100%RE multi-actor partnerships

Technical Scenario for 100% Renewable Energy in Nepal by 2050

Possible Transition Pathways for NDC & LTS Implementation

February 2023

ABOUT THE AUTHORS

The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human wellbeing and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organizations in a collaborative process that emphasizes strategic decision-making.

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CITATION

Teske, S., Niklas, S., Miyake, S. (2023) Technical Scenario for 100% Renewable Energy in Nepal by 2050: Possible Transition Pathways for NDC & LTS Implementation; prepared for World Future Council, WWF and Brot für die Welt by the University of Technology Sydney, Institute for Sustainable Futures; February 2023

ACKNOWLEDGEMENTS

The authors gratefully acknowledge data and advice contributed by the project's MAP members particularly, Prof. Dr. Ramesh Maskey and Mr. Nawa Raj Dhakal, for their valuable input and feedbacks as well as the Prakriti Resources Centre (PRC), the World Wildlife Fund Nepal (WWF Nepal), the World Future Council, the World Wide Fund for Nature Germany (WWF Germany), and Brot für die Welt. The work would not have been possible without the tremendous help and engagement of Arati Khadgi, Dipesh Joshi, Anna Skowron, Sälma El-Gamal, Tatenda Wangui, Lena Dente, Dr. Joachim Fünfgelt, Jaime Medina Fernandez, Fentje Jacobsen, Corinne Kowalski, Pradeep Bhattarai, Raju Pandit Chhetri, Shovana Maharjan, Prabin Man Singh and Kushal Gautam.

DISCLAIMER

The energy scenario software for the long-term projections and economic parameters is based on the development of the German Aerospace Centre (DLR), Institute for Technical Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart/Germany and applied to over 100 energy scenario simulations for global, regional and national energy analysis.

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ABOUT THE 100% RE MAP PROJECT

The scale of the transformation ahead calls for collaboration and collective action. Inclusive alliances must be built that include people from all sectors, regions, and walks of life. New approaches must be implemented that facilitate innovative ideas to move us forward toward a renewable energy future. New business models must be developed that take the fast moving and shifting business conditions into account. We need a positive vision for our future, one that empowers change-makers and builds capacities across all sectors. By focusing on the opportunities related to 100% RE, rather than focusing on the fear related to the looming climate crisis, we can unlock the transformative power of renewables.

The Multi-Actor Partnership for Implementing Nationally Determined Contributions with 100% Renewable Energy for All in the Global South (100% RE MAP) is a project to facilitate positive changes and advance the transformation necessary to ensure economic and social development in line with the Paris Agreement's climate target of 1.5 °C. By strengthening MAPs, we enable inclusive decision-making and unlock disruptive innovations for scalability. It is through partnerships that we can overcome short-term political interests, which can upend years of work when political power transfers take place. The project ensures strategic buy-in from opinion leaders, academia, civil society, government and think tanks, and is being implemented simultaneously in Nepal, Uganda and Vietnam. The 100% RE scenario covers state-of-the-art modelling technologies that highlight possible transition pathways towards 100% RE and enable comparisons to business-as-usual pathways.

PROJECT'S CONSORTIUM

The Prakriti Resources Centre (PRC) is an NGO focusing on sustainable development and environmental justice in Nepal. Its mission is the adoption of climate and disaster-resilient, sustainable and gender-responsive development policies, strategies and programs by local, provincial and federal governments.

WWF Nepal is a program office of the international NGO World Wildlife Fund (WWF). The Nepali office's priority is to support the country's conservation efforts and community development with an attempt to address the issues of livelihoods of local people living near protected areas.

WWF Germany is an independent, non-profit, non-partisan foundation, and part of the WWF network, which operates in over 100 countries and consists of national organizations and program offices.

Brot für die Welt is the globally active development and relief agency of the Protestant Churches in Germany. In more than 90 countries all across the globe, we empower the poor and marginalized and closely and continuously cooperate with local, often church-related partner organizations. Through lobbying, public relations and education we seek to influence political decisions in favor of the poor and to raise awareness for the necessity of a sustainable way of life.

The World Future Council is a foundation based in Hamburg, Germany. Against the background of ever-increasing global problems that affect all areas of human life, a global group of experts have set up the World Future Council as a politically neutral and independent body. It brings the interests of future generations to the centre of policy making and addresses challenges to our common future and provides decision makers with effective policy solutions.

The project is supported by the German Federal Ministry for Economic Cooperation and Development (BMZ)

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ACRONYMS AND ABBREVIATIONS

Alternative Energy Promotion Centre	(AEPC)
Direct Normal Irradiation	(DNI)
Brot für die Welt	(BfdW)
Concentrated Solar Power	(CSP)
Combined Heat and Power	(CHP)
Greenhouse Gas Emissions	(GHG)
Gross Domestic Product	(GDP)
International Energy Association	(IEA)
International Renewable Energy Association	(IRENA)
Intergovernmental Panel on Climate Change	(IPCC)
Liquefied Petroleum Gas	(LPG)
Multi-Actor Partnership	(MAPs)
Nationally Determined Contribution	(NDC)
Nepal’s Long-term Strategy to Net Zero Emissions	(NLTS-NZ)
Nepal 1.5 °C	(N-1.5 °C)
One Earth Climate Model	(OECM)
Organization for Economic Development	(OECD)
Prakriti Resources Centre	(PRC)
Terawatt-hour	(TWh)
United Nations Framework Convention on Climate Change	(UNFCCC)
University of Technology Sydney–Institute of Sustainable Future	(UTS-ISF)
With the Existing Measures	(WEM)
World Future Council	(WFC)
World Wildlife Fund for Nature	(WWF)

FOREWORD BY WWF NEPAL

Nepal is ranked as the 10th most vulnerable country in the global Climate Risk Index. Although, the emission of the country is very low, Nepal is facing enormous impacts from climate change affecting the nature, local livelihood as well as the development aspirations of the country. As a party to United Nations Framework Convention on Climate Change (UNFCCC) and having ratified the Paris Agreement, Nepal has shown its commitment to support the goal of limiting global warming to well below 2 °C, preferably to 1.5 °C compared to pre-industrial levels. This commitment is reflected by submission of first Nationally Determined Contribution (NDC) in 2016 and second NDC in 2020 with more ambitious targets to reduce greenhouse gas emissions. The second NDC has set a vision to achieve net zero greenhouse emission by 2050 which has been projected to be achieved within 2045 by Nepal's Long-term Strategy to Net Zero Emissions (NLTS-NZ) 2021. In order to achieve this target, a complete decarbonization and shift to 100% Renewable energy (RE) in all emission sectors is necessary.

This report highlights the possible transition pathways based on the current energy mix and planned energy (renewable and traditional) plans and programs of the government. The report builds on NLTS-NZ 2021 and presents a 100% renewable energy plan to decarbonize the energy sector of Nepal by 2050 within a carbon budget that will achieve a 1.5 °C increase in global temperature. This report has presented three scenarios- Reference scenario that assumes no technical interventions till 2050 with medium economic growth rate, with the existing measures i.e., intervention measures specified in the plans and policies implemented and adopted up to 2020, and Nepal 1.5 °C scenario that is built on the framework of targets and assumptions that accelerate rapid uptake of RE technologies mainly in electricity, heating, and transportation sector.

