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Green hydrogen potentials from surplus hydro energy in Nepal

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HIGHLIGHTS

- Methodological study for quantification of excess hydropower and hydrogen production.
- Cost projections scenarios from green hydrogen from surplus hydropower electricity.
- Identification of role of green hydrogen in multiple end-use areas of developing nation.
- Potential replacement of conventional fuel with hydrogen in transportation sector.

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ABSTRACT

This paper studies the potentials of green hydrogen production from hydropower energy and its application in electricity regeneration and replacement of petroleum products from the transportation sector in Nepal. The potential surplus hydroelectric energy, and hydrogen production potential from the surplus energy considering different scenarios, is forecasted for the study period (2022–2030). The results showed that hydrogen production potential ranges from 63,072 tons to 3,153,360 tons with the utilization of surplus energy at 20% and 100% respectively, in 2030. The economic analysis of hydrogen from hydropower projects that electricity is valued based on per kg of hydrogen when the surplus electricity is provided at feasible lower price values compared to the US $1.17. This study concludes that hydrogen production from spilled hydro energy and its use in the transportation sector and independent electricity generation is a niche opportunity to lead the country towards sustainable energy solutions and an economy running on hydrogen.

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Nomenclature

Variables

AGR	Annual Gasoline Replacement, kL
HP	Hydrogen Potential, tons
PL	Peak Load, MW
REP	Re-Electrification Potential, GWh
SE	Surplus Energy, GWh
TIC	Total Installed Capacity, MW
TR	Tariff Rate, US $/kWh
UEC	Unit Electricity Cost, US $/kgH$_2$

Abbreviations

CAPEX	Capital Expenses
FCEVs	Fuel Cell Electric Vehicles
FY	Fiscal Years
GDP	Gross Domestic Product
H—$_2$	Hydrogen
IEA	International Energy Agency
IPPs	Independent Power Producers
LPG	Liquefied Petroleum Gas
LCOH	Levelized Cost of Hydrogen Production
NEA	Nepal Electricity Authority
OPEX	Operating Expenses
PPAs	Power Purchase Agreements
RoR	Run-off-River
SUVs	Sports Utility Vehicles

1. Introduction

The global energy-related carbon emissions reached the historic high of 33.1 gigatons of CO_2 in 2018. The emissions from all fossil fuels were increased: the power sector alone accounted for nearly two-third of the emission growth [1]. The increased carbon emission led to the temperature rise and is expected to be 1.5 °C above the pre-industrial level in 2100. To restrict this temperature rise, there is need for a decline in the global emission by about 45% from 2010 levels by 2030, reaching net zero by 2050 [2]. Hydrogen (H_2) is fast emerging as an alternative energy carrier with the highest heat value of 120–142 MJ/kg compared to 44 MJ/kg of gasoline and 20 MJ/kg of coal [3]. Most of the countries around the world are focusing on green hydrogen technologies to reduce carbon emissions from industries, transport, and commercial sectors. By 2050, it is projected that the green hydrogen aims to exceed 540 million metrics tons with the transportation sector alone contributing to 154 million metric tons of the total share [4,5].

Hydrogen is not found freely in nature but can be produced from various primary energy sources such as biomass and fossil fuels, and secondary energy sources such as renewable electricity from solar, wind, and hydropower. The produced hydrogen can be used as fuel for a wide range of end-use conversion processes such as power, mobility, industries, and buildings [6]. Hydrogen is considered as a near-zero carbon emission energy carrier; however, hydrogen's lifecycle carbon footprint is generally determined based on the resources used, methods followed, and carbon emission used to extract it [7]. Accordingly, hydrogen is classified into grey, blue, or green. 'Grey hydrogen' is produced from fossil fuels, 'blue hydrogen' is produced from fossil fuels with carbon capture, utilization, and storage, meanwhile, 'green hydrogen' is produced from the renewables [7,8].

Hydrogen from renewables has become technically feasible and economically competitive in recent years. Renewable energy sources mainly: solar energy, wind energy, and hydropower energy have been prioritized to produce green hydrogen depending on the availability of these resources [9]. The major challenges of renewable electricity are the intermittency in energy production and storage of surplus energy during off-peak load. Producing hydrogen through electrolysis using renewable energy and combining it with different storage methods can create short-term seasonal or long-term reserves for re-electrification and end uses in various industrial heat and power generation, transportation, and commercial sectors [9]. The purest hydrogen is obtained by the electrolysis of water molecules using electrolyzers which can be powered by renewable electricity. Among the several methods of producing green hydrogen, the electrolysis method is more efficient, less carbon-intensive and, cost-effective in terms of generation cost. The cost of hydrogen is directly dependent on the price of supplied renewable electricity [10].

The hydrologic and economic restraints have led to lower capacity utilization of the total installed capacity in most of the hydroelectric powerplants around the world, be it large-scale dams or small-scale Run-off-River (ROR) plants. To increase the efficiency and capacity utilization of hydropower, conversion of water to hydrogen through electrolysis using excess energy or spilled energy not yet utilized could be an alternative option. Several studies have shown the possibilities of increasing the capacity utilization of hydropower plants by generating and storing hydrogen from the spilled energy during off-peak periods and during the high inflows of water in the rainy season [11,12]. Production of hydrogen from hydroelectricity is more cost-effective where hydroelectricity source is abundant and electricity cost is very low. Different hydro-rich countries like Brazil, China, Norway, Canada, and the U.S.A have been producing hydrogen from hydroelectricity by undertaking ambitious development projects of hydrogen energy [9,13,14]. The plants in these countries are large water storage dams, a similar approach can be followed in a country like Nepal where more than 90% of the hydropower plants are run-off-river types designed based on the dry season flow and a huge amount of energy is spilled during the rainy season [15].

Hydrogen production potential from hydropower can be estimated using two basic approaches. The first approach is by assuming a certain percentage of the available economic hydropower potential is utilized in the production of H_2 by electrolysis, similar to the study done in Venezuela [16]. The second approach is to assess hydrogen production potential based on the electricity that would have been surplus and curtailed due to demand reduction or increased production from increase in water inflows during the rainy season in the ROR plants. Studies done following the latter approach have shown that hydrogen production potential from surplus hydro energy is very effective and generates large values from the curtailed energy [12,15].

