationwide broadband expansion

Recently, Nepal has adopted the liberalization policy to encourage involvement of private sectors in ICT. There have been competitions in ICT sector that has helped to reduce the digital divide and considerably increase the ICT penetration rate. Nepal has more than 40 ISPs and six telecom operators (Telcos). Most of the ISPs and Telcos are urban centric. Existing urban centric network and services seem enough to achieve the targets set for urban communities. However, rapid pace of network deployment is required to meet the policy targets for the rural connectivity. Looking

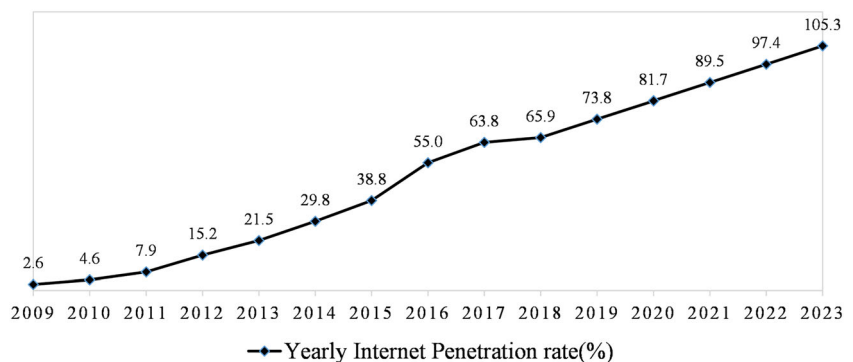


FIGURE 2 Overall internet (fixed, wireless, and mobile 3G/4G) penetration rate of Nepal (Source: MIS Reports of NTA, 2009-2018)

into the ICT status, the overall internet penetration rate of Nepal in the year 2018 was 65.9% as shown in the Figure 2. In the recent years, the fixed broadband growth trend like cable internet and Fiber to the Home (FTTH) services is more popular where subscribers with those services are linearly increasing, while Asymmetric Digital Subscriber Line (ADSL) subscription rate is almost constant, as shown in Figure 3. The Internet penetration rate since 2009 to 2018 is linearly increasing, as shown in Figure 3. Furthermore, Figure 3 also shows the linearly increasing trend of fix broadband (Cable/FTTH) growth of Nepal in terms of number of subscribers. However, Figures 2 and 3 show increasing penetration rate of internet access; this shows the false positive results for rural areas as the connectivity services are mostly available in the urban/city areas. The existing fiber distribution of major telecom operators like Nepal Telecom (NT) and Ncell, as shown in Figure 4, verify that the rural zone like Mid-Hill and the upper mountainous zones of Nepal lack connectivity indicating that less than 1% rural people have access to fixed internet and ICT services as estimated by Central Bureau of Statistics (2016).

Considering only fixed broadband, current Internet penetration rate of Nepal is only 12.35% and the mobile broadband (3G/4G/EVDO) is 44.36% (as of Dec. 2018). The fitted curve of Figure 2 shows that the overall internet penetration will cross 100% beyond the year 2023 including mobile GPRS users. But looking into the current fiber distribution status of NT and NCELL as shown in Figure 4, this cannot be achieved unless and otherwise the Mid-Hill and upper mountainous zone of Nepal is sufficiently covered with new network infrastructure. On the other hand, considering 2020 targets, ICT Policy-2015 (MoIC-ICT, 2015) and Broadband Policy-2015 (MoIC-BBP, 2015) have put some ambitious targets about network expansion and ICT enhancement throughout the country. Some of the policy initiatives include the following:

- Establish and implement backbone network as broadband access network throughout the country.
- Nepal will strive towards enhancing overall national ICT readiness with the objective of being at least in the top second quantile of the international ICT development index and e-Government ranking by 2020.
- At least 75% of the population will have digital literacy and skills by the end of 2020.
- By 2020, 90% of the population will be able to access the broadband network services.
- The role and significance of ICT industries and services (including telecom services) will help to enhance the Nepalese economy with added ICT value (including digital content and service industry) accounting for at least 7.5% of gross domestic product (GDP) by 2020.
- By 2020, entire population of Nepal is expected to have access to the Internet.
- About 80% of all citizens accessing government services would be offered online through Internet by 2020.

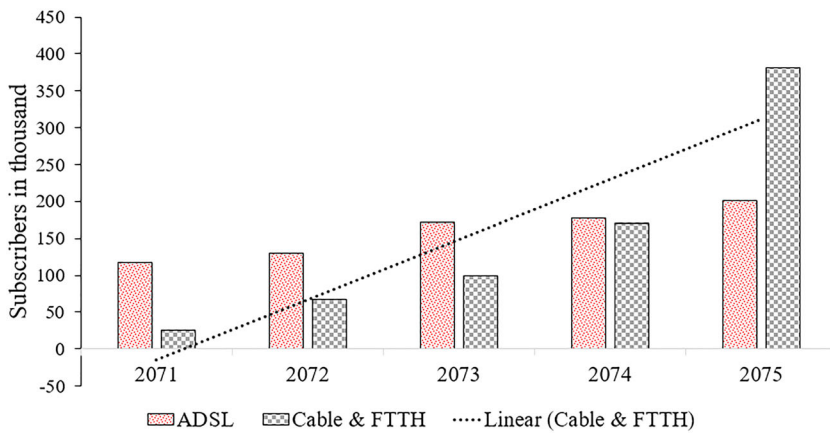


FIGURE 3 Fix broadband growth trend of Nepal (Source: MIS Reports of NTA, 2014-2018)

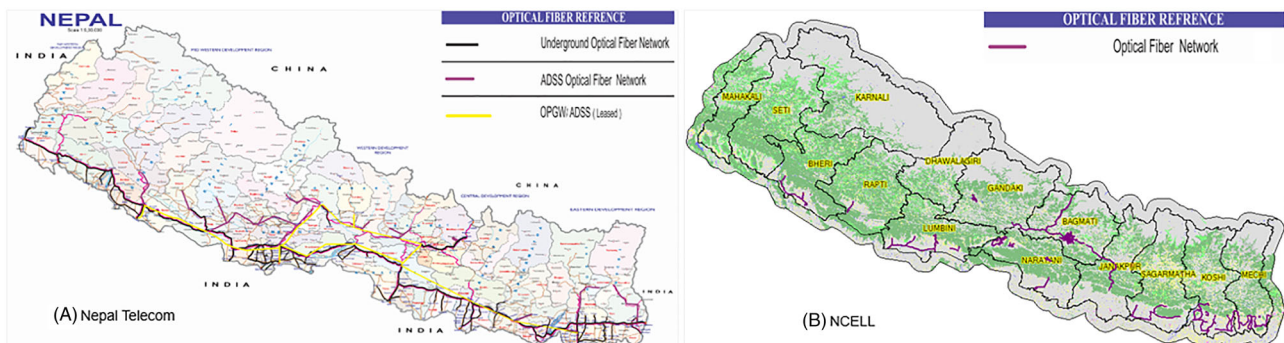


FIGURE 4 Existing fiber distribution of major telecom operators of Nepal: (A) Nepal Telecom and (B) NCELL (Source: NTA, 2018)

NTA has explored some of the important areas to utilize the RTDF and has started a project for district level optical fiber network connectivity along the Mid-Hill Highway. Furthermore, establishment of Mobile Base Transceiver Station (BTS) as well as access network expansion for connecting schools, hospitals, and rural community centers/village level administrative units throughout the country and making ICT accessible to persons with disabilities is the major action by NTA. This action aims to connect all municipalities, villages, and ward offices of rural Nepal. This action is more progressive towards ICT enhancement without considering sustainable and energy efficient network deployment that encourages ecofriendly activities in ICT implementation.

2.2 | RTDF Utilization to expand rural connectivity in Nepal

NTA has started expansion of broadband network services throughout the country by dividing the project tasks into 18 subtasks for seven provinces of Nepal. Till date, NTA has run a couple of projects towards ICT enhancement in the rural Nepal by leveraging the RTDF. Specifically, current projects have been outsourced to different operators for expansion of both backbone network and end-access network that use RTDF, as shown in Figure 5.

Optical fiber, VHF/VSAT technologies are the major connection media types decided for the network expansion. NT, United Telecom Limited (UTL), and Smart Telecom are the telecom operators that have received funds for expanding backbone network services. Whereas different ISPs have received funds for expanding the last mile broadband access network services to rural Nepal. The Mid-Hill highway optical fiber project is missioned to have nationwide ICT backbone network. Under this project, NT has received funds through a contract to laydown optical fiber in the provinces 1, 2, and 3 of Nepal. Similarly, UTL has received funds through a contract for provinces 4 and 5 to laydown fiber and Smart Telecom Pvt. Ltd. has received funds through a contract for provinces 6 and 7. Operators should lay down at least 96-core fiber in the Mid-Hill highway and 48-core fiber up to district headquarter (DHQ) and 24-core fiber up to rural municipalities wherever possible. Furthermore, the expected capacity of network up to DHQ is 100 and 10 Gbps up to municipalities.