This report has been developed with thorough consultations and engagement with members of Multi-Actor Partnership (MAP) platform formed under the project "Multi-Actor Partnership (MAPs) for Implementing Nationally Determined Contributions with 100% Renewable Energy (RE) for All in the Global South". I would like to thank everyone who contributed to preparing this document mainly Prakriti Resources Centre, WWF Germany, World Future Council, Brot für die Welt and the entire team of the University of Technology Sydney, Institute for Sustainable Futures.

I hope, the scenarios presented in this report will serve as a tool to compare potential development pathways from the broad range of possible futures and will be beneficial for planners, decision makers, research institutions and other organizations working in energy sector to enable the country to transition to 100% RE pathway. WWF Nepal is committed to taking forward the key results of the document and contribute to promotion of renewable energy through policy dialogue and investment-on-the-ground in collaboration with our partners.

Ghana Shyam Gurung, PhD
Country Representative
WWF Nepal

FOREWORD BY PRC

Nepal is one of the least carbon-emitting countries with no historical responsibilities. But it is among the most vulnerable countries to the impacts of climate change. Its fragile topography, climate-sensitive livelihoods of the people, and low adaptive capacity put Nepal in difficult national circumstances. However, Nepal is committed to taking ambitious climate actions adhering to the Paris Agreement's common but differentiated responsibilities and respective capabilities. This is communicated to the United Nations through its Nationally Determined Contributions (NDC) and Long-term Strategy for Net-Zero Emissions within a timeline of 2045.

Nepal has a vast potential to generate clean, green, sustainable and climate-resilient renewable energy from diverse sources. By 2030, the country plans to increase clean energy generation to 15,000 MW, with 5-10% coming from mini and micro-hydropower plants, solar, wind, and bio-energy, ensuring 15% of total energy demand is met by clean energy sources. This is a vital pathway to moving towards 100% renewable energy by 2050.

Nepal's electricity primarily comes from hydropower, but it imports fossil fuels worth nearly US$ 2.5 billion per year into the country. Ample opportunities lie ahead to replace this imported fossil fuel with domestically produced clean energy sources and contribute to the national economy. As a party to the Paris Agreement, by adopting a clean energy future, Nepal contributes to the vision of keeping the global temperature rise to 1.5 degrees Celsius above pre-industrial levels and supporting its sustainable socio-economic development.

This technical report prepared by the University of Technology Sydney with the engagement of Nepali stakeholders and experts provides various scenarios and pathways on how Nepal can achieve 100% Renewable Energy (RE) by 2050. It is expected to be a crucial tool for decision-makers, planners, government agencies, researchers and advocates to promote a clean energy mix in the country. PRC will also enable the outcomes of this report to systematically address climate change and decarbonize the economy with a commitment to keeping emissions to a minimum level and a path to achieving net-zero emissions, as stated by the government.

This report is a product of the "Multi-Actor Partnership (MAPs) for 100% Renewable Energy Project" prepared in partnership with WWF, World Future Council and Brot für die Welt. I sincerely thank the University of Technology Sydney team for helping us prepare this vital document under the project. I also appreciate the inputs from the Alternative Energy Promotion Centre (AEPC), MAP Platform members, individual experts and project partners who helped shape this report. Thank you.

Raju Pandit Chhetri
Executive Director
Prakriti Resources Centre, Nepal

Executive Summary for Policymakers

The University of Technology Sydney, Institute for Sustainable Futures (UTS-ISF) developed this energy pathway for Nepal under the project- Multi-Actor Partnership (MAPs) for Implementing Nationally Determined Contributions with 100% Renewable Energy (RE) for All in the Global South hereafter referred to as MAPs for 100% RE. This document is developed in close cooperation with WWF Nepal, PRC, WWF Germany, World Future Council, Brot für die Welt and with members of the MAP-platform formed under the MAPs for 100% RE project. This document illustrates energy scenarios aimed to provide scientific input to future energy planning for the Government of Nepal as well as for possible updates and/or specifications of Nepal's National Determined Contributions (NDC).

Scenario development – REFERENCE, WEM and Nepal-1.5°C

This report builds on Nepal's Long-term Strategy for Net-zero Emissions (NLTS-NZ 2021), which sets goals required to reduce net-zero emissions in 2020–2030 and, after a period of very low emissions, to reach full net-zero emissions by 2045.

- The **NLTS-NZ 2021 represents the REFERENCE scenario** in this analysis.
- The **With the Existing Measures (WEM) scenario is taken from NLTS-NZ 2021,** using the same methodology as the REFERENCE scenario but focusing on the intervention measures specified in the plans and policies implemented and adopted up to 2020.
- With NLTS-NZ-2021 as the foundation, the **Nepal 1.5 °C (N-1.5 °C)** scenario is built on a framework of targets and assumptions that strongly influence the development of individual technological and structural pathways for each sector.

The main assumptions considered in this scenario-building process take into account the emissions reductions, growth of renewable industry, fossil-fuel phase-out, future power supply, security of energy supply, sustainable biomass levels, electrification of transport, and hydrogen and synthetic fuels.

The N-1.5 °C scenario takes a more ambitious approach than the other scenarios to transforming Nepal's entire energy system to an accelerated new renewable energy supply. The consumption pathways remain similar to those of the WEM scenario. However, under the N-1.5 °C scenario, a much faster introduction of new technologies will lead to the complete decarbonization of energy for stationary energy (electricity), heating (including process heat for industry), and transportation. In the latter, there will be a strong role for storage technologies, such as batteries, synthetic fuels and hydrogen.

Under the N-1.5 °C scenario, the share of electric and fuel cell vehicles will increase. This scenario also relies on a greater production of synthetic fuels from renewable electricity, for use in the transport and industry sectors. Renewable hydrogen will be converted into synthetic hydrocarbons, which will replace the remaining fossil fuels, particularly in heavy-duty vehicles and air transportation—albeit with low overall efficiency typical of the synthetic fuel system. Because renewable synthetic fuels require a (gas) pipeline infrastructure, this technology is not widely used in Nepal's energy plan because the costs in the early development stages are relatively high. It is assumed that synthetic fuels and hydrogen will not enter Nepal’s energy system before 2040. Compensating for the high energy losses associated with producing synthetic fuels will require fundamental infrastructure changes, which seem too costly for a developing country. Electricity and hydrogen will play larger roles in the heating sector (mainly heat for industry), replacing fossil fuels. Therefore, electricity generation will increase significantly under this scenario, assuming that power from renewable energy sources will be the future’s main ‘primary energy’.

The N-1.5 °C scenario also models a shift in the heating sector towards the increased direct use of electricity because of the enormous and diverse potential for renewable power and the limited availability of renewable fuels for high-temperature process heat in industry. Increased implementation of a district heating infrastructure (interconnections of buildings in central business districts), bio-energy-based heat generation, and solar collectors and heat pumps for office buildings and shopping centres in larger cities are assumed, leading to a growth in electricity demand that partly offsets the efficiency savings in these sectors. A rapid expansion of solar and geothermal heating systems is also assumed.