Nepal is one of the hydro rich countries in the world with huge hydropower prospects. More than 20,000 MW of hydropower projects are at the developmental stage in Nepal. The forecasted domestic demand for electricity is much lower than the production within the next decade [5]. It is projected that around 3000 MW of energy is going to be surplus in Nepal by 2030 due to an imbalance in the supply and demand scenario [5,15]. More than 90% of the hydropower plants in Nepal are run-off-river types. As a result, the existing hydropowers have not been run on full capacity utilization and are not able to meet the electricity demand in the country during the dry season. During the rainy season, the hydro energy has been surplus and is being curtailed without generating any values. The energy supply mix shows that fossil-based energy has a share of 25% compared to 7% combination with electricity and renewable energy supply in 2019 [17]. Increased capacity utilization of hydropower and producing hydrogen from the hydropower surplus electricity is one of the possible options to addressing the energy distribution problem in Nepal [17]. To generate value, from the future surplus electricity, there is need to initiate the study related to hydrogen production potential in Nepal and in end uses. A study done in 2008 projected that Nepal has the potential to produce hydrogen from existing hydropower plants during the off-peak load by utilizing surplus electricity. The possibility of utilizing produced hydrogen energy to replace the existing fossil fuels was also done in the study. The result indicated the potentials of producing 8370 tons of hydrogen when 20% of surplus energy in 2005 was utilized, and that hydrogen has the potential to replace 31,680 kL of gasoline [18]. As there has been quite a rapid development in hydrogen production technologies compared to that of 2008, a new study is needed to identify the future potential of green hydrogen production and end-use for a hydro-rich country like Nepal. Nepal needs to focus on utilizing abundant hydro-energy to produce green hydrogen for sustainable energy solutions and for the transition to a hydrogen-based economy, balancing the future energy distribution scenarios: increasing the share of renewables and electricity.

The presented work systematically estimates the potential production of hydrogen in Nepal from the surplus of hydro energy that is projected to be spilled and not utilized. The economic analysis for the cost of energy to produce green hydrogen in different scenarios is investigated. The potential re-electrification using hydrogen to meet the electricity demand in places where grid connectivity is not accessible is identified. Effort has been made to estimate the potential replacement of gasoline using green hydrogen in the transportation sectors of Nepal.

2. Hydroelectricity current scenario in Nepal

The theoretical and economical hydropower potential of Nepal is 83,000 MW and 42,133 MW, respectively [19]. Although Nepal has huge hydropower potential, by the end of the year 2019, the total installed capacity of the hydropower plant was 1113.8 MW. This accounted for about 2.64% of the total economically feasible potential. The peak demand for electricity in Nepal was 1408 MW for 2019 and this demand was fulfilled by Nepal Electricity Authority (NEA) own generation of 2548 GWh, 2190 GWh power purchased from Independent Power Producers (IPPs), and 7551 GWh purchased from India. Currently, NEA owns 553 MW installed capacity and IPPs own 561 MW. To address electricity supply constraints in Nepal, NEA has accelerated the development and implementation of NEA-owned hydropower plants. A total of 340 Power Purchase Agreements (PPAs) were signed by the end of 2019 with various IPPs for a combined installed capacity of 6044 MW [20]. The Government of Nepal carries an ambitious plan to increase the hydropower generation capacity by 3 GW in 3 years, 5 GW in five years, and 15 GW in 10 years [21].

Nepal has taken a huge leap toward hydro energy generation through capacity addition. In the meantime, a large amount of energy is projected to be surplus due to lower demand and distribution constraints. The mountainous topography has made it difficult to build a comprehensive transmission electrical grid in different parts of Nepal. The seasonal power generation in Nepal, as most of the rivers are run-off river (RoR) types, has resulted in the poor 'load factor'. The power generated by hydropower stations during the rainy season in 2019 surpassed the peak demand that varies from 800 MW to 1450 MW [20]. In the same year, the power was inadequate to fulfill the total dry peak demand. Table 1 shows the maximum, minimum, and dry peak demand recorded in the system load curve for the fiscal year 2019/2020 [20]. The maximum demand for 2019/2020 was 1407.53 MW recorded on 9th September 2019 against the installed capacity of 1113.8 MW and the minimum demand was 815.48 MW recorded on 23rd April 2020. The total electricity generated in 2019 was 4738.16 GWh which suggests a capacity factor of approximately 48%. Such a low-capacity factor is one of the reasons for very high tariff rates of electricity in Nepal compared to the neighboring countries, making the power trade a difficult option [22].

A considerable gap in the energy demand and supply scenario in Nepal is projected in the upcoming decade. With the increased capital investment in hydropower, the total installed capacity exceeds the demand. Fig. 1 presents the energy balance projection scenario of Nepal for 2020–2030, assuming a constant 5% Gross Domestic Product (GDP) growth rate [20]. By 2030, almost 3000 MW of hydroelectricity is projected to be spilled. In such a scenario, hydrogen production potential from surplus energy and its application in the end-use areas: off-grid electricity regeneration, and gasoline fuel replacement potentials is calculated and analyzed in this study. The following sections elaborate the details about the hydrogen production from surplus energy, cost of energy, and

Table 1 – Annual maximum, annual minimum, and peak electricity demand 2019/2020 [20].

Demand type	Demand (MW)	Date	Peak demand hours
Annual Maximum	1407.94	September 9, 2019	19:05 h.
Annual Minimum	815.48	April 23, 2020	19:00 h.
Dry peak demand	1374.90	January 12, 2020	18:30 h.

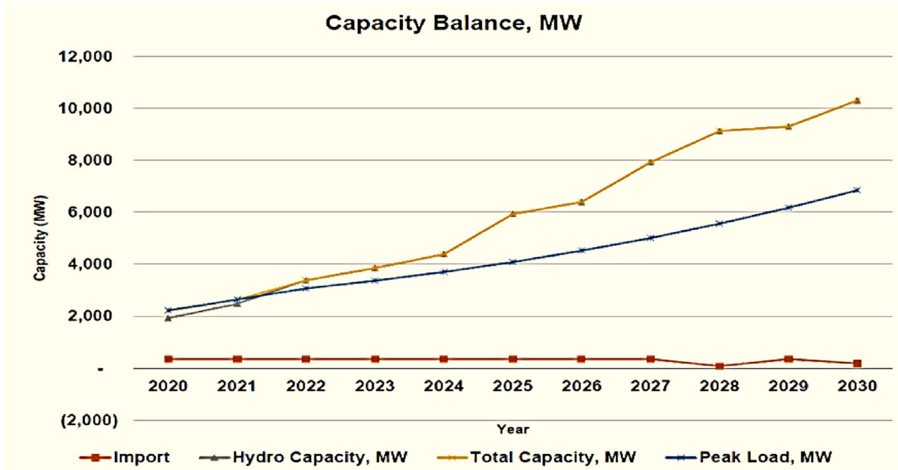

Fig. 1 – Capacity balance projection Nepal: 2020–2030. Adapted from Ref. [20].

subsequent application on electricity regeneration and transport sector.

3. Hydro to hydrogen study methods

3.1. *Hydrogen generation from hydropower*

Hydrogen production potential is calculated based on the surplus hydro energy. The surplus hydropower energy potential (SE) is calculated using the energy capacity balance projection data provided by Nepal Electricity Authority shown in Fig. 1, [20].

The total projected peak load (PL) is subtracted from the total projected annual capacity installation (TIC) and is multiplied by the overall capacity factor of hydropower. The capacity factor of hydropower plants for electricity generation to be used for hydrogen production is considered to be 60% based on the study done in Refs. [15,21]. The formula used to calculate the annual surplus hydro energy from hydropower is given by Equation (1).

Surplus Hydro Energy calculation:

$$SE = [(TIC - PL) * 365 * 24 * 0.6] / 1000[\text{GWh}] \tag{1}$$

Where SE is Surplus hydro Energy, TIC is Total annual Capacity Installation, and PL is Peak load.