The 7.8 Richter scale devastating earthquake in Nepal in 2015 severely affected the ICT infrastructure including BTS, transmission towers, fiber backhaul, and microwave links throughout the Nepal (Dawadi & Shakya, 2016). Considering the earthquake prone area, NTA has set the priority to establish effective disaster communication networks and Internet connectivity to those areas. Specifically, the work is divided into two parts: (a) District Optical Fiber Network, *aka* Mid-Hill, Project, and (b) Broadband Access Network project to connect all community schools, hospitals, government offices, rural municipalities, and ward offices. The funds through contracts are released for broadband deployment in different districts of Nepal including earthquake affected areas, as presented in Figure 6. The project aims to connect 720 municipalities, 6081 ward offices, 6325 community schools, and 5160 health centers. Limited fiber networking option is also available via leasing spare cores on Optical Ground Wire fiber cable running through the Nepal Electricity Authority (NEA) power grid. However, this NEA-based network is scarce and not available in the most part of the rural Nepal. The NTA projects for expanding network infrastructure including broadband expansion to rural Nepal aims to open several opportunities for digital transformations of Nepalese communities and reduce the digital divides. The successful completion of the project is expected to contribute to (a) increase fix/mobile broadband users, (b) increase consumer surplus, (c) increase competition that will lead to better service to consumers, (d) increase investment for better service to users, (e) improve quality of life in rural communities, (f) decrease in internet usage tariffs but enhance the quality of service (QoS), (g) good governance, and many more (Khanal, 2018). Every 10% increase in broadband penetration is expected to result in 1.38% growth of GDP in economy of developing countries (Qiang, Rossotto, & Kimura, 2009). Hence, increasing digital connectivity is expected to help improve the economic growth of the country and bring improved socioeconomic value across the entire ecosystem by enabling new business models, more jobs, effective governance, automated industrialization, smart agriculture, smart transportation systems, and so on.

Furthermore, meeting the 2020 targets set by NTA is quite challenging for the country, if speedy deployment, efficient monitoring and evaluation of the projects are not carrying out by the operators. Considering increased ICT accessibility as an outcome of this project, content creation,

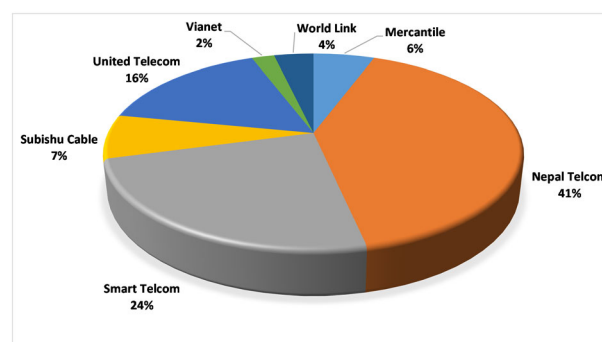


FIGURE 5 Rural Telecommunications Disbursement Fund distribution share of different packages to operators of Nepal (National Planning Commission [NPC], 2018)



FIGURE 6 Internet Service Providers received funds for broadband network expansion at different districts (National Planning Commission, 2018) (Map source: election.gov.np)

delivery, and security become major concerns together with the greening of network infrastructure for the ecofriendly environment and long-term sustainability for service providers and the society. In the following section, we discuss the importance of green networking and its benefits by leveraging SDN and IPv6 as a long-term solution towards green ICT ecosystem.

3 | SOFTWARE DEFINED IPV6 NETWORKS AND THE GREEN NETWORKING

3.1 | Green ICT

Greening ICT is expected to help reduce the negative impact caused by powering ICT infrastructure. The way of reducing the energy consumption by the ICT equipment and reducing CO₂ emission by properly managing the ICT equipment to consume less power is regarded as green ICT. Use of green technologies for ICT infrastructure helps reduce CO₂ emission than that of produced by using traditional technologies. For example, tele-computing and virtual meetings are expected to reduce 68 MtCO₂ by 2030 (Fernando & Okuda, 2009). Similarly, according to WWF, 100 MtCO₂ emission could be reduced if 5% cars were operated with tele-computer and 15% airplane trips were substituted by virtual meeting. It is understood that the ICT is not the only the part of environmental problem; greening ICT could reduce negative impact of ICT in the environment. Reliable ICT infrastructure could help reduce third-party energy wastes and achieve higher level of efficiency; for instance, video conferencing could replace in-person meetings through virtual meetings that lead to reduction of travelling behavior; smart electrical grid could help to utilize electricity optimally and so on. The major motivation behind green ICT is to reduce energy consumption and CO₂ emission in the delivery networks, minimize operational sustainability in wireless networks, minimize the service provider operational cost, and improve the QoS (Peoples, Parr, McClean, & Morrow, 2012).

3.2 | Software defined IPv6 (SoDIP6) network

The advancement on networking began with the invention of two separate but interrelated paradigms in the field of networking these are Software Defined Network (ONF, 2012; Kreutz, Ramos, Verissimo, Rothenberg, Azodolmolky, & Uhlig, 2014) and Internet Protocol version 6 (IPv6) (Deering & Hinden, 1998). After the exhaustion of IPv4 addresses, the continuity of such a vertically integrated complex type of network is achieved through different migration approaches (Dawadi, Joshi, & Khanal, 2015; Wu, Cui, Wu, Liu, & Metz, 2013) during the period of transition.

Shortage of IP addresses, configuration, and management complexity with security, quality, and energy issues are the major factors of the existing legacy IPv4 network that makes the world to move into IPv6 addressing with its enormous address space to support massive number of devices in emerging Internet of Things (IoT). Similarly, SDN is the software controlled and programmable network that in fact segregate the control plane and data plane for easy management and operation. Adoption of SDN and IPv6 networks to replace traditional network is presented in the literature (Dawadi, Rawat, & Joshi, 2018), while the joint approach of network migration and cost is presented in the literature (Dawadi, Rawat, Joshi, & Keitsch, 2018). SDN adds enormous opportunities with the flexibility and programmability in the networking. SDN and IPv6 technologies can operate with each other where SDN deals with the management of the networking operations as management layer and IPv6 operates in the network layer. The next-generation green and smart networking can be achieved with the implementation of SoDIP6 network.

Migration of IPv4 to IPv6 network is happening worldwide. For example, the bigger ISPs like Comcast (66.30%), SoftBank (33.77%), ATT (65.95%), Verizon Wireless (85.51%), Deutsche Telekom (56.04%), and KDDI (41.96%) have significant progress on IPv6 deployment (ISOC, 2018). Similarly, several network migration approaches and strategies for the implementation of IPv6 along with legacy IPv4 networks have been developed (Dawadi et al., 2015; Wu et al., 2013). SDN technology centralizes the control plane and provides vendor neutral solution for device configuration with flexibility and programmability in the network that in fact brings revolution in the efficient network management with optimized operational expenditure (OpEX) (Bogineni, 2014; Hernandez-Valencia, Izzo, & Polonsky, 2015) for service providers. SDN migration approaches with use cases are discussed in details at ONF TR-506 (2014). Panopticon (Levin, Canini, Schmid, Schaffert, & Feldmann, 2014), Fibbing (Vissicchio, Tilmans, Vanbever, & Rexford, 2015), and HARMLESS (Csikor, Toka, Szalay, Pongrácz, Pezaros, & Rétvári, 2018) are some of the approaches proposed to upgrade existing legacy system to SDN. Data Centers worldwide are migrating to SDN (Dai, Xu, Huang, Qin, & Xu, 2017; Göransson, Black, & Culver, 2017). Its successful deployment in the data center network encourages Internet and telecom service providers to migrate their legacy network into programmable next-generation network. SDN Phase wise migration is abruptly gaining the progress. The major stakeholders like Stanford Campus Network, Google Data Center, NTT communication, and AT&T have already deployed the prototypes and implementing SDN with the migration in a phase (AT & T, 2014; Kobayashi et al., 2014; ON.LAB, 2014; ONF TR-506, 2014). This encourages other service providers to migrate their network to SDN and IPv6.

3.3 | Green networking with SDN and IPv6

Energy consumption by the network equipment and the link utilization varies with respect to network traffic load and pattern. This variation is less in case of legacy IPv4 devices, and hence, the devices always have peak energy consumption even if ICE devices are in idle condition. The integration of control and data plane within the individual devices of the legacy networking system needs heavier processing that leads to higher energy consumption as compared with legacy devices over SDN. Hence, legacy IPv4 network has greater energy waste problem because of its complexity in management, control, and operation (Bruschi et al., 2014). Several studies have been performed for the energy aware routing scheme to minimize the energy consumption and carbon footprint reduction to show that IPv6 and SDN have greater flexibility towards green networking (Chabarek et al., 2008; Gaddour, Koubâa, & Abid, 2015; Gesi, 2012; Giroire, Moulhierac, & Phan, 2014; Hu, Luo, Wang, & Deng, 2016; Maaloul et al., 2018; Ruiz-Rivera, Chin, & Soh, 2015; Saad, Chauvenet, & Tourancheau, 2012; Tuysuz, Ankarali, & Gözüpek, 2017; Zhu, Liao, De Laat, & Grosso, 2016). SDN devices being programmable and controllable, network switches and links can enter into low power state in the sleep mode and the device architecture can be designed to have actual load based proportional energy consumption (Assefa & Ozkasap, 2018). Hence, energy saving in SDN is viable algorithmically or through hardware improvements (Chiaraviglio, Ciullo, Mellia, & Meo, 2013; Coiro, Chiaraviglio, Cianfrani, Listanti, & Polverini, 2014; Kun, Xiaohong, Maode, & Pei, 2017; Moaiyeri, Doostaregan, & Navi, 2011; Rawat & Reddy, 2016; Salehi & DeMara, 2015).