The increasing shares of variable renewable power generation, principally by solar PV, will require the implementation of smart grids and the fast interconnection of micro- and mini-grids with regional distribution networks, storage technologies such as batteries and pumped hydro, and other load-balancing capacities. Other infrastructure requirements will include an increasing role for on-site renewable process heat generation for industries and mining, and the generation and distribution of synthetic fuels.

Projection of future energy demand

This report focuses on the three major energy consuming sectors for future energy demand projection: **i) households; ii) industry and business; and iii) transport.**

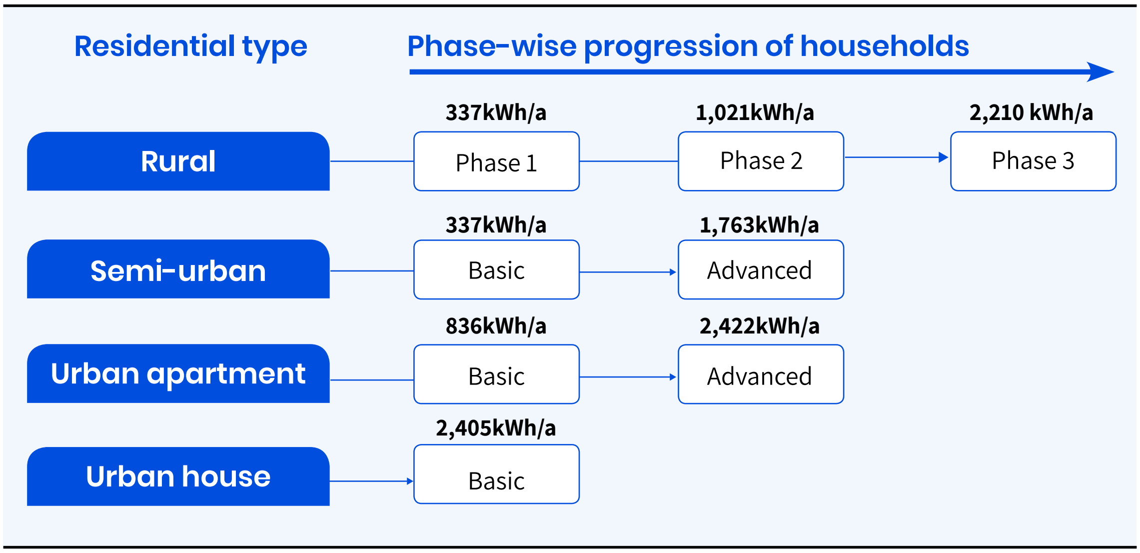
To develop a projection for the residential electricity demand in Nepal over the coming 30 years to achieve the Nepal 1.5 °C (N-1.5 °C) scenario, a bottom-up electricity demand analysis was performed.

The N-1.5 °C aims to ensure the access to energy—especially electricity—for all by 2050, while increasing the electrification and comfort standards to the levels of OECD countries. The growing economy requires a reliable power supply for small and medium businesses, industry, and the transport sector. It is assumed that households will use modern energy-efficient applications, according to the highest efficiency standards, to slow the growth of the power demand and to allow the parallel expansion of the energy infrastructure and the construction of renewable power plants. Electrification will be organized from the ‘bottom up’ in a new and innovative approach developed by UTS-ISF.

Household energy demand-Electricity

In 2019, Nepal’s households by size and types were dominated by medium to large families. However, the current average electricity demands of Nepalese households are significantly lower than those of OECD countries. For example, an urban household in Nepal consumes on average 836kWh/a, whereas an urban household (apartment of 2 people) in OECD country (specifically Switzerland) consumes on average 3,025kWh/a.

For this study, the households in Nepal are categorized into four categories: rural, semi-urban, urban apartment and urban house. The figure below shows this categorization and phase-wise progression of each household type in relation to their annual electricity consumption in kWh/a.



The electricity demand will gradually increase as the electric applications for each of the three-household type progress from those households with very basic needs, such as light and mobile phone charging, to a household standard equivalent to that of industrialized countries. The different levels of electrification and the utilization of appliances are described with the affixes 'phase 1', 'phase 2', and 'phase 3' for rural households. In contrast, semi-urban and urban apartment have two groups: one for the basic level and one for the more-advanced stage of electrification and finally urban house has only one basic level. The households will develop over time, from the basic group towards the more advanced group. In 'phase 3', rural household includes an electric oven, refrigerator, washing machine, air-conditioning, and entertainment technologies, and aims to provide the same level of comfort as households in urban areas in industrialized countries.

Furthermore, the phase-out of unsustainable biomass and liquefied petroleum gas (LPG) for cooking is particularly important in decarbonizing Nepal's household energy supply. Therefore, a staged transition towards electrical cooking is assumed.

Household fuel demand—Cooking

The main energy demand for Nepalese households is for cooking. Firewood is the main energy source for rural households, whereas cylinders of LPG are the main source of energy for cooking in semi-urban and urban households. Cooking with electricity (for example, from mini-grids in rural areas) using high-efficiency appliances could make cooking cheaper than it is for many households currently using firewood and charcoal. Based on the current cooking energy usage, a transition scenario from fuel-based cooking to electric cooking (e-cooking) has been developed for the N-1.5 °C scenario. In the past, Nepal replaced inefficient stoves with more-efficient ones, which has had a positive effect on (indoor) air pollution and reduced the need for fuel for each cooking stove. However, with an increasing population and a growing number of households, the overall fuel demand is likely to remain at high levels, and a phase-out of emissions and fuel demand cannot be achieved with this measure.

On average, 3.3% of all fuel-based cooking applications will be gradually phased out per year and replaced with electric cooking appliances under the N-1.5 ˚C pathway. The total phase-out of fuel-based systems will be for environmental and economic reasons. Fuel-based cooking requires fuel that generates emissions, and the fuel supply is, in most cases, not sustainable. Collecting fuel wood puts forests under pressure, is time-consuming, and has a negative economic impact on the country's productivity. Burning LPG causes CO_2 emissions, and its production is based on fossil gas, which must be phased-out by 2050 to remain within the global carbon budget to limit the global mean temperature rise to a maximum of +1.5 °C. E-cooking can be supplied by renewable energy sources and will be emissions-free.

Industry and business energy demand

The analysis of Nepal's economic development is based on a breakdown of the fiscal year 2020/21 and assumes that the overall structure of the economy will not change, and that all sectors will grow at a rate equal to that of the Gross Domestic Product (GDP) over the entire modelling period. The N-1.5˚C pathway calculated the future industry energy demand on the basis of an assumed breakdown of GDP by sub-category—which differs slightly from that identified in the Economic Survey of Nepal due to used energy scenario model (One Earth Climate Model - OECM). To translate the breakdown of GDP from that of the Economic Survey to the OECM, certain industries have been clubbed together or renamed. For example, the value of 'wholesale and retail trade; repair of motor vehicles and motorcycles' identified by the Economic Survey has been added to the OECM's 'Manufacturing' sector. The identified sectors have been used to calibrate the bottom-up energy demand model with the current energy demand.