Based on the surplus hydropower energy that could be used to produce hydrogen, the hydrogen production potential is calculated for the 5 different scenarios for the study period of 2022–2030, as shown in Equation (2).

$$HP = (SE) / (50 * 1000)[\text{tons}] \tag{2}$$

Where HP is Hydrogen Potential.

The energy consumption by the electrolyzer is taken as 50 kWh per kg H_2, without including energy consumption by auxiliary equipment required for the treatment and compression of gases [17]. The unit energy consumption is estimated to remain constant throughout the study period.

The following 5 different scenarios are identified for the hydrogen potential calculation in this study:

1. Scenario 1 (S1-HP) - 100% surplus hydro energy utilization
2. Scenario 2 (S2-HP) - 80% surplus hydro energy utilization
3. Scenario 3 (S3-HP) - 60% surplus hydro energy utilization
4. Scenario 4 (S4-HP) - 40% surplus hydro energy utilization
5. Scenario 5 (S5-HP) - 20% surplus hydro energy utilization

3.2. *Energy cost to produce hydrogen*

The Unit Energy Cost (UEC) to produce green hydrogen from hydro energy is studied for the different scenarios mainly percentage reduction in the current tariff rate allocated by the Nepal Electricity Authority. Table 2 shows the different tariff rates fixed by Nepal Electricity Authority (NEA). During the off-peak period, the per-unit energy charge is US $0.039 for 132 kV and US $0.040 for 66 kV application [20]. The usual tariff rate is taken as a business as the usual or base case for this study along with other scenarios on percentage reduction on the usual tariff rate. The energy consumption per unit kg of hydrogen is multiplied with a tariff rate (TR) to determine the energy cost per unit kg hydrogen as shown in Equation (3).

$$UEC = 50 \times TR[\text{US \$ / kgH}_{2\neg}] \tag{3}$$

Where UEC is Unit Energy Cost, and TR is Tariff Rate.

Approximately 400 MW of hydroelectricity is projected to be surplus during the monsoon season (June–September) of 2021 [20] in Nepal. The surplus hydroelectricity has possibilities of utilization to produce green hydrogen by further reducing the cost of electricity during off-peak load. By so

Table 2 – Energy charge US $/kWh Nepal [20].

Consumer Category	Energy Charge US$/kWh		
	Peak Time (17.00–23.00)	Off-peak Time (23.00–5.00)	Normal Time (5.00–17.00)
Industrial (132 kV)	0.085	0.039	0.069
Industrial (66 kV)	0.086	0.040	0.070

doing, the otherwise spilled energy can generate economic outcomes and increase the plant capacity factor. The study of the annual reports provided by NEA and IPPs [20,21] suggests that independent power producers are providing surplus electricity to Nepal Electricity Authority during the rainy season at zero cost. The consultation with the experts suggests that such independent power producers and NEA itself, are in need of alternative methods of utilizing such surplus energy at near-zero cost and hydrogen production is one of the options. The cost of electricity is estimated at the range of 0.0078 US $/kWh kgH_2 to the maximum of business as usual i.e., 0.039 US $ kWh kgH_2 [20] by consulting with the expert from Nepal Electricity Authority, IPPs, and others. The surplus energy, when provided with the marginal cost to produce hydrogen, the effect of capital expenses (CAPEX), and operating expenses (OPEX) of electrolyzers in the Levelized cost of hydrogen (LCOH), is dominant for low to mid-range load factor. A study has shown that hydrogen production is a viable option if the operating hours are above 2100 when LCOH is comparable with the steam methane reforming method [23]. For this study, five different scenarios: percentages reduction on the surplus energy and off-peak load are estimated to analyze electricity cost to produce a unit kg of hydrogen.

1. Business as usual (S1-UEC)- Usual Tariff Rate fixed by NEA Nepal
2. Scenario 2 (S2-UEC) - 20% of the usual Tariff rate
3. Scenario 3 (S3-UEC) - 40% of the usual Tariff rate
4. Scenario 4 (S4-UEC) - 60% of the usual Tariff rate
5. Scenario 5 (S5-UEC) - 80% of the usual Tariff rate

3.3. *Re-electrification potential using hydrogen*

The hydrogen produced from the surplus hydro energy can be further used to generate electricity using fuel cells independently. The electricity generated from hydrogen has potential application to generate power in remote places, where grid electricity is not available. Also, the electricity generated from hydrogen has the potential to replace fossil-based energy from industrial and commercial sectors like diesel-based generators. The potential re-electrification using hydrogen is calculated estimating that 1 kg of hydrogen can produce 20 kWh of electricity based on the current efficiency of fuel cells at 60% [17]. The electricity regeneration is calculated using the amount of hydrogen produced based on a percentage of surplus energy utilization using equation (4) defined as:

$$REP = [(HP * 20)] \;/\; 1000[\mathrm{GWh}] \tag{4}$$

Where REP is Re-Electrification Potential.

To analyze the re-electrification potential from hydrogen, the same scenarios while calculating hydrogen potential from the surplus energy are assumed.

1. Scenario 1 (S1-REP) - Re-electrification using hydrogen from 100% surplus hydro energy utilization
2. Scenario 2 (S2-REP) - Re-electrification using hydrogen from 80% surplus hydro energy utilization
3. Scenario 3 (S3-REP) - Re-electrification using hydrogen from 60% surplus hydro energy utilization
4. Scenario 4 (S4-REP) - Re-electrification using hydrogen from 40% surplus hydro energy utilization
5. Scenario 5 (S5-REP) - Re-electrification using hydrogen from 20% surplus hydro energy utilization

3.4. *Potential gasoline replacement using hydrogen*

Hydrogen from surplus hydropower has an immense potential to replace the existing gasoline fuels in Nepal. The import of petroleum products such as petrol, diesel, kerosene, aviation oil, furnace oil, and LPG from India has been increasing rapidly. The petrol, diesel and kerosene import in 2019/2020 accounted for 512,128 kL, 1,473,536 kL, and 18,924 kL, respectively [24]. In such a scenario, hydrogen with high energy content by weight can replace the dependency on petroleum products in the transportation sector. To calculate the amount of gasoline fuel replacement using hydrogen, it is estimated that 1 kg of hydrogen is energetically equivalent to a US gallon of gasoline which means 1 ton of green hydrogen can replace 3.785 kL of gasoline [18].

The equivalent amount of annual gasoline replacement (AGR) by the hydrogen produced from surplus hydrogen at different scenarios is based on the equation (5):

$$AGR = HP{*}3.785[\mathrm{kL}] \tag{5}$$

Where AGR is Annual Gasoline Replacement.

Five different scenarios are studied to analyze gasoline fuel replacement using hydrogen. The hydrogen produced utilizing surplus energy at different scenarios is considered as a base for this calculation.