Many organizations worldwide have been maintaining their networking infrastructure (servers, routers, switches, and computers) in their own organizational premises. This scenario is more prominent in case of developing countries like Nepal. Due to the emergence of cloud computing, the network infrastructures are migrating to data centers. The internet/intranet services are provided as utilities from remote datacenters with higher bandwidth and lower latency. Esaki (2015) estimated that moving the legacy infrastructure into cloud data centers would reduce CO₂ emission by 40% and energy saving by 15%. Hence, individual management of network infrastructure like allocation of separate human resources (HR), applications, security solutions, servers, switches, cooling system, etc., in small enterprises results in higher cost in terms of operation and management with higher energy consumption and CO₂ emission. Radio frequency (RF) and wireless sensor network enable smart devices or things in this planet connected, controlled, and managed. IPv6 over Low Power Personal Area Network (Kushalnagar, Montenegro, & Schumacher, 2007) is specially designed for energy efficiency in IoT implementations. The amount of energy consumption is proportional to the amount of traffic condition flowing through the link. Hence, link pruning or making low traffic link into sleep and getting alternate routes according to traffic condition could help reduce the energy consumption by the link. Feature for adjustment of link capacity with dynamic traffic condition is not available in legacy networks. For example, 10 Mbps port consumes less energy than 100/1000 Mbps port/link. About 10Mbps links at real time consume 4 watts lower than that of 1Gbps link (Rawat, & Reddy, 2016). SDN has the capability to adjust the network parameters (speed of port/link, sleep/on mode based on link activity, etc.) on the fly.

Zhu et al. (2016) has studied the power consumption by a network switch including link utilization. Power consumption by a switch is static and dynamic type. Static power consists of chassis, fabric, etc., while dynamic power is the power consumed by interfaces with traffic across it. Assuming this, we get the better energy saving with IPv6 router as compared with IPv4 router since IPv6 router does not fragment the oversized packets. Due to higher transmission unit and support for Jumbo-gram packet transmission, IPv6 network is faster that leads to reduction of energy consumption with the reduced transmission period. The Greek IPv6 pilot under GEN6 project demonstrated that a reduction of carbon footprint and power saving of 17 to 30% can be achieved running services over IPv6 network (Varvarigos et al., 2012). Due to the migration of organizational network infrastructure into data centers (DC), the energy consumption and CO₂ emission by individual organization re transferring to DC. According to recent studies, DCs consume approximately 1.5% of the total electricity produced in 2012. Similarly, ubiquitous mobile devices add approximately 1% to the overall energy usage for ICT (Gelenbe & Caseau, 2015). On one hand, the CO₂ emissions in ICT sector is estimated to be 2 to 10% of total world CO₂ by 2020 (Maaloul et al., 2018), and on the other hand, the global e-Sustainability Initiative (GeSI) estimated that ICT contributes to 9GtCO₂ reduction by 2020 (GeSI, 2012; Lambert et al., 2012). ICT will enable others to achieve significant emissions reductions, helping other industries and consumers avoid the estimated 7.8 GtCO₂ emissions by 2020. Additionally, WWF report mentions that applying ICT solutions to different sectors such as energy, buildings, transport, and commerce can save up to \$600 billion US dollar and create 15 million green jobs globally by 2020. Similarly, average estimated total potential for CO₂ emission reduction due to ICT use by 2030 will be about 4620 MtCO₂ (WWF, 2011). The actual prediction of these facts is difficult because of lack of precise data for the prediction. However, this seems more to be an optimistic estimation, and researchers agree that ICT is a tool that could contribute to better power management and reduction of carbon footprint (Higón, Gholami, & Shirazi, 2017).

4 | ENERGY FORWARD FOR RURAL NEPAL

Energy is the major component that drives the ICT and hence uplift people's socioeconomic status. ICT help manage the energy efficiency on every sector where proper utilization of energy is required in the sectors like smart building, smart transportation, smart logistics, smart grids (SGs), and dematerialization. According to National Planning Commission (NPC) report (NPC, 2017), above 80% land of Nepal is covered by hilly zones. High investment is required to build and expand any kind of services to rural Nepal. For example, ICT infrastructure expansion and expansion of electrical distribution network to remote areas have hindered government and the public/private sectors to provide service accessibilities to remote areas. The NPC report reveals that approximately 30% of the total population of Nepal, mostly in remote villages, lives in darkness. Only 60% of the whole population has access to grid electricity. Midregion, far-western region, and rural areas of Nepal are more adversely affected by the lack of transmission lines and the reliable communication means. In total 456 sites in all seven provinces of Nepal are identified for potential hydropower with capacity ranging from 27 to 94.75 MW, and a total capacity of approximately 384 MW. Based on these findings, grid extension plan has been designed and planned to be constructed by 2023. Similarly, the transmission lines are designed to be constructed by 2028 considering the power load increased by 15% annually. Similarly, study of NPC reported the potential sites in local level for solar and biomass energy that contributes to distributed generation of power sources.

The lack of energy severely hampers the broadband rollout towards rural Nepal because every active network equipment needs sufficient and reliable power supply. Current scenario of energy supply in Nepal indicates that grid-based power supply throughout Nepal will be sufficient only after 2028. However, the availability of alternative energy like solar and micro-hydro will be attracted to power supply ICT equipment in the rural Nepal; the "2020 broadband deployment targets" of Nepal might be deferred.

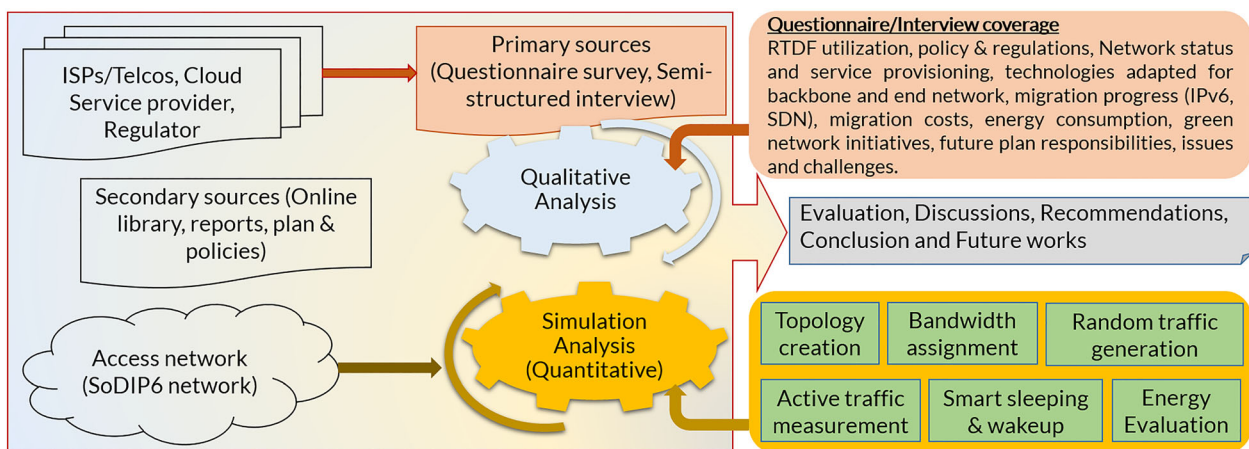
5 | RESEARCH DESIGN AND METHODOLOGY

The study on this article is designed into two parts. The first part consists of an exploratory qualitative data analysis after having questionnaire survey and semistructured interview. Primary data were collected from the techno-economic and regulatory perspectives from Regulator, ISPs, Telcos, and cloud service providers of Nepal. The related domains covered in primary data collections via questionnaire survey and interview are summarized in Table 1. Though research studies related to Nepalese ICT and the digital economy are very limited, we obtained secondary sources of data for analysis from online research libraries, regular reports published by ministries, and regulator and planning commission of Nepal. Most of the data obtained from questionnaire survey and interviews were qualitative in nature. We lack some facts regarding network equipment upgrade/replacement costs and the cost of energy consumptions to be obtained from the stakeholders due to cause of proprietary data that they could not share with us. The qualitative nature of data obtained is enough to carry out the analysis and discussions presented in this study with the defined scope of work. The background study is presented in Section 2, and findings of survey is presented in Section 6.1 regarding current ICT status and broadband deployment trend of Nepal. This addresses the first research question. To address the second research question regarding contribution of SoDIP6 network in green ICT, power supply status of Nepal is presented in Section 4 and Section 6.2 presents an empirical data analysis basically of quantitative nature via simulations to evaluate energy efficiency of SoDIP6 network and its comparison with legacy networking system. Section 7 addresses the third and fourth research questions laid out in this article. Hence, the first

TABLE 1 Samples and domain knowledge captured by questionnaire survey

Organizations (Stakeholders)	Selected Numbers	Domain Knowledge Captured by Questionnaire Survey
Major Nepalese ISPs	4 (66%)	<ul style="list-style-type: none"> - Current network infrastructure and its energy consumption scenarios - Readiness status for network migration (skilled human resources, network migration/deployment cost, future plan, etc.) - Expectations from government and regulatory bodies - Latest network deployment challenges and sustainability issues - Corporate social responsibilities
Major Nepalese cloud service providers	3 (66%)	- Same as above
Telecom operators	2 (33%)	<ul style="list-style-type: none"> - Broadband expansion plan - Legacy network energy consumption scenarios - Readiness status for network migration (skilled human resources, network migration/deployment cost, sustainability plan, etc.) - Existing issues and challenges - Corporate social responsibilities
Telecom Regulator	1 (100%)	<ul style="list-style-type: none"> - RTDF utilization - Broadband project and its expected impacts - Policy initiatives regarding broadband expansion & network migration - Policy issues and implementation challenges

Abbreviations: ISPs: Internet Service Providers; RTDF: Rural Telecommunications Disbursement Fund.