Transport energy demand

The assumed trajectory for the transport sector in the N-1.5˚C pathway is consistent with the National Determined Contribution (NDC) of the Government of Nepal published in 2020, which identified the following three goals:

1. 25% of all vehicles will be e-vehicles by 2025 including private two-wheeler and 20% of public four-wheeler vehicles.
2. By 2030, sales of e-vehicles will increase to include 90% of all private passenger vehicle sales, including two-wheelers, and 60% of all public four-wheeler passenger vehicle sales (the public passenger target does not consider electric rickshaws or electric tempos).
3. By 2030, 200 km of electric rail network will be developed to support public commuting and mass transportation of goods.

The average lifespan of motorcycles and scooters in Nepal is 10 years, whereas cars are used for around 20 years. Based on these lifespans for motorcycles and cars, a country-wide overall market share of electric drives for the entire existing car fleet may not exceed 5% by 2030 for passenger and freight cars. Furthermore, it is assumed that the railway system will not be expanded beyond the current plans after 2030.

Currently, the infrastructure required for electric mobility, in terms of maintenance and service centres and charging stations across urban and rural areas, is lagging. The resilience and reliability of the electricity supply—especially in rural areas—is still under development and faces challenges. Therefore, a rapid expansion of the charging infrastructure, which will increase the load even further, will depend on the progress of electricity services. However, the decarbonization of Nepal's energy sector will require increased electrification of the transport sector, and the expansion of a resilient power supply based on sustainable power generation technologies.

Energy supply - Assessment of Nepal's solar and wind potential

In order to assess Nepal's region-specific future energy situation and additional capacities in the power grid and/or mini-grids; population density, access to electricity infrastructure, and economic development projections are key input parameters.

Similarly, Nepal's resource potential from new renewable energy sources such as solar and wind potential is needed to assess the future energy situation. This was assessed as an input for the energy scenario development. The '[R]E Space' methodology is part of the One Earth Climate Model methodology. GIS mapping was used to ascertain Nepal's new renewable energy resources (solar and wind). It was also used in the regional analysis of geographic and demographic parameters and the available infrastructure that could be leveraged in developing the scenarios.

Solar potential

The average annual solar irradiation (DNI) level in Nepal is 0.2–8.5 kWh/m^2 per day, and the higher end of that range is in the northwest of the country, in the mountainous regions in Karnali Province. Nepal's solar potential has been mapped under two different scenarios.

Scenario 1. Available land—excluding protected areas (PA), extreme topography (slope > 30% [mountain areas], S30), and certain land-cover classes, including closed forests, wetlands, moss and lichen, snow and ice, and water (permanent water bodies) (LU).

Scenario 2. See 1, with additional restriction that excludes areas ≤ 10 km from existing transmission lines (PT10).

Under Scenario 1 (LU + PA + S30) an area of 24,125 km^2 is potentially suitable for utility-scale solar PV capacity of 603.1GW. Scenario 1 excludes all protected areas and areas with slopes > 30%, because installing solar panels in steep mountainous areas is unrealistic. The solar potential areas for Scenario 2 (LU + PA + S30 + PT10) have been calculated under the additional restriction that power lines must be within a range of 10 km. As a result, the solar potential decrease to 17,273 km^2. Under Scenario 2, utility-scale solar farms in Nepal can potentially harvest 431.8 GW of solar PV.

Wind potential

The overall wind resources on land are significantly smaller in Nepal compared with the solar potential. The wind speeds in Nepal range from 0.06 to 28.3 m/s at 100 m height, and high-wind-speed areas are predominantly located in the northern regions, in Karnali Province. The average annual wind speed in Nepal is 3.23 m/s. In this analysis, we have included only areas with an average annual wind speed of ≥ 5m/s. Nepal's wind potential has been mapped under two different scenarios.

Scenario 1. Available land—restricted by protected areas (PA), extreme topography (slope > 30% [mountain areas], S30), and existing land use, including forests and urban areas (LU).
Scenario 2. See 1, with additional restriction that excludes areas ≤ 10 km from existing transmission lines (PT10).

Open forest, shrubs, herbaceous vegetation, bare/sparse vegetation, and agricultural land were included in the available land (LU) for the two wind scenarios, whereas the land-cover classes closed forests, wetland, moss and lichen, urban/built-up areas, snow and ice, and permanent water bodies were excluded in this analysis of wind potential. The overall total wind potential under all restrictions is just over 5,900 MW for

Scenario 1. Overall, the spatial analysis identified very limited wind potential in Nepal, especially under Scenario 2 – approximately 250 MW - because there are limited areas with an annual wind speed of ≥ 5 m/s and most of these areas are not located within close proximity to transmission lines (≤ 10 km).

Nepal's energy pathway until 2050

Three different energy scenarios for Nepal have been prepared to describe and compare potential development pathways from the broad range of possible 'futures'. The N-1.5 °C scenario was designed to demonstrate the efforts and actions required to achieve the ambitious objective of a 100% renewable energy system and to illustrate the options available to change our energy supply system into one that is truly sustainable. The scenarios may serve as a reliable basis for further analyses of possible concepts and actions needed to implement technical pathways to achieve measurable results.