1. Scenario 1 (S1-AGR) -Gasoline fuel replacement using hydrogen from 100% surplus hydro energy utilization
2. Scenario2(S2-AGR)-Gasoline fuel using hydrogen from 80% surplus hydro energy utilization
3. Scenario 3 (S3-AGR)-Gasoline fuel using hydrogen from 60% surplus hydro energy utilization
4. Scenario 4 (S4-AGR)-Gasoline fuel using hydrogen from 40% surplus hydro energy utilization
5. Scenario 5 (S5-AGR)-Gasoline fuel using hydrogen from 20% surplus hydro energy utilization

4. Results and discussions

Results are presented and discussed in individual sections: hydrogen generation from hydropower for the five different scenarios, unit energy cost for different tariff rate to produce hydrogen from surplus hydroelectricity, independent electricity generation potential to replace fossil-based electricity supply, and increase access to electricity in remote areas not connected to the grid, and the potential gasoline replacement from transportation. Each section is followed by a brief discussion on the applicability of findings to other regions.

4.1. *Hydrogen generation from hydropower*

Fig. 2 shows that the surplus electricity for 2019 had the potential of producing 25,569 tons of hydrogen potential. When 20% of this surplus energy is used to produce hydrogen, there is the potential of 5240 tons of hydrogen that can replace 19,833 kL of gasoline fuel. Around 99,091 kL of gasoline fuel can be replaced with 100% utilization of surplus energy which accounts for around 19% of total gasoline (petrol) import of 512,128 kLin Nepal in 2019.

The potential hydrogen production forecast is calculated using equation (2) for surplus energy at different scenarios (use of surplus energy at various percentages) and presented in Fig. 3. The projected surplus energy ranges from a minimum of 2102 GWh for 2022 to 16,820 GWh for 2028. When this surplus energy is used to produce hydrogen for different percentage utilization scenarios, the total annual hydrogen production varies between a minimum of 8410 tons and a maximum of 336,384 tons for the study period of 2022–2030. The minimum amount of hydrogen produced for the year 2022 is 8410 tons for 20% surplus energy utilization and the maximum amount is 336,384 tons for 100% surplus energy utilization. The highest potential hydrogen production was recorded for the year 2028, as the surplus energy generation for this year is the highest and this hydrogen can replace approximately around 1.2 million kL of gasoline fuels from transportation and industrial sectors in Nepal. This represents 25% of the total projected demand: 4.5 million kL of gasoline fuels for the same year. When only 20% of the surplus energy is utilized to produce hydrogen, then nearly 67,277 tons of hydrogen can be produced in 2028 and this is enough to regenerate around 1346 GWh of electricity using fuel cells during the same year.

The hydrogen produced from the hydropower has potential to be applied as feedstocks in the urea and ammonia industry as well. For example, the hydrogen produced from 20% to 80% surplus energy utilization scenarios for the year 2022 when used to produce urea, the amount of urea produced ranges from a minimum of 33,638 tons to a maximum of 326,292 tons of urea-based on methods discussed in Ref. [25]. This maximum amount of urea production possibility in the year 2022 from green hydrogen exceeds the annual import of around 300,000 tons of Urea in Nepal from third countries. The annual total demand for Urea fertilizer in Nepal is around 800,000 tons. To meet this demand, the annual green hydrogen demand is around 82,475 tons, and this demand is exceeded by the hydrogen produced which utilizes 40% surplus energy by the year 2025. This implies that the green hydrogen has the potential to meet the feedstock requirement to produce Urea in Nepal.

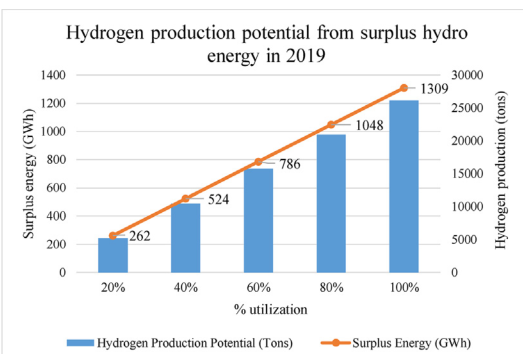

Fig. 2 – Potential hydrogen production from excess hydro energy in Nepal in 2019.

4.2. *Energy cost to produce hydrogen*

The surplus energy in the context of Nepal can be provided at a lower cost to produce green hydrogen, otherwise the energy would be spilled. Fig. 4 indicates the cost of production of hydrogen for business-as-usual or scenario 1 (S1-UEC) as

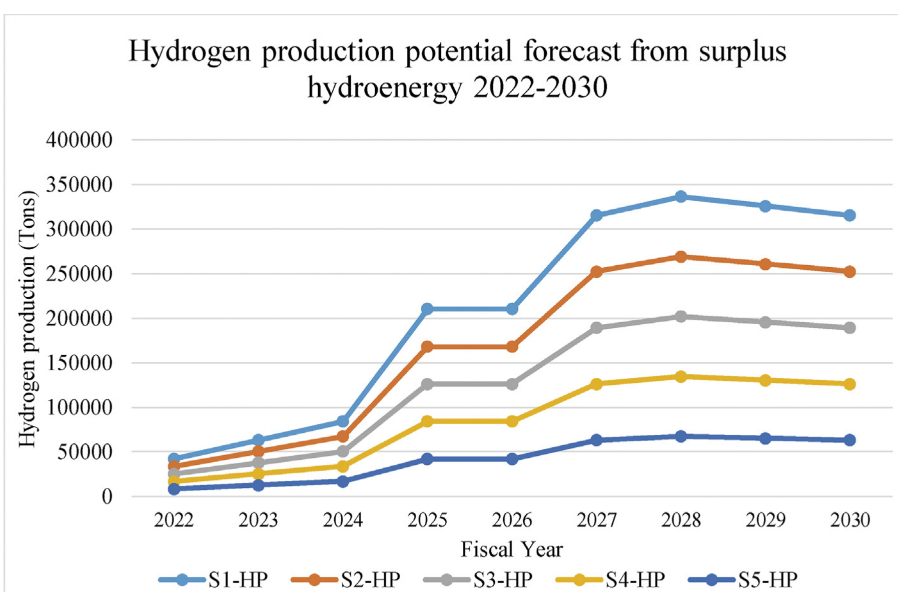

Fig. 3 – Potential Hydrogen production (HP) forecast at different scenarios using Surplus Energy for 2022–2030.