**FIGURE 7** Methods and framework for the proposed approach

part of the analysis provides the broader perspectives of current ICT infrastructure deployment scenario at Nepal, while empirical analysis and study on green networking help address all research questions and encourage service providers to implement SDN enabled IPv6 network during their infrastructure expansion. The methods and conceptual research framework showing overall steps of study is depicted in Figure 7.

5.1 | Sampling, data collections, and experimental setup

The number of stakeholder organizations chosen and the domain knowledge captured from survey and interview are presented in Table 1. As a requirement to capture data from the techno-economic perspectives, we applied judgmental sampling for this survey and interview. A set of 38 questions for ISPs and Telcos, 11 questions for regulator, and 22 questions for cloud service providers were prepared for this research. However, Nepal has more than 40 ISPs; four major Nepalese ISPs were chosen out of six major ISPs for this survey. Most of the other ISPs are the secondary ISPs who purchase internet bandwidth from major ISPs and provide services to customers. Among the emerging cloud service providers in Nepal, three were chosen for the questionnaire survey. Specifically, head of technical operations was interviewed. Answers of the questionnaire survey were collected from email communications.

In the preliminary analysis, as a pilot experiment, we used OpenDaylight Controller, Kill a Watt, NEC's OpenFlow PF5240-ProgrammableFlow Switch, and Mininet to perform energy consumption evaluation of proposed SoDIP6 network taking the use case of

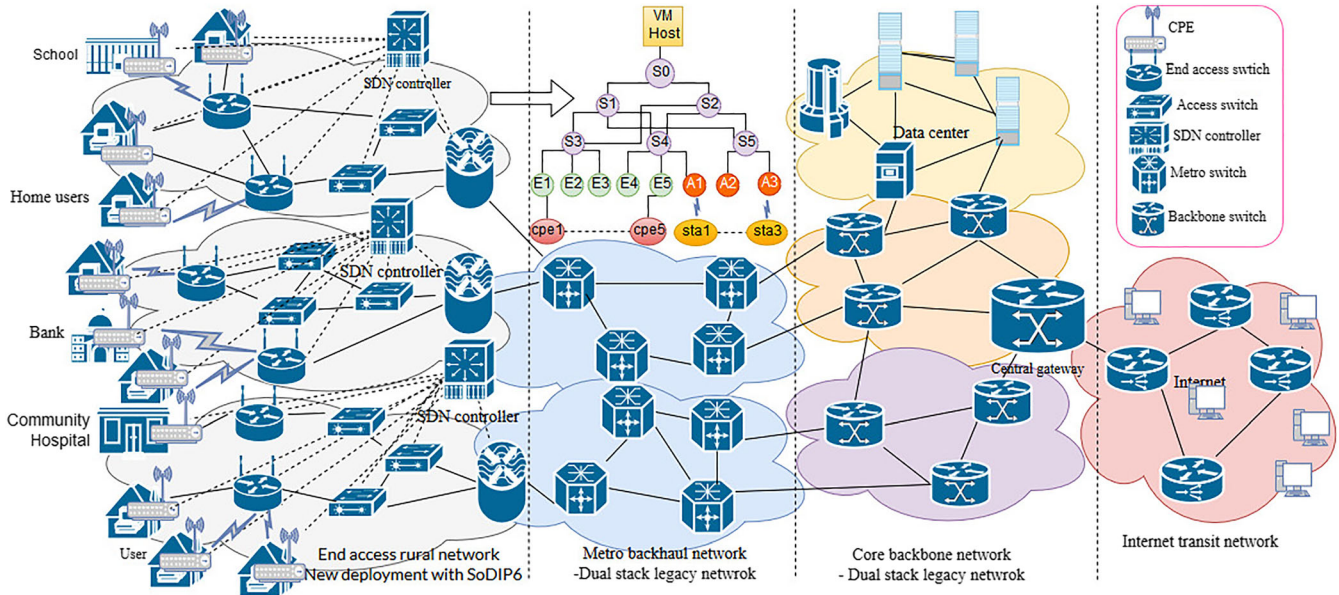


FIGURE 8 SoDIP6 capable end access rural network in the hierarchy of nationwide Internet Service Provider networks

university campus network.* In this simulation, we consider a typical ISP that extends wired/wireless services to enterprises and individual home users at rural Nepal. The experimental SoDIP6 network only at the end user access network is considered as a use-case for the energy consumption analysis, as shown in Figure 8. Our assumption of the end access technologies that are almost heterogeneous in nature and their power consumption model considering the legacy IPv4 system to provide internet services to rural area is almost similar in the study by Baliga, Ayre, Hinton, and Tucker (2011) & Vereecken et al. (2011)). The experimental testbed depicted in Figure 8 consists of 14 switches, 8 Customer Premise Equipments (CPEs), and 24 links in which we categorized switches like S0 to S5 are access switches, and E0 to E5 are end user switches. Similarly, A1 to A3 are base station access points. Hence, we refer additional research studies (Cuomo, Cianfrani, Polverini, & Mangione, 2012; Deruyck et al., 2010; Vereecken et al., 2011; Vu et al., 2014) to consider average power consumption of network devices and links in our analysis presented in Table 2. We investigate the feasibility of SoDIP6 network for a service provider taking this case and study how SDN enabled IPv6 network could reduce energy consumption and carbon footprint emission while providing reliable and fast internet/network services. Based on the current infrastructure deployment initiation for Nepal, we consider rural networks as the home/access networks under the hierarchy of Telcos/ISP networks in our experimental analysis. The testbed is setup over two Ubuntu Virtual Machines (VM), ie, one for OpenDaylight Controller and another to run the network topology is the Mininet-WiFi VM each having 8GB RAM over an windows server host with 2.1GHz octa-core processor and 32GB of RAM. Link bandwidth between switches is set to 1000 Mbps and between switch to CPE is set to 5Mbps. We develop daemons for random IPv6 traffic generation, power consumption recording, per port traffic measurement in switches and links, sleep switch based on controller's traffic status evaluation in the entire network, and auto wakeup. Random IPv6 traffic is generated on every 2 minutes using "iperf" tool and "ping6 traffic" on every minute. Active traffic on the switches and their ports were measured using "vnstat" (traffic monitoring tool), while the SDN controller signals the switches into sleep mode if it is in the idle state. Power consumption of each switch and link were monitored periodically over a span of 24 hours. We consider Wake on LAN (WoL) concept implemented by Vu et al. (2014) to auto wakeup the switch and activate links.

Total power consumption in ISP network is

$$P_{\text{total}} = P_{\text{access-network}} + P_{\text{metro-network}} + P_{\text{core-network}} = \sum P_{\text{node}} + \sum P_{\text{link}}$$

where power consumption by CPE or switch is represented by P_{node} and power consumption by link is represented by P_{link} in the access, metro, and core network. Considering access network only, the node represents the CPE and end access switches, while link represents wireless and wired links. The power of switch in the active mode varies due to change in its active ports and traffic load (Rodrigues et al., 2015). Hence, considering the basic formulation of power consumption in ISP network by Chiaraviglio, Mellia, and Neri (2012), the total power consumption by an ISP's end access network having two modes (active and sleep) of operation can be formulated as:

*Portion of this paper was presented on ICNC-2019, Hawaii Conference, <http://www.conf-icnc.org/2019/>.

TABLE 2 Assumptions on power consumption by end access network devices

Description	Value	Remarks
Average base power consumption by an end access active switch	110Watt	- Cisco Catalyst 3750 Metro series—provider edge, Cisco 1941 Series integrated services routers
Average power consumption by active link	40Watt	- Varies from 20 to 60 W
Average power consumption by active CPE	7 W	- Varies from 5 to 10 W
Link bandwidth among the access switch	1Gbps	Assigned for simulation
Link bandwidth from end access switch to CPE	5Mbps	- Assigned for simulation
Average power consumption per Mbps (end access switches)	0.01 W	- Port power coefficient
Percentage of energy consumed by switches/CPEs at sleep mode	40%	- Assuming flow rules are saved in memory during sleep mode for immediate recovery after wakeup.

Abbreviation: CPEs: Customer Premise Equipments.