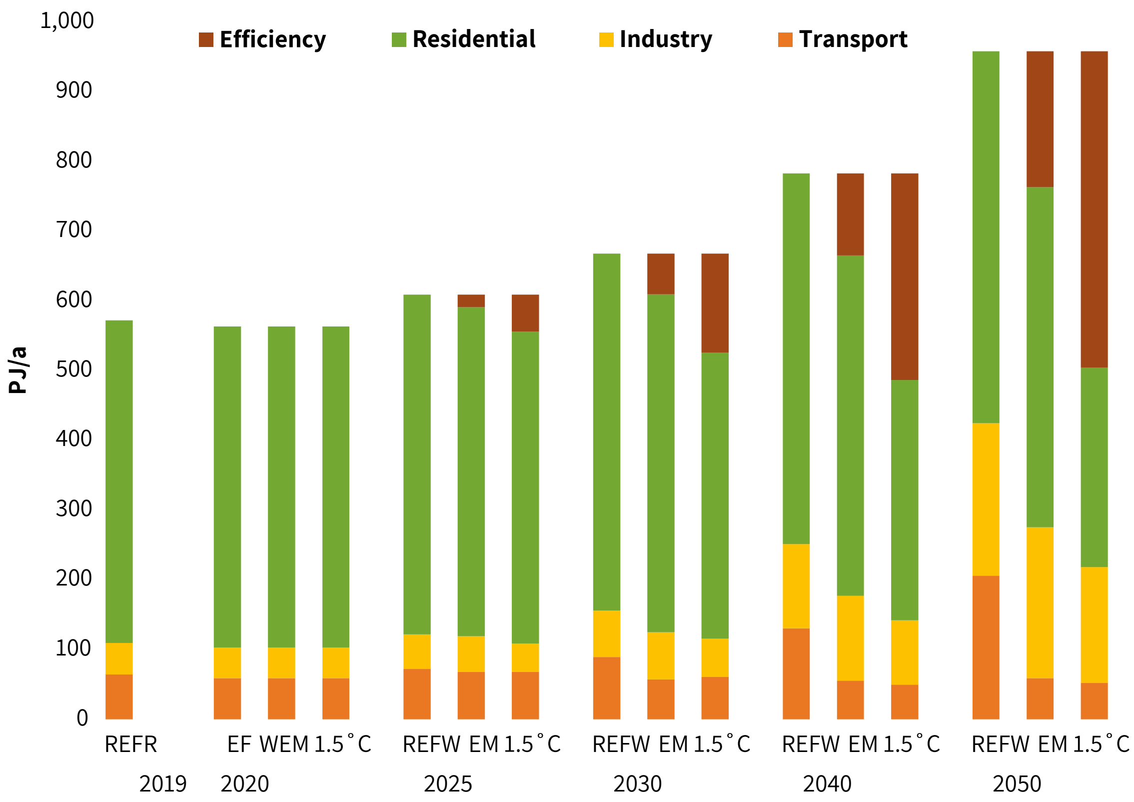
Final energy demand

The projections for population development, GDP growth, and energy intensity are combined to project the future development pathways for Nepal's final energy demand. In the REFERENCE scenario, the total final energy demand increases by 67% from 600 PJ/a to 1000 PJ/a in 2050. In the WEM scenario, the final energy demand will increase at a much lower rate (by 33%) compared with current consumption and is expected to reach 800 PJ/a by 2050. The N-1.5 °C scenario will reduce final energy demand further partially due efficiency gains.

The residential sector will remain dominant in Nepal's energy demand, but the energy demand of the industry sector will increase constantly. By 2050, industry will consume at least four times more energy than in 2020, making this sector the second highest consumer after transport in all three scenarios.

The energy demand of the transport sector will quadruple by 2050 under the REFERENCE scenario, whereas it will stabilize under WEM and the N-1.5 °C scenario. The main reason for the significant difference in growth projections is the high rates of electrification in the latter two pathways.

The large efficiency gains achieved in the N-1.5 °C pathway is attributable to the high electrification rates, mainly in the cooking and transport sectors, because combustion processes with high losses are significantly reduced.



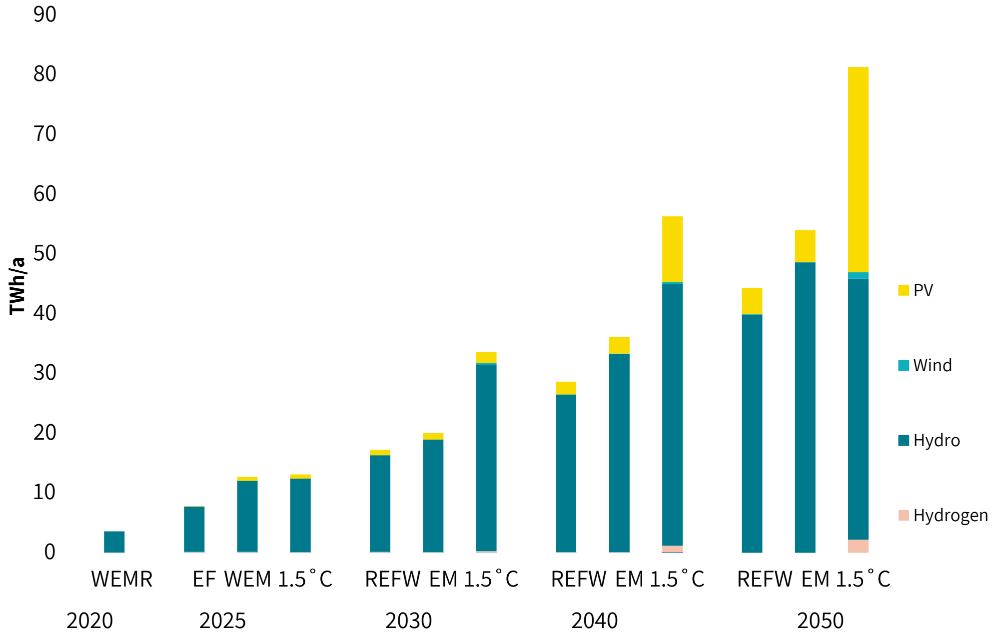
Projection of the total final energy demand by sector (excluding non-energy use and heat from combined heat and power (CHP) auto producers)

Electricity generation, capacity, and breakdown by technology

The development of the electricity supply sector is characterized by a dynamically growing renewable energy market and an increasing share of new renewable electricity, mainly from solar PV. The additional electricity demand caused by accelerated electric cooking and electric vehicles under the N-1.5 °C scenario will greatly benefit new renewables, whereas hydropower will continue to generate bulk electricity for industry and export. By 2050, 100% of the electricity produced in Nepal will come from conventional and new renewable energy sources under the WEM scenario. 'New' renewables—mainly decentralized and utility-scale solar PV, but also a limited amount of wind power—will contribute 20% of the total electricity generation in 2040. By 2025, the share of new renewable electricity production will reach 6% and increase to 44% by 2050 under the N-1.5 °C scenario. The installed capacity of new renewables will reach about 3.5 GW in 2030 under all three scenarios and increase to 13.2 GW by 2050 under the REFERENCE scenario. Both the WEM and the N-1.5 °C scenarios will lead to higher capacities.

A 44% electricity supply from new renewable energy resources under the N-1.5 °C scenario will lead to around 35.4 GW of installed generation capacity in 2050, about twice the capacity achieved under WEM and 2.7 times higher than that achieved under the REFERENCE scenario. Hydropower will remain the main power source in all scenarios for more than another decade. However, just after 2040, solar PV will overtake hydropower in installed capacity. After 2045, the continuing growth of solar PV and additional wind power capacities will lead to a total capacity of 25 GW, compared with 10 GW hydropower under the N-1.5 °C scenario.