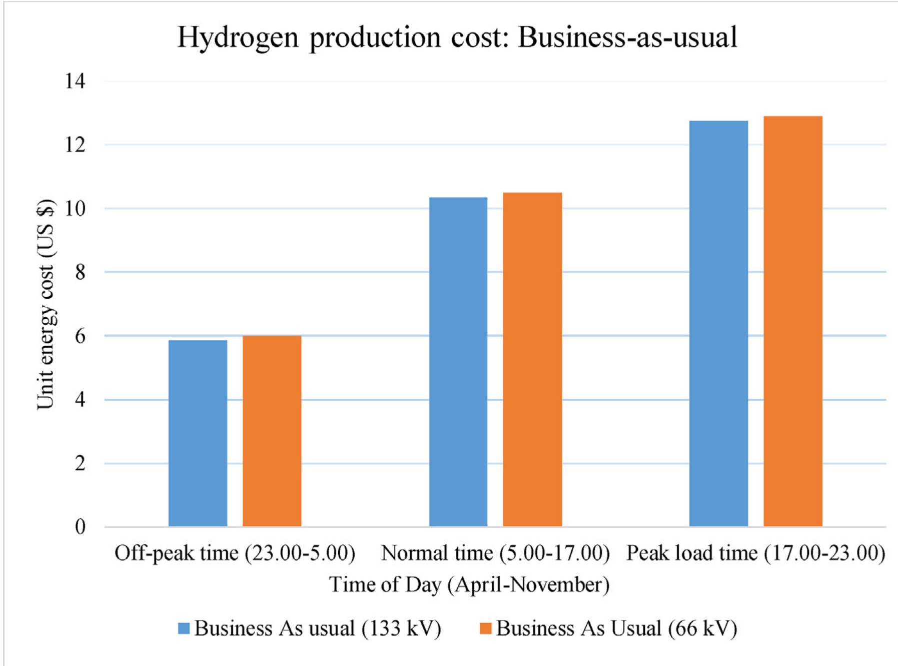

Fig. 4 – Electricity cost for hydrogen production for business-*as*-usual at three different times of the day.

discussed in the methodology section. The electricity cost to produce 1 kg of hydrogen is around US $5.91 during the off-peak period (23:00–5:00) when the load generation exceeds the demand and electricity spilled. When hydrogen is produced during the normal day time (5:00–17:00), the electricity cost nearly doubles with the value of US $ 10.35 and if hydrogen is produced during the peak load time (17:00–23:00), then the cost records the highest with US $ 12.75. The production price of hydrogen at the business-*as*-usual rates of electricity is comparatively higher than that in the international market. The proposed hydrogen production is aimed at using spilled and surplus energy, which otherwise would have been curtailed without generating any values, the actual unit cost of electricity used to produce hydrogen can be reduced and brought to near zero value or marginal cost. The electricity cost when reduced from the usual tariff rate significantly reduces the cost required to produce hydrogen.

Fig. 5 and Fig. 6 elaborate on the unit electricity cost and cost to produce hydrogen for three different times of the day and for five different scenarios. When the usual tariff rate is reduced by 80% (S5-UEC), the unit electricity could be provided at US $0.0078. A total of 1 kg hydrogen production electricity cost would be around US $1.17, US$2.07, and US $2.55 during the off-peak load, normal time, and peak load time, respectively, which is cheaper and cost-competitive to hydrogen production price in the international market.

The electricity cost at different tariff rate scenarios clearly shows that hydrogen production in Nepal can be cheaper and cost-effective compared to other countries. The cost of electricity to produce hydrogen ranges from a minimum of 1.17 US $/kgH_2$in the best-case scenario to a maximum of 6.04 US $/kgH_2$ when surplus electricity is utilized during the off-peak load time. A similar type of study done in Ecuador shows the cost of hydrogen production to be about 1.77 US $/kgH_2$ in the best case scenario [13]. The hydrogen production cost from natural gas using steam methane reform varies from 1.25 US $/kg to 3.50 US $/kg, with a natural gas price of 0.3 US $/kg [7]. The hydrogen production energy cost is comparatively cheaper than the conventional technologies. The study done by IEA shows that hydrogen costs from hybrid solar PV and onshore wind systems in Nepal are around 2.8–3.0 US $/kgH_2$ [4]. In this regard, the energy cost to produce hydrogen from hydropower calculated in this study for scenario five is nearly 1.7 times cheaper and cost competitive in the international market.

4.3. *Potential electricity generation from hydrogen*

Around 53 MW of electricity is generated in Nepal from two thermal power plants using diesel to meet the peak demand [26]. The energy supply mix of 2019 shows a very low utilization of electricity and renewables of about 7% of the total. There is the requirement of increased electricity use from the overall industrial, commercial sectors, and transportation sectors to reduce the dependency on fossil fuels. In many cases, direct grid electricity connectivity is not possible and diesel-based generators are used to supply power. The overall oil product-based energy consumption was around 1896 ktoe in 2018 in Nepal which is equivalent to 22 GWh [27]. In such cases, electricity from hydrogen using fuel cells is carbon friendly and can be a cheaper alternative to fossil fuels. The electricity demand increases with the introduction of new economic activities. Table 3 shows that by 2030, electricity

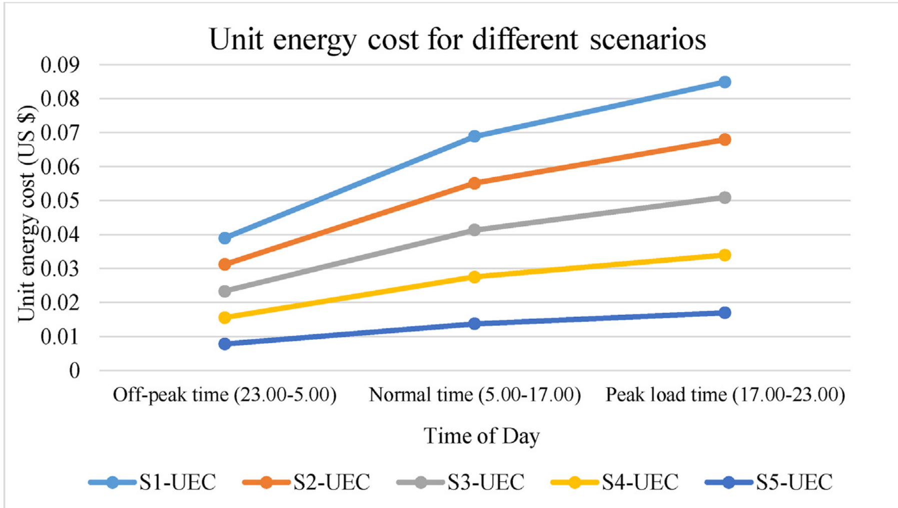

Fig. 5 – Unit energy cost for different cost reduction scenarios for surplus hydro-energy.

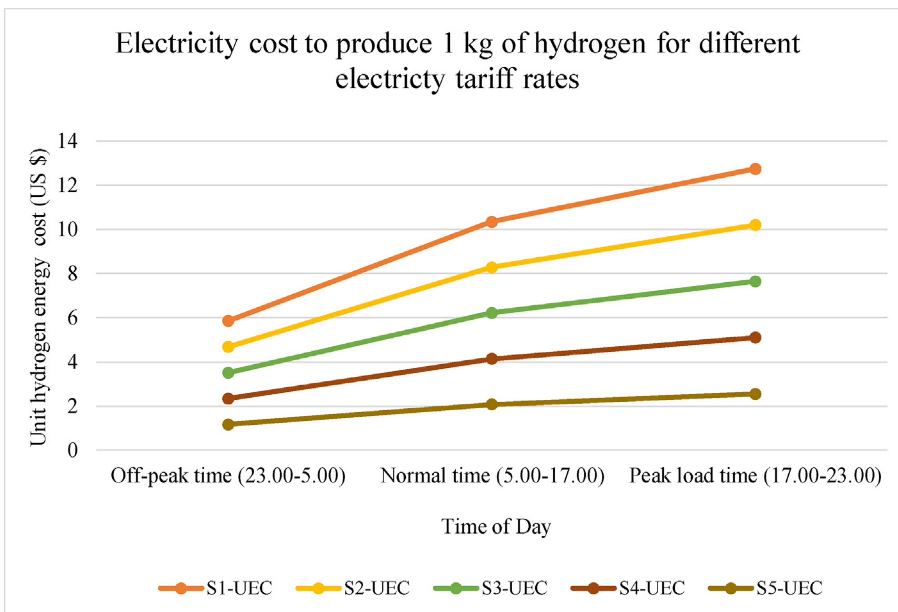

Fig. 6 – Energy cost to produce 1 kg of hydrogen for different tariff rate reduction scenarios.

demand doubles under the 5% GDP growth rate and almost quadruples under the 10% growth rate [28].