TABLE 3 Respondent's view from the survey and interview

Respondent	Summary of Response
Telecom operators	<ul style="list-style-type: none"> - Being the incumbent and the operator, Nepal Telecom is striving towards affordable broadband services throughout the country. - With the growing network size, annual energy bill is increasing and greatly varying because of irregular electricity supply. To avoid disruption due to varying and often interrupted electricity supply, operators use diesel generators to provide backup power supply. NT's network stations at most of the places, including rural and remote places, have backup power in the form of diesel generators and, in some cases, solar cells as well. - Regarding the green network focus, NT replaces or upgrades the network equipment on a regular basis with proper radio frequency planning while expanding the network for energy optimization and network performance upgrades. Apart from that, the new devices are mainly software driven and have small size compared with the previous generation devices. They are also more optimized for efficient use of power and have lower carbon footprint. As a result, power efficiency is increasing but in many cases, this gain in efficiency is offset by the rise in the number of devices and stations. - The backbone network of Telcos including NT is fully IPv6 capable. However, the actual IPv6 traffic is still minimal due to lack of customer demand and organic traffic in IPv6. Moreover, the native IPv6 capability at the end user level is also limited by the capability of the CPE, many of which are old and have minimal or no IPv6 support. - Because of the continued use of IPv4 along with network address translation (NAT) as well as no specific customer demand or business requirement, the service providers are still providing their services using mostly IPv4. This has lowered the level of motivation for service providers to adopt IPv6 on a larger and wider scale. - NT is currently doing research on openBTS/openCellular technologies including SDN implementation in telecom networks for affordable and efficient services to rural Nepal. - Infrastructure security has become the major challenges for the operators due to anti-government political movement and other known/unknown issues in the rural area of Nepal. Since the Telecom infrastructure such as towers, cables, poles and shelters are easily available and soft targets, these infrastructure elements are a prime targets during civil protests, agitations, insurgencies and other unruly activities.
Internet service providers	<ul style="list-style-type: none"> - Internet users in some of ISPs are increased by three times in last three years, while they provide internet, corporate lease, and IPTV services to the customers. - ISPs are all aware of the IPv6/SDN network migration. However backbone networks are IPv6 ready, lack of customer demand, skilled human resources, higher upgrade costs and technology limitation, IPv6 based services are not yet commercialized. Similarly, only some of the network routers are OpenFlow enabled but SDN migration in the ISP network is not in the priority. - ISPs are providing free WiFi services in the public places like hospitals, airport, and rural community centers while also supporting connection for Telemedicine services as a part of corporate social responsibilities. - Focus towards green networking is becoming the major concern as the energy bill every year is increasing. However immediate migration to energy aware latest technologies is not viable due to higher cost of investment. - ISPs are expecting subsidies from the government not only in the broadband expansion utilizing RTDF, but also they expect like tax exemptions in the import of energy aware latest network equipment, local content generation and public-private partnership to expand ICT services in the rural Nepal. - Accessibility, infrastructure security and sustainable ICT services are the major issues in rural Nepal due to diverse demography and difficult terrain.

(Continues)

TABLE 3 (Continued)

Respondent	Summary of Response
Cloud service providers	<ul style="list-style-type: none"> - Data center switches are already IPv6 compatible but lack of customer demand and skilled human resources; the IPv6-based services are not yet commercialized. - Existing router/switches do not support OpenFlow; hence, migration to SDN incurs higher cost for replacement or upgrade of existing network.
Telecom regulator	<ul style="list-style-type: none"> - Telecom policy is amended to address rural connectivity by utilizing RTDF. Broadband network expansion under RTDF subsidization is expected to meet the policy targets sooner or later for the rural communities. - Major telecom operators like NT, SmartTel, and UTL are awarded contract for nationwide backbone network expansion while major ISPs are awarded contract for broadband end access network expansion. Government priority is first the coverage and connectivity throughout Nepal. - Focusing on green networking via policy decision has not been enforced yet. Considering climate change and global warming issues of Nepal, green networking is the subject of study in the near future.

Abbreviation: CPEs: Customer Premise Equipments; ICT: information and communications technology; ISPs: Internet Service Providers; NT: Nepal Telecom; RTDF: Rural Telecommunications Disbursement Fund; SDN: Software Defined Networking; UTL: United Telecom Limited.

$$(P_{\text{total}})_{\text{access}} = \sum_{i=1}^{ns} \left\{ P_{\text{sleep}_i} + x_i (P_{\text{active}_i} - P_{\text{sleep}_i}) \times \sum_{j=1}^{ks} (f_{tr_j} \times P_{pc_j}) \right\} + \sum_{k=1}^{nl} x_k P_{\text{link}_k} \quad (1)$$

where “ns” represents the number of nodes, “ks” represents the number of active ports of that node, “nl” represents the number of links, “f_{tr}” represents per active-port load proportional traffic demand, and P_{pc} represents the port power coefficient. Binary variable x_i, x_k ∈ {0,1} has the value of 1 if the node or link is active, 0 otherwise.

6 | RESULTLS AND ANALYSIS

6.1 | Summary of findings from the survey

The current trend of deployment of backbone network and broadband access network in Nepal utilizing RTDF is summarized in Section 2.2 of this paper. Additionally, summary of responses from the survey is presented in Table 3. NT is the government incumbent operator, and NTA is the autonomous regulatory body of Nepal. Except this, identity of other private entities (respondents) is not disclosed in this study. The major findings of this survey are as follows.

- IPv6 implementation is in the early stage in Nepal, while backbone networks are capable to operate with IPv6, but the end access network devices like CPE are to be replaced for which it requires higher cost for replacement.
- ISPs and Telcos of Nepal are in the stage of research and training for SDN implementation, while its migration in the existing network has not in the priority. There is a lack of skilled HR to operate newer technologies like IPv6 and SDN.
- Broadband expansion throughout Nepal creates many business opportunities that could help to reduce digital divide besides its operational challenges like infrastructure security, accessibilities, and power supply to network equipment.
- Focus to greening of network during the early stage of network deployment is the government concerns because the running project is under RTDF subsidization.
- Government subsidy is expected to migrate existing networking infrastructure into SDN enabled IPv6 network with content development, delivery, and management. These all are expected to be driven by policy initiatives as an incentive to operators for the sustainable and green ICT of the nation.

6.2 | Energy efficiency evaluation of end access SoDIP6 network

Different technical and managerial approaches to energy saving in a SoDIP6 network are discussed in Section 7. In this section, we focus only to evaluate the energy efficiency of SDN enabled IPv6 network based on power consumption by switches and links using the concept of smart wakeup and sleep cycles. In the existing legacy IPv4 network, the network switches and links are active 24 hours, and hence, we assume they consume maximum energy all the time. Figures 9 and 10 show the pattern of energy consumption by all testbed switches and links over the

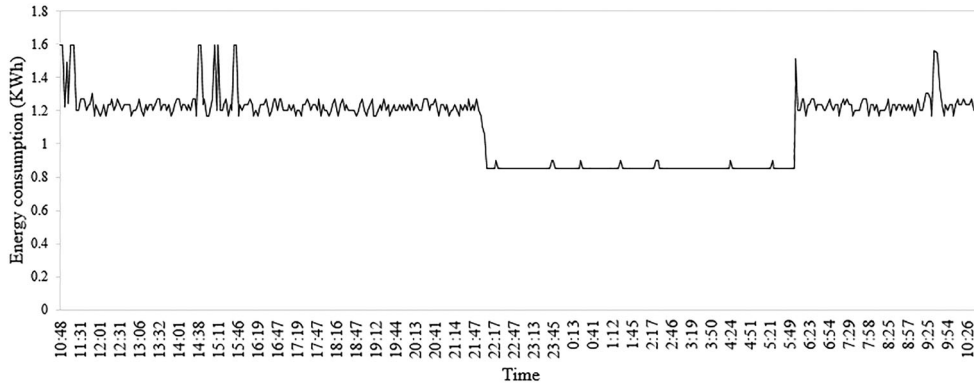


FIGURE 9 Energy consumption pattern by all switches (testbed over 24-h period of monitoring) in the SoDIP6 network

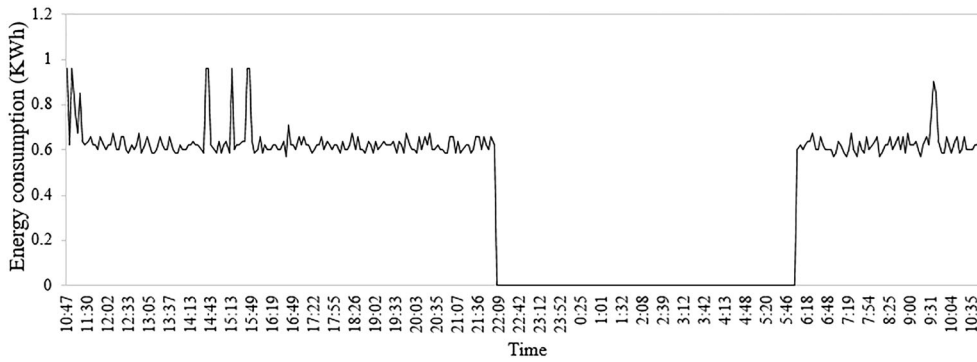


FIGURE 10 Energy consumption pattern by all links (testbed over 24-h period of monitoring) in the SoDIP6 network

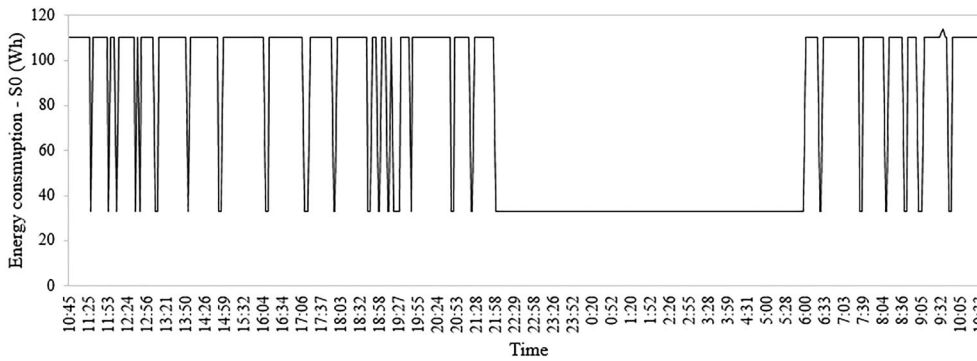


FIGURE 11 Energy consumption pattern by a SoDIP6 enabled switch (s0) (over 24-h period of monitoring)