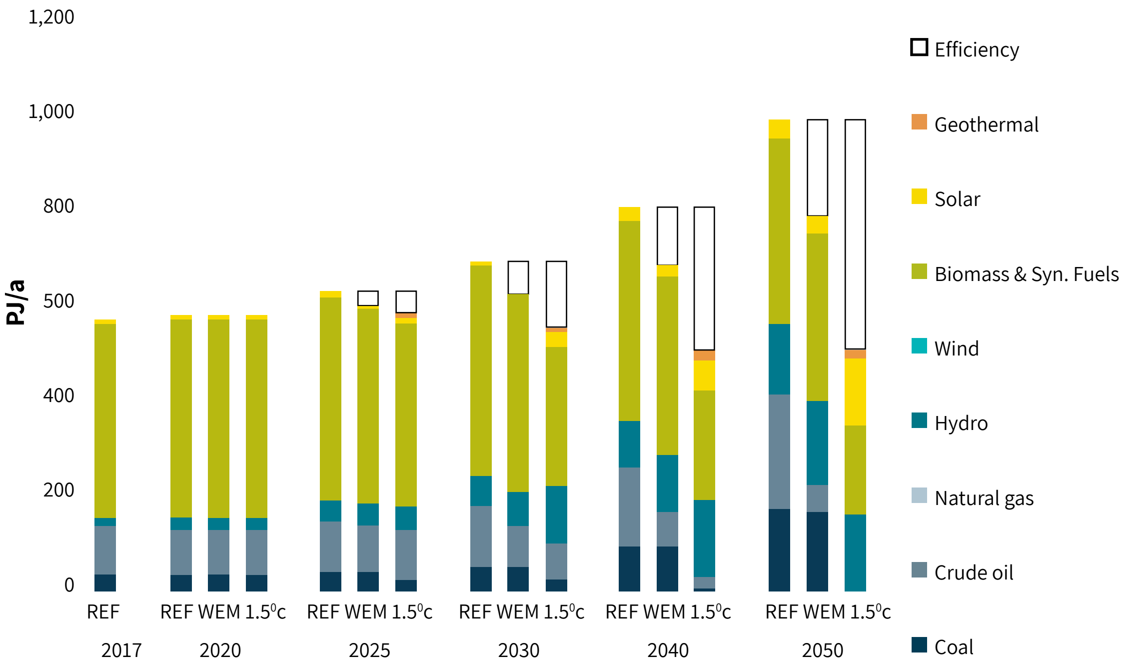
This will lead to a high share of variable power generation and demand-side management, and the management of electric vehicle charging and other storage capacities, such as stationary batteries and pumped hydropower. The development of smart grid management will be required from 2025 onwards to increase the power system's flexibility for grid integration, load balancing, and a secure supply of electricity.



Breakdown of electricity generation by technology

Primary energy consumption

Based on the assumptions discussed above, the resulting primary energy consumption under the three documented pathways is shown in the figure below. Under the WEM scenario, the primary energy demand will increase by 79% from today's 560 PJ/a to around 1000 PJ/a in 2050. Compared with the REFERENCE scenario, the overall primary energy demand will be reduced by 41% in 2050 under the WEM scenario. The N-1.5 °C scenario will result in primary energy consumption of around 500 PJ in 2050, 49% less than under the REFERENCE scenario. The N-1.5 °C scenario aims to phase-out oil in the transport sector and for industrial use as fast as is technically and economically possible, through the expansion of renewable energies. The fast introduction of very efficient vehicle concepts in the road transport sector will replace oil-based combustion engines. This will lead to an overall renewable primary energy share of 82% in 2030 and 73% in 2050 under the WEM scenario and of more than 73% in 2050 under the N-1.5 °C scenario (including non-energy consumption).



Projection of total primary energy demand by energy carrier (including electricity import balance)

Cost analysis – Power generation

The electricity generation cost under N-1.5˚C scenario is around 10% higher than that of the REFERENCE and WEM scenario until around 2035. However, around 2035, electricity generation cost under N-1.5˚C scenario will rapidly drop lower than the REFERENCE and WEM scenario due to cost advantages from increased investments in solar PV and electrification.

Nepal's total electricity supply costs will increase with the increasing electricity demand across all three scenarios. The N-1.5 °C pathway has the highest total electricity costs, but these will directly replace bio-energy and oil fuel costs.

Investments in power generation

Nepal will invest in new power generation—mainly hydropower (including decentralized mini- and micro-hydro)—over the next decades under all three scenarios. The main difference between the N-1.5˚C scenario and the REFERENCE and WEM scenarios is the investment in other technologies—primarily solar PV. The wind potential of Nepal is very limited because the average wind speeds are low around the urban areas and the geographic situation in rural areas is not suitable, with high mountains, steep slopes, and remote villages with limited or no road access, which are also often not connected to Nepal's power grid network. The electrification of remote villages under the N-1.5 °C pathway is mainly based on solar PV power mini-grids with (battery) storage systems.

However, wind energy systems can and should play a role in some limited locations. The generation pattern is different from that of solar and will therefore reduce the energy storage requirements because electricity generation is distributed throughout the day and is not limited to daylight hours.

The additional investment in solar PV under the N-1.5 °C scenario will amount to around 1.5 trillion Nepalese Rupees (US$10 billion) over 30 years. Compared with the WEM scenario, the additional electricity generated with solar PV will be 1 billion kWh (1 TWh/a) by 2030 and 29 billion kWh/a (29 TWh/a) by 2050. This electricity will primarily be used to replace biomass for cooking and heating and to charge various electric vehicles.

Future investments in the heating sector

The main difference between the N-1.5 °C pathway and the REFERENCE and WEM pathways is the significant reduction in bio-energy use and the diversification of heating technologies. Electrical heat pumps, geothermal heat pumps, and solar thermal applications for space and water heating and drying will lead to a considerable reduction in the use of biogas and solid biomass, and therefore reduce the fuel costs. The investment costs under the N-1.5 °C will be 47% higher than under the REFERENCE scenario but the fuel costs will be 57% lower. The overall heat sector costs—investment and fuel costs—over the entire scenario period until 2050 will be 2.3 trillion Nepalese Rupees lower under the N-1.5 °C scenario than under the REFERENCE scenario and 1.1 trillion Nepalese Rupees lower than under the WEM scenario.

Investment and fuel cost savings

Finally, the fuel costs of all three scenarios in the power, heating and transport sectors are compared. The REFERENCE scenario has the highest fuel costs of all the scenarios, mainly due to the high reliance on biomass for heating and cooking, and on oil for the transport sector. All three scenarios have very low fuel costs for the power sector because generation is based on hydro and solar power—the remaining fuel costs are for diesel generators. Increased electrification will lead to higher investment costs in power generation and higher overall electricity supply costs for Nepal. Under the most ambitious electrification strategy of the N-1.5 °C pathway, investment will be 1.7 trillion Nepalese Rupees (US$13 billion) higher over the 30 years until 2050 than under the REFERENCE pathway. Fuel cost savings in the heating sector until 2040 alone will be able to re-finance the additional investments in power generation. Additional power generation investments will be compensated by fuel costs savings in the decade that they are made. Across the entire scenario period, fuel cost savings under the N-1.5 °C scenario will be 6.47 trillion Nepalese rupees (US$51.8 billion), more than three times higher than the additional investment in power generation until 2050. Whereas fuel cost predictions are subject to a great deal of uncertainty, the distinct result makes the cost-effectiveness of electrification very clear.

Power sector analysis for Nepal

The OECM calculates the demand and supply by cluster. The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, will allow a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, OECM model cannot simulate frequencies or ancillary services, which would be the next step in a power sector analysis. Variable power generation technologies are dependent on the local solar radiation and wind regime. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database renewable.ninja, which allows the hourly power output from wind and solar power plants at specific geographic positions throughout the world to be simulated.

The OECM power analysis model calculates the development of the future power demand and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- Households
- Industry and Business
- Transport

Each sector has its specific consumer groups and applications, the same set of parameters was used to calculate load curves:

- Electrical Applications in use
- Demand Pattern (24 h)
- Efficiency Progress (base year 2018 for 2020 until 2050), in 5-year steps

Sharp increase in electricity load expected

By 2050, the overall electricity load of Nepal will increase by a factor 8.6 relative to that of 2020, with variations between 6 and 10 by provinces. The increase in load is attributable to the increase in the overall electricity demand with the electrification of cooking, heating, and cooling, which constitutes an increase of the living standards of all Nepalese households as they acquire more residential appliances. Furthermore, the growth of the commercial and industrial sectors of Nepal and the electrification of transport will lead to a sharp increase in the electricity demand and therefore the overall power load.