This scenario can be addressed by hydrogen production from the surplus energy and it meets the growing electricity demand and the use of fossils to generate off-grid power. In the rainy season, excess hydropower capacity can be stored in the form of hydrogen to be used in the dry season to meet the peak demand and eliminate the electricity import scenario from India.

The study shows that around 7000 GWh of electricity can be generated when utilizing 100% surplus energy. The regenerated electricity from green hydrogen independently using fuel cells has the potential to replace the fossil-based fuel source for independent and off-grid uses. The projected

Table 3 – Electricity demand in Nepal under different economic growth rates [28].

Electricity Demand	Base Case (5% GDP Growth)			7% GDP Growth Rate			10% GPD Growth Rate		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
MW	1756	4103	6361	2600	4475	7287	2790	5176	9267
GWh	13,079	21,567	33,437	13,666	23,521	38,299	14,664	27,217	48,706

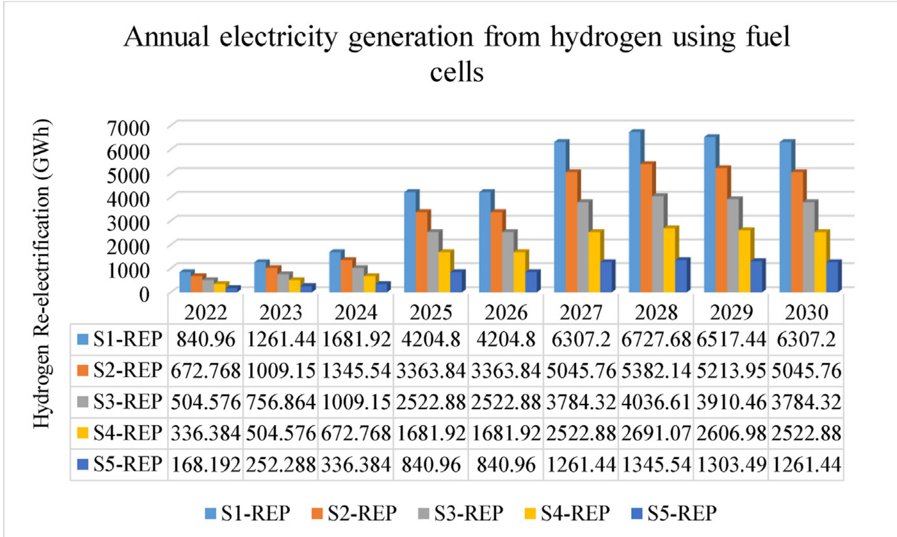

Fig. 7 – Electricity generation potential from hydrogen using fuel cellsfor differentscenarios

hydrogen production from surplus hydro energy per year if used to regenerate electricity through Combined Cycle Gas Turbine or fuel cell per year, the result showed that annual electricity generation from hydrogen throughout 2022–2030 ranged from 840.96 GWh to 6727.68 when 100% surplus energy is utilized to produce hydrogen as shown in Fig. 7 and Fig. 8. This maximum quantity of 6727.68 GWh accounts for 20% of projected electricity demand under 5% GDP growth demand for 2030 as shown in Table 3.

The maximum energy generated from the diesel-powered thermal plant in Nepal assuming 100% capacity utilization is around 464.28 GWh can be completely replaced by electricity generated from hydrogen in 2022, utilizing 60% of surplus hydroelectricity. Around 2582 Ktoe of the supplied energy in 2018 was fossil related which is equivalent to 30 GWh [29]. The electricity generated using hydrogen for the 20% utilization scenario for 2022 is more than 5 times the energy supplied by the oil product in 2018. So, the electricity regenerated from hydrogen using fuel cells can replace the fossil-based energy dependency in the supply mix.

Overall, the above positive result suggests that the 'hydropower to hydrogen to power' pathway can produce more than 6000 GWh of electricity through the re-electrification of stored hydrogen. The regenerated electricity can be used in rural areas where grid electricity is not viable and feasible due to economic and geographical constraints and can replace the energy demand in other sectors like diesel generators, boilers, and those for industrial heating purposes.

4.4. *Potential replacement of gasoline fuels by hydrogen*

Nepal has been importing petroleum products such as petrol, diesel, kerosene, aviation oil, furnace oil, and LPG from India based on the agreement between the Indian Oil Corporation and Nepal Oil Corporation (NOC). The demand for diesel and petrol has risen swiftly with an increased number of diesel

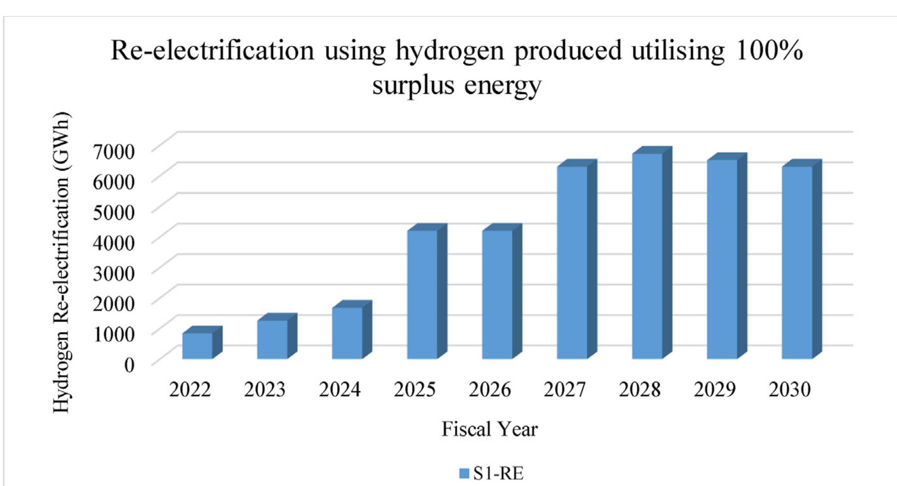

Fig. 8 – Hydrogen Re-electrification (RE) potentials utilizing 100% surplus hydro energy.