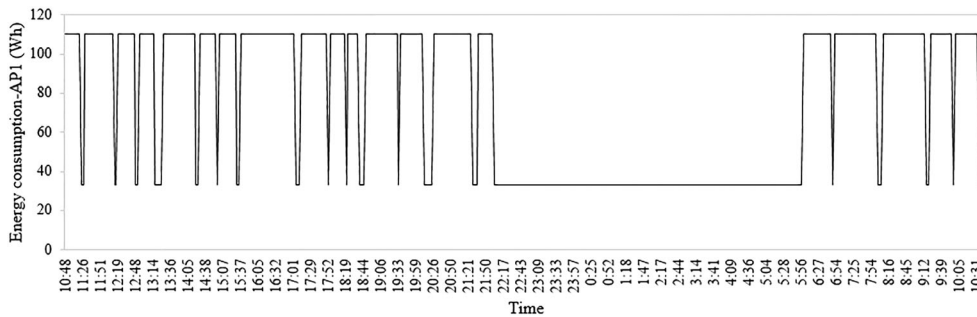


FIGURE 12 Energy consumption pattern by a SoDIP6 enabled Access Point (AP1) (over 24-h period of monitoring)

period of 24 hours, while Figures 11 and 12 show the pattern of energy consumption by a SoDIP6 enabled switch (s0) and an Access Point (AP1). We assume the rural people's sleeping habit of 8 hours/day (10 PM to 6 AM). With this particular experimental analysis, the annual energy saving of more than 308.94 KWh per switch and 194.287KWh per link can be achieved. This is about 31.50% energy saving in switches and 55.44% energy saving in the links. Additional energy saving can be achieved by considering the rural enterprise office hours from 10 AM to 5 PM, and switches would be in sleep state during the nighttime from 5 PM to 10 AM. Hence, energy saving in SoDIP6 network is more efficient in addition to its several benefits such as reduction of CO₂ emission, saving of OpEX cost, and reduction in annual energy bill. The outcome of our empirical analysis, as shown in Figures 11 and 12, indicates that switches and APs frequently entered into sleep mode even in the normal hours that leads to entire network rarely reached to peak energy consumption except some moments with spikes as shown in Figures 9 and 10.

6.3 | Related Works

Nedevschi, Popa, Iannaccone, Ratnasamy, and Wetherall (2008) formulated a power model to implement two approaches: sleeping and rate adaptation of network elements for reducing energy consumption in the traditional network environment. Their comparative study on those two approaches contributes to save the energy significantly. This concept is now recognized as smart sleeping and adaptive link rate in SDN environment. Chiaraviglio et al. (2012) formulate an Integer Linear Programming problem for energy evaluation of entire ISP networks from core to end access. Their works mostly focused on shutting down the nodes and links during idle condition in the legacy networking system. Vu et al. (2014) presented sleep and WOL method for OpenFlow enabled SDN switches over SDN enabled IPv4 networking system in which shutting down idle ports can achieve 9.8% energy saving, while sleeping the switch can save up to 60% of total power consumption. We incorporated the concept of sleeping the idle switch and WOL approach to evaluate the energy consumption over our testbed. A comparative table of different energy saving approaches in SDN considering link rate adaptation, traffic demand, energy aware routing, smart sleeping and wakeup, minimizing Ternary Content Addressable Memory (TCAM), and network virtualization, etc., is presented by Tuysuz et al. (2017). Most of these approaches are mutually exclusive so that each one is contributory towards energy saving in SDN.

Progressive works are going on towards greening of ICT network via energy saving in wired and wireless communications with SDN. But based on our knowledge, there are limited studies on joint implementations of SDN and IPv6 technologies considering green networking for rural connectivity (Dimogerontakis, Vilata, & Navarro, 2013; Hasan, David, Scott, Brewer, & Shenker, 2012; Ruponen, 2013). Being both are underlying network-related operation and management technologies, we introduce joint approach (SDN and IPv6 networks) for energy efficiency and minimizing issues like affordability, scalability, skilled manpower, and many more during migration (Dawadi, Rawat, Joshi, & Keitsch, 2018). Thus, the major motivation of this study is to experimentally evaluate the energy efficiency of SDN enabled IPv6 network by implementing smart sleep-awake operations and traffic load of the entire end access rural network. We also discuss about the alternative energy management and CO₂ emission reduction strategies so that it helps encourage stakeholders towards greening of their ICT infrastructure during their network expansion.

7 | DISCUSSIONS AND RECOMMENDATIONS

Our preliminary study shows that only major ISPs like WorldLink, Subisu, Vianet, Websurfer, Mercantile, and Classic-Tech have backbone network ready for IPv6. But ISPs are not well aware of migrating traditional network to SDN. Taking this as an opportunity, we recommend ISPs and Telcos of Nepal to have SDN enabled IPv6 network deployment during their network expansion towards rural Nepal. Gaining the experience from this SDN enabled IPv6 network at the customer end, operators are expected to encourage themselves to migrate their backbone and metro network towards SoDIP6 network in the near future. The newly deployed access network will be programmable and more visible. Thus, energy-saving schemes can be applied to make devices including CPE and associated links sleep and awake according to network traffic load. In the following section, we present different energy saving and CO₂ emission reduction practices for green networking and put some recommendations to stakeholders for greening of the nationwide ICT infrastructure.

7.1 | Energy-saving and carbon footprint reduction practices

The major challenge of ICT service providers is the transformation of existing ICT network equipment into energy aware green networking system. ESAKI (2015) and Bolla et al. (2012) elaborated major three energy saving approaches in the ICT network. These are reengineering, smart sleeping, and dynamic adaptation. We consider the concept of both smart sleeping and load proportional traffic demand of switch as a part of dynamic adaptation in the SoDIP6 network in our experimental analysis. Reengineering focuses on the design of ICT equipment with complementary metal oxide semiconductor (CMOS) technology for energy saving (Moaiyeri et al., 2011; Salehi & DeMara, 2015) as well as the refinement on the memory technology like TCAM compression for packet processing that optimizes the internal organization of devices (Kannan & Banerjee, 2013; Shue

& Gupta, 2010). Dynamic scaling can be achieved by means of performance scaling, that is, reducing the CMOS applied voltage and changing clock frequency and turning off the subcomponents of equipment during the idle condition. In dynamic adaptation, devices are designed to modulate the packet processing capabilities and network interface with respect to actual traffic load and requirements (Bolla et al., 2012). Adaptive link rate and low power idle are the two techniques under dynamic adaptation in which first allows for dynamic modulation of link capacity or processing engine to meet traffic loads and service requirements, while second technique forces device or link to enter into low power states during idle time at which devices are not processing the packets. During the off-peak hour when network traffic flow is low, reducing the operating frequency of network devices can have significant energy saving. For example, saving of energy can be achieved in SDN by lowering the speed of link basically applicable during the SDN policy updates because SDN policies can be updated with 10Mbps links that consumes 4 watts lower than 1Gbps link (Rawat & Reddy, 2016). Similarly, dynamic changes in routing in the legacy IPv4 routing engine is nearly impossible while dynamic optimization in SDN is fairly simple. For instance, as a part of dynamic adaptation, energy aware routing/switching in SDN is an established approach in which traffic can be rerouted through alternate paths with low or no active traffic so that unnecessary devices or links can be sent to sleep mode for energy saving (Huin et al., Dec. 2018). Smart sleeping is an approach in which the ICT equipment turned into sleep mode if there is no traffic or low traffic is passing through it. Similarly, idle link from where no traffic is passing through can be turned off. Deployment of additional communication infrastructures for SGs should therefore carefully consider the trade-off between the gain in terms of energy saving and the cost of the operating devices while avoiding the posing an unnecessary energy burden to end-customers. The broad choice among the technologies and networks will enable the most efficient, early, and economically viable implementation of SGs. Through government funding under RTDF, Nepalese ISPs and Telcos are expanding their new networking system towards rural Nepal. Taking this as the best opportunity, SoDIP6 network deployment would help to receive all the benefits associated with it.

In addition with above three energy saving approaches as they can be categorized into 'optimization' for energy saving, in the context of rural ICT network, we consider greening of network from the techno-economic and managerial perspectives. Hence, we recommend the additional practices for energy saving and carbon emission reduction with SoDIP6 network in three main categories, as depicted in Figure 13. These are (i) optimization and placement, (ii) policy and deployment, and (iii) monitoring and management of ICT infrastructure. The discussions on subtopics identified on each category are provided in the following sections.

7.1.1 | Network function and server virtualization

Network function virtualization (Faraci & Schembra, 2015) and server virtualizations help reduce the energy consumption in a network (Bolla, Lombardo, Bruschi, & Mangialardi, 2014). The software and network operations previously run in the separate commodity hardware can be moved and relocated to a single hardware with virtualization technologies. It means number of computers are integrated or re-located into a single computer leading to energy optimization and better operations (Botero & Hesselbach, 2013). Organizations can have a single platform and multiple applications that improves scalability and reduce energy consumption (Jin, Wen, & Chen, 2012).