This increased load will require an expansion of Nepal’s power distribution and transmission grid, both within Nepal and as interconnections with neighbouring countries—especially India.

The calculated load for each province depends on various factors, including the local industrial and commercial activities. A detailed analysis of the planned expansion of economic activity for each province was beyond the scope of this research and the results are therefore estimates. The residual load is the difference between the power generation and the demand—a negative residual load indicates an oversupply, whereas a positive value implies an undersupply.

Nepal—Projection of load, generation, and residual load until 2050

Nepal Development of Load and Generation		N-1.5 °C			
		Maximum Load	Maximum Generation	Maximum Residual Load (oversupply)	Peak Load Increase
		[MW]	[MW]	[MW]	[%]
Province 1	2020	210	300	0	100%
	2030	828	1,322	−494	394%
	2050	2,092	3,724	−1,632	995%
Madhesh	2020	228	327	0	100%
	2030	961	1,551	−590	422%
	2050	2,444	3,756	−1,312	1073%
Bagmati	2020	251	349	0	100%
	2030	964	1,676	−712	384%
	2050	2,281	4,857	−2,576	910%
Gandaki	2020	102	142	0	100%
	2030	393	659	-−266	384%
	2050	930	1,799	−870	910%
Lumbini	2020	211	330	0	100%
	2030	788	1,442	−654	373%
	2050	1,774	3,979	−2,204	840%
Karnali	2020	70	109	0	100%
	2030	261	467	−206	373%
	2050	587	1,306	−719	840%
Sudurpaschim	2020	116	195	0	100%
	2030	377	822	−60	63%
	2050	726	2,226	−1,500	626%
Nepal	2020	1,188	1,753	0	100%
	2030	4,572	7,939	−3,367	385%
	2050	10,834	21,647	−10,813	912%

The development of power generation is assumed to grow proportionally to the growth in demand in each province. A more detailed assessment of the exact locations of power generation is required to optimize the required expansion of transmission grids. To reduce the residual load to avoid an over- and/or undersupply for each province, either increased grid capacity or more storage systems will be required.

Increased electric mobility will require additional capacity in the power grid to accommodate the higher charging loads for vehicles. This analysis shows that with the smart distribution and management of electric vehicle charging stations, additional transmission lines will be required. The high share of solar PV will lead to high generation peaks during summer months and low generation capacities during winter. To manage the generation peaks of solar PV generators, utility-scale installations will require on-site storage capacity, whereas roof-top PV will require increased 'behind-the-meter' storage facilities.

Power analysis

The N-1.5 °C scenario prioritizes the use of decentralized regional roof-top solar PV and utility-scale solar PV power generation to complement the planned expansion of Nepal's hydropower generation capacity. This will rapidly increase the electricity available for the country's economic development while keeping electricity generation carbon free.

By 2030, variable solar PV power generation will reach around 8%, whereas the proportion of dispatchable renewables—mainly hydropower—will remain over 90% in all regions. The current actual interconnection capacities—including those under construction—between all regions seem sufficient until 2030 if battery storage capacities, in parallel with the expansion of solar PV, are implemented. The modelling results indicate that the planned transmission grid upgrades within Nepal will be sufficient in the short term.

However, Nepal operates a large fleet of run-of-river hydropower plants with no water reservoir storage capacities or pumped hydro storage and should evaluate the extent to which their untapped potential can be utilized in a sustainable way.

The projected sharp increase in solar PV systems will require both short-term and long-term (seasonal) storage after 2030. The N-1.5 °C scenario will lead to an installed capacity of 2 GW by 2035—similar to the current hydropower capacity—and close to 25 GW solar PV by 2050—2.5 times the projected hydropower capacity for 2022.

With peak-shaving, solar production spikes can be reduced, with only a minor effect on the overall annual generation because the peak events will be relatively infrequent. To build up the additional storage capacity required, it is assumed that a proportion of the solar PV capacity will be installed with battery storage. The suggested solar battery system should be able to store the entire peak capacity for 4 full load hours.

The N-1.5 °C scenario requires that all utility-scale solar PV and 75% of all roof-top PV systems built after 2030 be equipped with battery or other storage technology systems. To conclude, a large solar PV power generation share of around 70% by 2050 is feasible for Nepal under the documented assumptions.

The role of micro grids in the future of Nepal's energy supply

Micro-grids will remain the backbone of electricity supply for rural and remote regions in Nepal. A mix of micro- and/or pico hydro powerplants, solar photovoltaics and bio energy fuel generation in combination with battery electric and heat-based storage systems has significant technical and economic advantages over the expansion of high voltage lines for remote areas. The economic advantage is expected to grow as costs for storage systems and solar photovoltaic generators are expected to decline further over the coming decade.

Furthermore, micro-grids can be expanded to follow a growing regional electricity demand and are faster to build—and more economic—than additional transmission power lines. Micro-grids can provide the 'seed' for Nepal's electricity grid: a growing number of micro-grids in rural communities can be connected to grid-clusters which can eventually be connected to the existing power grid network.

1. Introduction

In 2000–2019, Nepal ranked among the top 10 countries (annual averages) on the Global Climate Risk Index, which measures the extent to which countries and regions are affected by weather-related loss events (storms, floods, heat waves, etc.)[1]. Furthermore, global circulation model projections indicate that the temperatures over Nepal will increase between 0.5 °C and 2.0 °C, with a multi-model mean of 1.4 °C, by the 2030s and between 3.0°C and 6.3 °C, with a multi-model mean of 4.7 °C, by the 2090s[2]. With these changes, the magnitudes of drought, forest fires, and floods will increase, resulting in human and economic losses to the nation.

In the Second Nationally Determined Contribution (NDC), 2020, the Government of Nepal has set targets to reduce greenhouse gas emissions (GHG) and fulfil its commitments made under the Paris Agreement to limit the global average temperature rise to 1.5 °C. This will lower the risks for Nepal significantly more effectively than an increase of 2 °C or higher[3].

Against the backdrop of various problems and challenges posed by the negative impacts of climate change on the national economy, one of the strategies and working policies in Nepal's National Climate Change Policy 2019 encourages the production and use of renewable energy and energy-efficient technologies[4].

As the source that powers various sectors across Nepal's economic activities (such as the residential, industries, transport sectors), the energy sector can potentially contribute significantly to emission reductions.

In October 2021, the Government of Nepal published Nepal's Long-term Strategy for Net-zero Emissions (NLTS-NZ 2021), which sets goals required to reduce net-zero emissions in 2020–2030 and, after a period of very low emissions, to reach full net-zero emissions by 2045[5]. To achieve this, some of the strategies outlined in NLTS-NZ 2021 will increase the use of renewable energy in all sectors, improve energy efficiency, and decarbonize the transportation sector.