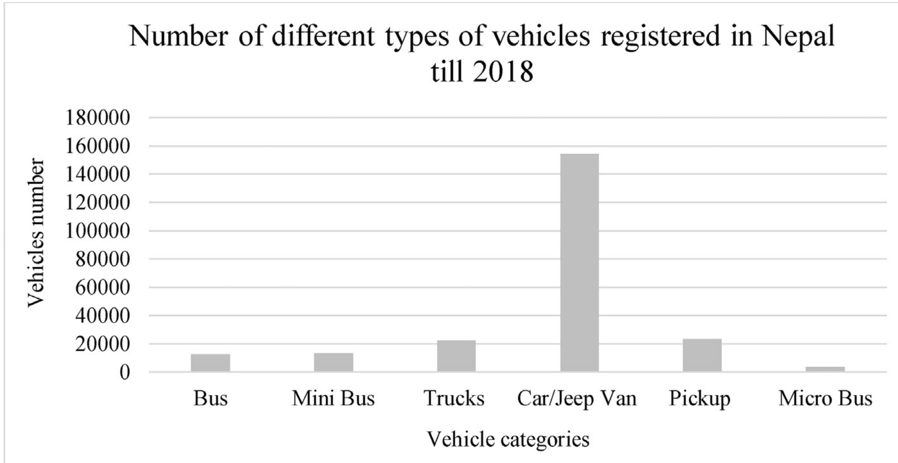

Fig. 9 – Total number of vehicles registered in Nepal by the end of the year 2018.

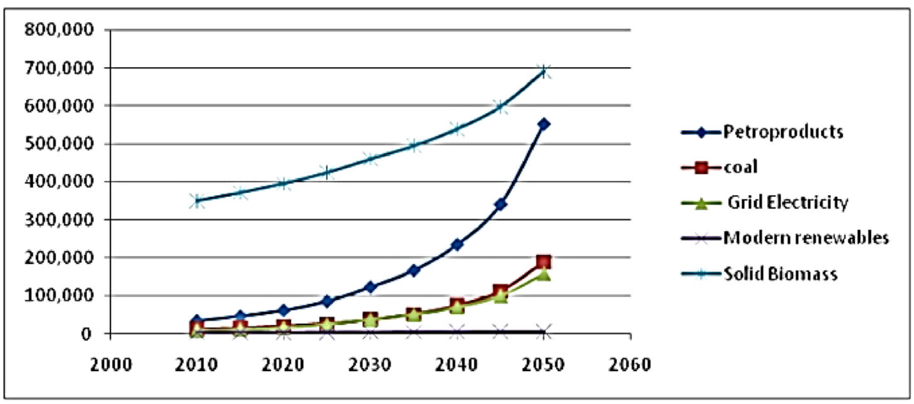

Fig. 10 – Energy consumption projection in Nepal at a high economic growth rate [31].

and petrol-based vehicles like mini-bus, microbus, truck, and diesel cars. Fig. 9 shows the total number of vehicles in Nepal at the end of the fiscal year 2018 [30]. After the two-wheelers, cars/van/jeep categories top the chart showing the dependency on the petrol and diesel-based fuels. Fig. 10 shows the energy consumption pattern in Nepal within 2050 in the high economic growth rate scenario. The figure indicates that the consumption of products will rise

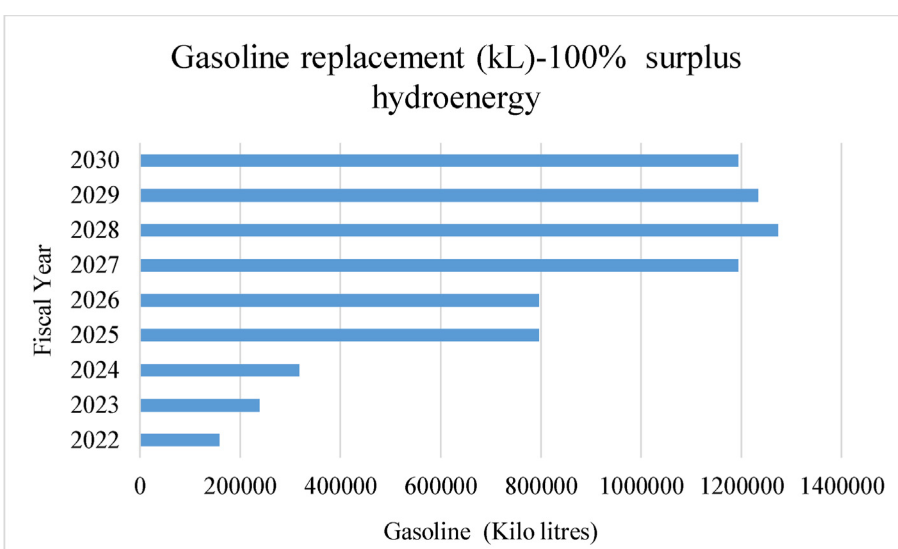

Fig. 11 – Gasoline fuel replacement potential using hydrogen from 100% surplus energy.

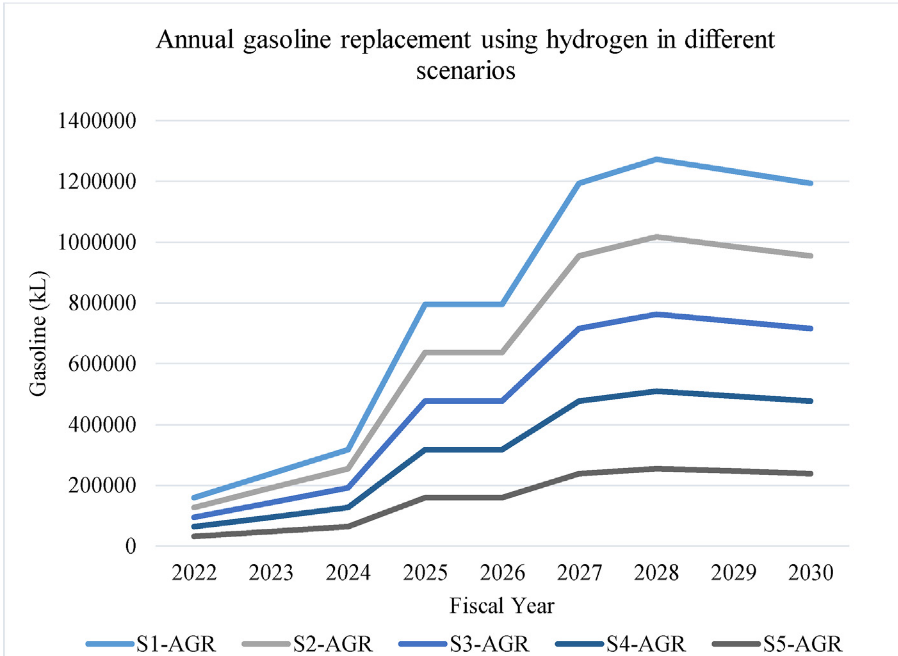

Fig. 12 – Replacement possibilities of gasoline with hydrogen in the transportation sector based on different scenarios.

exponentially to meet the country's energy demand, accounting for 35% [31].