7.1.2 | Network resource optimization

Resource monitoring and its optimum utilization according to network traffic load have a leading role in the reduction of energy usage and carbon footprint. SDN enabled IPv6 network is flexible and programmable so that its intelligent traffic analysis and bandwidth monitoring features help maintain the QoS and proper resource utilization. SDN controller can make decisions based on the traffic volume in the network for promoting green network and efficient network utilization by rerouting the network traffic and putting the idle devices into sleep mode (Fernandez-

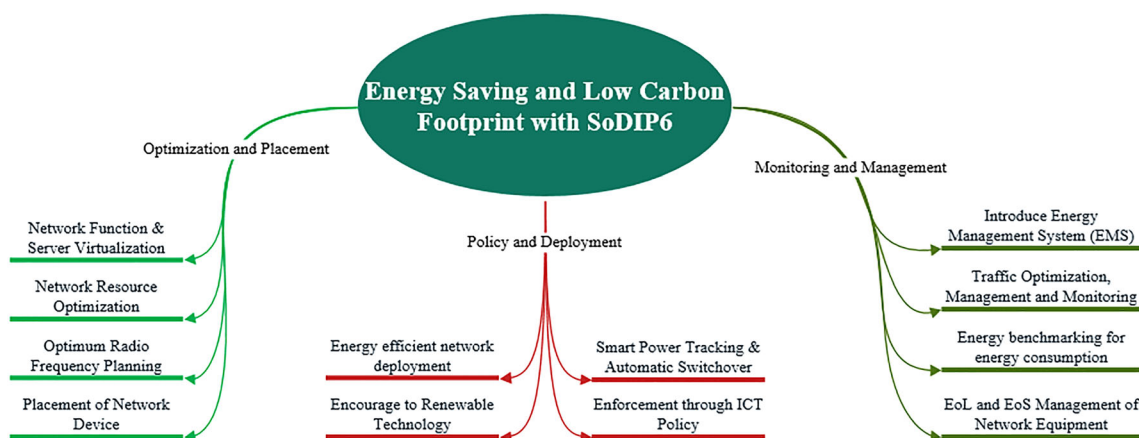


FIGURE 13 Energy-saving practices with SoDIP6 network

Fernandez, Cervello-Pastor, & Ochoa-Aday, 2016; Giroire et al., 2014; Huin et al., Dec. 2018; Nam, Thanh, Thu, Hieu, & Covaci, 2015). Similarly, the unused links in the network can intelligently set into sleep mode to save the energy. Heller et al. (2010) has introduced ElasticTree as an approach in SDN and claimed that 50% power saving can be achieved where optimizer module allocates suitable link to efficiently handle the traffic load to meet QoS requirements. Energy efficient routing protocols can be applied in the network for proper saving of energy and routing management according to energy status (Li, Shang, & Chen, 2014).

7.1.3 | Optimum RF planning

Wireless base stations are the most energy hungry network components in wireless communications (Anastasi, Conti, Di Francesco, & Passarella, 2009). Radio access networks (including BTS and MS) consume almost 80% of total power in cellular network (Rahman, 2009). Optimum RF planning would help to reduce the energy consumption in wireless network with reduction in organization OpEX (Boiardi, 2014). Focusing on sparsely disperse rural population, virtual coverage implementation like use of openBTS and openCellular technologies could be more energy efficient and cost effective for the Internet and Telcos service operators. This will allow operators to control their cellular networks via programs in which idle BTS could be sent into low power mode and wake them up when needed (Anand, Pejovic, Belding, & Johnson, 2012; Anthony, Gabriel, & Shao, 2016; Heimerl, Ali, Blumenstock, Gawalt, & Brewer, 2013; Mpala & van Stam, 2012; Prasannan et al., 2013).

7.1.4 | Placement of network devices

Suitable placement of SDN devices in a network can help to save significant amount of energy consumption by the network (Rawat, & Reddy, 2016). Implementation of SDN allows us to deploy passive devices (data plane) in rural areas where these passive data plane devices can be controlled remotely via the SDN controller. This helps to avoid the need of bigger number of skilled HR to reside in the rural zone for the network operations and management. A more secure infrastructure can be established by placing the controllers in the managed network center, which can be easily accessed to control the rural data plane networks from the control center. For example, every district headquarter of Nepal is reachable by fiber networks. While in the early stage of network expansion, beyond the district headquarter, devices with data plane only can be deployed in rural areas. The controllers that are managed and operated from headquarter create more secure and managed network environment. The requirement of number of controllers in the network depends on the network load and the traffic patterns. The proper placement of controller (Sallahi & St-Hilaire, 2015) with proper design of network having number of switches and connection can improve the overall efficiency of network with reduction in organization CaPEX and OpEX (Das & Gurusamy, 2018). Hasan et al. (2012) believed that SDN-enabled IPv6 Network creates more opportunities to rural network operators by providing simpler and more efficient network operations by decoupling construction of physical infrastructure from the configuration of networks resulting in reduction in cost with minimizing gap of technical and business barriers.

7.1.5 | Energy-efficient network deployment

In the context of Nepal, ICT network is expanding and hence increasing the number of ICT users (MoCIT, 2018). Telcos and Internet ISPs expand their networks by considering their business opportunities. The increase in OpEX in terms of increased annual energy bills can be reduced if focusing on the green networking (Faraci & Schembra, 2015). It means, while deploying the new network, SDN enabled IPv6 network is the potential solution to be considered for overall efficiency and future sustainability.

7.1.6 | Encourage to renewable energy technology

Wind, water, solar, and the warmth in the earth are the major renewable resources that can supply needed power in a sustainable way. Regarding the rural Nepal situation of power supply, installation and operation of micro-hydro power plants are increasing (Acharya & Bajracharya, 2013). The excess power from micro-hydro is planned to supply to national grid, but this can be achieved only after 2022, according to report of NPC (2017). The current electricity crisis at rural Nepal can be somehow minimized by using alternative energy (aka green energy) to supply power to the networking equipment.

7.1.7 | Smart power tracking and automatic switchover

Flexibility in network operations and network programmability features add significant contributions to implement SG and automatic switchover of the system according to traffic load condition. SoDIP6 network is expected to enable efficient monitoring of energy usage by the ICT equipment and automatic switchover of the system according to energy status. This is more applicable in electrical grid network with diverse set of energy sources as it helps to manage power outage.

7.1.8 | Enforcement through ICT policy

Nepalese government does not seem to have an emphasis on green ICT, energy-saving schemes, and CO₂ emission reduction plan. Policies and strategies have not yet been incorporated for ICT ecosystem. The country lies between two big industrialized countries China and India where the Himalayan belt of Nepal acts like GHG sinking zone impacting more on the climate change. Considering the climate change effect and increasing demand of energy with rapidly increasing of internet users, green ICT with carbon trading strategies should be the government's focus so that ICT could be the tool for energy optimization and reduction of GHGs. While, expanding ICT infrastructure to rural Nepal, piloting the network expansion with SoDIP6 network and installation of eco-friendly equipment would help to have green ICT. We review some policy directions, agenda, and advice related to Green Telecommunications by India government (Gupta & Gupta, 2018); South Asian Telecommunication Regulators' Council (SATRC, 2012), China (Zhang & Liang, 2012); and initiations for green ICT by other nations as reported by Asia Pacific Tele-community (APT, 2011). Then, we summarize some policy directions in Table 4 that are expected to be useful in the Nepalese context towards green ICT so that the regulator can refer to for policy initiatives and implementations.

Regulators can apply ITU standards (ITU-T L.1310) (ITU, 2013) for energy efficiency metrics and measurement methods for telecommunication equipment. Similarly, regulator can introduce incentives to energy-efficient operators as a reward like several European countries offering incentives to operators on replacement of older technologies/equipment with newer ones focusing on green technologies (Meo, Rouzic, Cuevas, & Guerrero, 2014).

7.1.9 | Energy management system

Generally, energy management system (EMS) is a system of computer added tools used by service providers to monitor, control, and optimize the performance of electrical generation system. ISPs and Telcos could apply centralized energy and carbon emission monitoring system under the framework of EMS. Regulator is to be allowed to access the energy system of operators via power tracking tool so that regulator can monitor the electrical generation system and the ICT equipment like BTS tower, edge, and backbone switches that help to produce different kinds of reports regarding energy consumption and carbon footprint emissions. Details about the energy audit and management system with different case studies have been presented by Brems, Steele, and Papadamou (2016).

7.1.10 | Traffic optimization, management, and monitoring

Monitoring of energy consumption by network equipment helps to better understand to manage and find the best strategy to adopt in order to maximize reduction of unnecessary usage of electricity. Similarly, BTS energy management is becoming fundamental needs for sustainable development in the ICT sector (Spagnuolo, Petraglia, Vetromile, Formosi, & Lubritto, 2015).