The study conducted in Refs. [13,18] shows the potential of replacing gasoline from the transportation sector using hydrogen. To address fossil fuel dependency and reduce carbon emission, hydrogen could be an excellent option. Hydrogen with the highest energy content of common fuels by weight (nearly three times of gasoline) can replace more than 1.2 million kL of gasoline fuels from the transportation sector of Nepal.

Fig. 11 indicates the potential amount of annual gasoline fuel replacement with the hydrogen produced, utilizing the 100% surplus energy projected previously. Around 159,152 kL to 1,273,213 kL of petrol can be replaced using hydrogen generated from 100% surplus electricity (S1-AGR). Similarly, Fig. 12 shows the overall gasoline replacement potential using hydrogen for different scenarios. The higher the hydrogen production, the higher is the gasoline fuel product replacement. The demand for hydrogen to replace the petroleum product can be met by initiating hydrogen production during off-peak load and surplus during the rainy season. Replacing petroleum products can reduce carbon-related emissions from the transport sectors.

5. Conclusion

Although Nepal has a techno-economic hydropower potential of around 43,000 MW, only around 2.64% has been harnessed until 2019. To increase the hydro production potential, a pipeline of 340 new PPAs has been signed for the combined installed capacity of 6000 MW by the next decade between NEA and IPPs. The capacity balance projection shows a wide disparity in capacity installation and demand. Around 3000 MW of electricity is projected to be surplus by 2030. It has been observed that hydrogen production potential is 63,072 tons–3,153,360 tons with the use of surplus energy at 20% and 100%, respectively. This can replace about 20% of the demand for fossil fuels in 2030. The electricity cost to produce a unit kg of green hydrogen could be as low as -electricity at 80% of the normal price, then per unit hydrogen production can be cheaper and very cost-effective compared to other countries. The lack of access to electricity resulted from the problem of grid connectivity and geographical constraints in many places, and electricity insufficiency during the dry season can be addressed by producing hydrogen energy from the surplus electricity during the wet season in Nepal and independent re-electrification can be achieved using fuel cells. The study reveals that using only 80% of surplus hydro energy in 2027, the total quantity of re-electrification is expected to reach 5000 GWh, exceeding the total electricity generation by all existing hydropower in Nepal in 2018. More than 1.2 million kL of gasoline fuel can be replaced using hydrogen produced from surplus energy in Nepal by 2030. Nepal has excellent potential to produce green hydrogen and inject it into the existing fossil-based energy system. The produced hydrogen can be an excellent option in addressing the energy crisis problem in Nepal and decarbonize the existing transportation sector.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Emissions – global energy & CO2 status report 2019 – analysis - IEA [Online]. Available: https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions. [Accessed 3 December 2020].

[2] Grubler A, et al. "A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy Jun. 2018;3(6):515–27.

[3] Dolci F. Green hydrogen opportunities in selected industrial processes. *JRC Tech. Rep.*, no. June 2018:1–29.

[4] IEA. The future of hydrogen – analysis - IEA [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen. [Accessed 26 August 2020].

[5] Thapa BS, Thapa B. Green hydrogen as a future multi-disciplinary research at kathmandu university. J. Phys. Conf. Ser. Aug. 2020;1608(1):012020.

[6] Staffell I, et al. The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 2019;12(2):463–91.

[7] Dagdougui H, Sacile R, Bersani C, Ouammi A. "Hydrogen production and current technologies," in *hydrogen Infrastructure for energy applications*. Elsevier; 2018. p. 7–21.

[8] Bourne S. The future of fuel: the future of hydrogen. Fuel Cell Bull 2012;2012(1):12–5.

[9] Dincer I. Green methods for hydrogen production. Int J Hydrogen Energy 2012;37(2):1954–71.

[10] Kothari R, Buddhi D, Sawhney RL. Comparison of environmental and economic aspects of various hydrogen production methods. Renew Sustain Energy Rev 2008;12(2):553–63. Pergamon.

[11] Pareek A, Dom R, Gupta J, Chandran J, Adepu V, Borse PH. Insights into renewable hydrogen energy: recent advances and prospects. Mater. Sci. Energy Technol. 2020;3:319–27.

[12] Padilha JC, da Trindade LG, de Souza RF, Miguel M. An evaluation of the potential of the use of wasted hydroelectric capacity to produce hydrogen to be used in fuel cells in order to decrease CO2 emissions in Brazil. Int J Hydrogen Energy 2009;34(19):7898–902.

[13] Posso F, Espinoza JL, Sánchez J, Zalamea J. Hydrogen from hydropower in Ecuador: use and impacts in the transport sector. Int J Hydrogen Energy 2015;40(45):15432–47.

[14] Korobov D, Mostertz M. "Production and utilization of green hydrogen," *20th World Hydrog*. Energy Conf. WHEC 2014;3(2013):1448–60.

[15] Bhatt RP. Hydropower development in Nepal - climate change, impacts and implications. In: Renewable hydropower technologies. InTech; 2017.

[16] Posso F, Zambrano J. Estimation of electrolytic hydrogen production potential in Venezuela from renewable energies. Int J Hydrogen Energy Aug. 2014;39(23):11846–53.

[17] Zhou A, Zhou W, Manandhar P. A study on the prospect of hydropower to hydrogen in Nepal. Manila, Philippines; 2020.

[18] Ale BB, Bade Shrestha SO. Hydrogen energy potential of Nepal. Int J Hydrogen Energy 2008;33(15):4030–9.

[19] Government of Nepal water and energy commission secretariat electricity demand forecast report. 2017.

[20] Nepal Electricity Authority. A year in review-2019/2020. " Kathmandu; 2020.

[21] Present situation and future roadmap of energy, water resources and irrigation sector (white paper) honorable barshaman pun energy. Water Resources and Irrigation Minister; 2018.

[22] Mcbennett B, Rose A, Hurlbut D, Palchak D, Cochran J. Cross-border energy trade between Nepal and India: assessment of trading opportunities. 2020.

[23] Proost J. State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings. Int J Hydrogen Energy Feb. 2019;44(9):4406–13.

[24] Nepal oil corporation, "import and sales of petroleum products. 2019 [Online]. Available: http://noc.org.np/import. [Accessed 18 December 2020].

[25] Luitel P. Feasibility study OF the establishment OF a chemical fertilizer plant IN Nepal. " Kathmandu; 2015.

[26] G. of N. Ministry of Energy. Water resources and irrigation, "power Plants :: thermal,". 2020 [Online]. Available: https://www.doed.gov.np/license/55. [Accessed 21 December 2020].

[27] Nepal - countries & regions - IEA [Online]. Available: https://www.iea.org/countries/nepal. [Accessed 5 December 2020].

[28] Trace S. Electricity in Nepal EEG energy insight. 2019.

[29] Data & statistics - IEA [Online]. Available: https://www.iea.org/data-and-statistics?country=NEPAL&fuel=CO2 emissions&indicator=CO2 emissions by sector. [Accessed 27 September 2020].

[30] Department of transport and management, "vehicle registration in Nepal,". Kathmandu; 2018.

[31] WECS Government of Nepal. Nepal's energy sector vision 2050. 2013.