TABLE 4 Recommended policy directions and implementing/enforcing agencies

Policy Directions	Implementing Agencies	Enforcing Agencies
- Rural Nepal has greater potential of solar energy. 1 KW solar photovoltaic system every month prevents 136 kgCO ₂ from entering the environment (NPC, 2017). It is required to encourage the operators to use solar energy to power their network equipment as much as possible for which mobile towers are to be powered by hybrid (electrical grid and renewable energy technology) supply.	- ISPs/Telcos	- NTA/MoCIT
- All service providers have to declare the carbon footprint of their network operation once in a year.	- ISPs/Telcos	- NTA/MoCIT
- All service providers should conduct energy and performance assessment of equipment and services in telecom network once in a year.	- ISPs/Telcos	- NTA/MoCIT
Green passport certification is to be provided to every network equipment during import in addition with type approval.	NTA	MoCIT
All service providers should aim at yearly carbon emission reduction target for the mobile/ISP network.	ISPs/Telcos	- NTA/MoCIT
- All service providers should declare energy consumption and carbon (kg) emission status in their network as green parameters to the regulators annually.	- ISPs/Telcos	- NTA

Abbreviations: ISP: Internet Service Provider; NTA: Nepal Telecommunications Authority; MoCIT: Ministry of Communication and Information Technology.

7.1.11 | Energy benchmarking for energy consumption

Energy audit is the part of energy management system. Benchmarking or auditing of network operations and services help to identify and quantify the cost-effective energy saving opportunities and report opportunities for service providers. In the context of Nepal, regulator can apply energy audit policy at least once a year to the ICT industries and identify the environmental impact of ICT via energy use and CO₂ emission.

7.1.12 | End of Life (EoL) and End of Sale (EoS) management of network equipment

End of Life (EoL), End of Sale (EoS), and the Last Day of Support (LDoS) of network equipment are the important parameters required to be maintained by every organization while running network services. Due to lack of sufficient fund, fairly sustained service providers of developing countries do not plan for the device replacement according to EoL and EoS of network equipment. Due to rapid innovation in hardware as well as software system, ICT equipment's productive life cycle is comparatively shortened. New equipment produced are more energy efficient. Hence, it is the role of ISP/Telcos operator to keep records of their network equipment and act accordingly with the product life cycle.

7.2 | Challenges and opportunities for Nepalese service providers

This section presents the challenges that stakeholders are facing and opportunities for them regarding the new network deployment in lights of the domain knowledge obtained during questionnaire survey. The major challenges of network migration and way forward for service providers of developing nations like Nepal are as follows:

- **Cost of migration:** The network components may require either replacement or upgrade of hardware/software system to be compatible with new networking technologies like SDN and IPv6. This incurs with high cost for network migration and human resource development. However, migration to IPv6 network is inevitable for service providers; meantime, the emergence of SDN put additional pressure for their network migration. Major ISPs of Nepal have their backbone network ready with IPv6 operation, but the challenges of access network migration like replacing of CPE and non-demand from the customer side creates wait and see situation for ISPs, Telcos, and Data Center service providers of Nepal. Expanding the rural network first time by the NTA initiated project utilizing RTDF with the legacy equipment creates additional burden of cost for service providers to migrate this network into SoDIP6 network in the future. Hence, planning of migration of existing network in a phase wise manner and creating/expanding any new networks with OpenFlow and IPv6 supported infrastructure would be an intelligent and more cost-effective approach of network transformations for the service providers. Encouragement to service providers with suitable regulatory framework and provision of subsidization scheme to promote technology migration by the government would help to address this challenge. Similarly, for the reduced cost of maintenance, optical fiber network is comparatively more efficient to lay down submarine cables in the rural areas (Murata, Mano, & Morioka, 2011).
- **Skilled HR:** For the existing system operation and management, there is no scarcity of skilled HR and the existing system is well stable. There is always a scarcity of skilled HR who can expand and operate new system, and technologies as the service providers have to expand their infrastructure with newer technologies and migrate their existing infrastructure in a phase-wise manner. Existing legacy network transitioning to SoDIP6 network is a long-term plan in which the organizational budget, HR, and system/application readiness play a major role for transition. However, technically migration of legacy network to SoDIP6 network is viable. The scarcity of skilled human resource to migrate existing network and establish SoDIP6 network is another major challenge for service providers. Regulator has to conduct research and training to develop skilled HR in addition to service provider's in-house research and training. As far as we have realized, industry-university tie-up is not strong enough in Nepal. Better collaboration of industries with universities is required to produce resources as per market demand to address resource shortage issues.
- **Applications/protocol supports and security:** During the phase of transition, ie, in the early stage of new system implementations, the available applications and protocols may not be compatible and stable. The worldwide status of network migration (ISOC, 2018) shows that IPv6 implementations are widely supported and nearly matured with availability of different migration approaches. Similarly, SDN implementations in the ISPs and Telcos networks are under research and development, tests, and implementation phase (Kobayashi et al., 2014; ON.LAB, 2014; ONF TR-506, 2014). Service providers of developing nations are not in the stage of well secure applications and protocol development. Hence, there is always the fear of system/application security and service interruption while implementing newer technologies. These can be considered as the challenges for service providers.
- **Demography and geography of Nepal:** The major cause of detraction to enhance ICT in rural Nepal is of diverse demography and difficult geographic distributions since there is always fear of business continuity issues for service providers with low purchasing power of rural communities. According to MoPE (2017), projected population of Nepal in 2016 was 28.4 million where urban population was almost 20 million and rural population was 8.4 million. By geography, Nepal's land is divided into three regions, these are Mountain (altitude between 4877 and 8848

meters), Hills (altitude between 610 to 4876 meters), and Terai (regions below elevation 610 meters). Mountains and Hills cover almost 77% of total land but population account 49.7%, while 23% land coverage of Terai region has population ratio of 51.3%. Most of the urban cities are located in the Terai zone. Population growth rate of Terai is higher than other two regions, and peoples are migrating to Terai from the Hill and Mountain. This is because of difficult geography of Hill and Mountain, lack of basic facilities and infrastructure for living, favorable environment for the rebellion, and other political movements against government like 10-year Maoist insurgency (Thapa, 2003) caused many people displaced from the hilly region. The 2015's devastating earthquake highly affected the Hilly zones of middle and western part of Nepal. This caused positive vibes to the people for urbanization with building earthquake proof houses in rural areas. Similarly, Nepal government has launched the national reconstruction project and is subsidizing the rural people to build their houses under government's regulatory framework. This helps to minimize the migration issues.

The process of ICT infrastructure and service expansion in rural Nepal is costly with lack of proper transportations and absence of proper infrastructure security facilities. The destruction of infrastructure like telecom towers and equipment during 10 years of Maoist movements between periods from 1996 to 2006 AD (Thapa, 2003) was one of the obstacles of network expansion for private operators. However, the major insurgency was settled, still few known/unknown political movement exists and create less secure environment to the investors to expand services to rural and far rural areas of Nepal.

- Government plan and policies: Most of the opinions of service providers reflect to the lack of government's proper policy, guidelines, and subsidy plan to promote ICT and green networking at Nepal. State should timely address the pace of global technological change via policy initiatives and create suitable environment to adapt new technologies. Recent initiatives of utilizing RTDF to provide subsidy to expand ICT infrastructure is expected to be contributory towards building smart societies and economic growth of Nepal.

The recent political transformations towards stability and government subsidy plan to develop nationwide ICT infrastructure as well as increasing pattern of automation in government offices and companies create good opportunities for service providers to expand infrastructure and services with latest technologies so that all the stakeholders would be benefitted. Upgrading existing service system's hardware devices and software system to make it compatible with newer technologies is fairly complicated than to establish new system with latest technologies. Hence, in the situation of backbone network with IPv6 ready, it would be an opportunity for service providers to establish access network with energy-efficient SoDIP6 network and ensure latest service technologies for the long-run sustainability. Implementing edge network with SoDIP6 in the broadband expansion initiatives would encourage for phase-wise backbone network migration with optimized OpEX.

8 | CONCLUSION AND FUTURE WORKS

Being a mountainous country, the adverse effects of global warming and climate change will be higher for Nepal. ICT is considered as a tool of transformations in the emerging economy. However, its impacts on energy consumptions and GHG emissions have to be tackled with higher priority. Newer technologies help existing rural as well as urban communities easily by transferring into smart communities (smart city, smart village etc.). With the increasing number of Internet users in the developing nations like Nepal, the increasing demand of energy in the field of ICT and its effects should be addressed in a timely manner. In this paper, current status of ICT infrastructure deployment including SDN and IPv6 implementation status by Nepalese ISPs and Telcos with challenges and opportunities are presented. Greening of network and its contribution to organizational OpEX saving via SoDIP6 network implementations are discussed. Additionally, this paper has experimentally evaluated the energy consumption by SDN enabled IPv6 network considering the testbed with ISP end access network. The results show that SoDIP6 can achieve 31.50% energy saving in switches and 55.44% saving in the links as compared with legacy IPv4 networking system. We have also presented a discussion on energy saving approaches in terms of technology, operations, and management with recommendations to concerned stakeholders of Nepal. We recommend harmonizing the Nepal's ICT/Broadband policy with energy policy so that the targets set by ICT policies will be tangible ones towards greening of the nation-wide network infrastructure. Similarly, SoDIP6 network is more contributory towards greening of nationwide ICT infrastructure. Hence, it is required to encourage ISPs/Telcos to deploy SoDIP6 network during their new network expansion that would help to realize the benefits of migrating their legacy network into SoDIP6 Network. Policy implications and the impact analysis of ICT infrastructure expansion at rural Nepal in the different dimensions like e-education, e-agriculture, tele-medicine, and energy consumption behavior. for the rural communities as well as energy efficiency evaluation of SoDIP6 network using different energy saving practices discussed briefly in this paper are considered to be our future research.

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