The present report builds on NLTS-NZ 2021 and presents a 100% renewable energy plan to decarbonize the energy sector of Nepal by 2050 within a carbon budget that will achieve a 1.5 °C increase in global temperature, with 66% certainty (based on IPCC AR6, 2021). In light of the dominance in Nepal of hydropower electricity, a renewable energy source, this report breaks down renewable energy into 'conventional renewables', including bioenergy and large hydropower plants, and 'new renewables', including solar and wind energy systems and micro/mini hydropower stations.

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1. D. Eckstein, V. Kunzel, and L. Schafer, "Global Climate Risk Index 2021," Germanwatch e.V., Bonn, 2021.
2. A. Dixit, D. Gyawali, M. Upadhya and A. Pokhrel, "Vulnerability through the Eyes of the Vulnerable: Climate-Change-Induced Uncertainties and Nepal's Development Predicaments," Institute for Social and Environmental Transition–Nepal (ISET-N, Kathmandu) and Institute for Social and Environmental Transition (ISET, Boulder, Colorado) for the Nepal Climate Vulnerability Study Team (NCVST), Kathmandu, 2009.
3. Government of Nepal, "Second Nationally Determined Contribution (NDC)," Government of Nepal, Kathmandu, 2020.
4. Government of Nepal, "National Climate Change Policy, 2076 (2019)," Government of Nepal, Kathmandu, 2019.
5. Government of Nepal, "Nepal's Long-term Strategy for Net-zero Emissions," Kathmandu, 2021.

The scenarios for the energy pathways do not claim to predict the future but provide a useful tool with which to describe and compare potential development pathways from the broad range of possible 'futures'. The Nepal 1.5 °C (N-1.5 °C) scenario is designed to calculate the efforts and actions required to achieve the ambitious objective of a 100% renewable energy system and to illustrate the options available to change the Nepalese energy supply system into a truly sustainable one. It may serve as a reliable basis for further analyses of the possible ideas and actions required to implement pathways to achieve the desired results.

100% renewable energy scenarios for electricity generation, energy demand, energy supply, and transport are included. The investments required to achieve these scenarios and the policies that will enable them are described for the specific scenarios.

Finally, the report includes simulations of the national grid capacity required now and, in the future, and the necessary linkages between different parts of the country's power grid. The simulations support the assessment of the grid expansion requirements, the power-trade balance, and the investments required to strengthen the backbone of Nepal's electricity infrastructure to ensure its reliability and resilience.

With this report, we aim to inform policymakers, researchers, and practitioners of the extent of the intervention required for Nepal to reach its target of 100% renewable energy by 2050. The decade-by-decade scenarios can inform important milestones that will allow further sector-wise energy-related targets to be defined and tracked.


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2. Research Scope

Since 2017, the UTS-ISF has undertaken detailed country-specific energy analyses, ranging from the global south, including Tanzania, to industrialized countries, including for Switzerland, Italy, and the USA. We have also developed scenarios for India, the largest country neighbouring Nepal and important to the Nepalese energy sector.

All UTS-ISF energy analyses include the following aspects:

- A renewable energy resource analysis based on spatial GIS data under constrained land availability conditions (excluding protected areas, areas with a steep slope, and certain land-cover classes, such as closed forests, wetlands, snow and ice, and permanent water).
- The development of the future energy demands for 2025, 2030, 2035, 2040, 2045, and 2050, based on the latest available statistics—base year for energy demand is 2019 —broken down into the main energy sectors (power, buildings, industry, and transport).
- The sectorial energy demand (see above) is broken down into (up to) seven provinces.
- The development of three scenarios:
  - **REFERENCE** scenario—based on the government plan;
  - **'With the Existing Measures WEM'** scenario— using the same methodology as the REFERENCE with a focus on the intervention measures implemented and adopted up to 2020;
  - **1.5 °C scenario**[6] —100% renewable energy plan to decarbonize the energy sector by 2050 within the carbon budget required to achieve a temperature rise of 1.5 °C with 66% certainty (based on IPCC AR6, 2021).
- These scenarios are combined with renewable energy scenarios with different variable power generation shares (solar photovoltaic [PV], wind, bioenergy, and hydropower).
- Based on the different power demand-and-supply scenarios, a projection of the required load from industry, commercial, and residential demands is compared with the available power generation capacity —to stress-test the security of supply.
- The power generation capacity is simulated at 1-hour resolution for seven provinces with regional long-term average meteorological data for solar and onshore wind.
- Current and future required national grid capacities are simulated, together with the required linkages between different parts of the country's national power grid and import/export transactions with neighbouring countries.

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[6] 1.5 °C scenario: Series of scenarios with total global carbon budget of 400 $GtCO_2$ to limit the global mean temperature rise to a maximum of 1.5 °C with 67% likelihood, as defined in IPCC AR6.

This simulation is particularly important regarding the role of large hydropower plants and the exchange of electricity between Nepal and India. Included are the:

- grid expansion and storage requirements;
- visualization of the hourly demand and supply curves;
- carbon emissions (annual and cumulative);
- effects of all scenarios on employment;
- investment required in additional power generation capacity—including fuel costs and fuel cost savings, and operation and maintenance costs for all power generation capacities;
- the power sector trade balance (electricity and fuel) with neighbouring countries;
- a cost comparison of all scenarios.

3. Scenario Assumptions

A. Nepal: Country overview

The country overview is based on research by PRC, WWF Nepal, WWF Germany, World Future Council, and Brot für die Welt. The socio-economic assumptions, all data related to the energy demand and supply and GHG emissions, and statistical data that have been used for the development of the energy scenarios are based on the following publications:

- Second Nationally Determined Contribution (NDC), Government of Nepal Kathmandu, December 2020 (SNDC 2020)[7]
- Nepal's Long-term Strategy for Net-zero Emissions, Government of Nepal Kathmandu, October 2021 (NLTS-NZ 2021)[8]
- Economic Survey 2020/21, Government of Nepal Ministry of Finance, Singh Durbar, Kathmandu, May 2021 (ECS 2020)
- Technology Needs Assessment for Climate Change Mitigation, Government of Nepal, Ministry of Forests and Environment, August 2021 (TNA 2021)
- Preliminary report of the National Population Census 2021 of Nepal
- Third National Communication to the United Nations Framework Convention on Climate Change

I. Political context

Nepal is located in the heart of the Himalayan Mountains between China and India, with a land area of 147,181 square kilometres[9], and is the 100th largest country in the world, with a size similar to that of Bangladesh[10]. According to the Government of Nepal, Ministry of Foreign Affairs, a Constituent Assembly election was held on April 10, 2008. On May 28, 2008, the newly elected Constituent Assembly declared Nepal a Federal Democratic Republic, abolishing the 240-year-old monarchy. Nepal today has a President as Head of State and a Prime Minister leading the Government. The Constituent Assembly has made significant progress in writing a new democratic constitution for Nepal during its first 4-year term. The country has also undertaken extensive democratic consultations on the constitution including collecting public input on the contents of the new constitution and intense deliberations in the Assembly[11]. As the First Constituent Assembly failed to promulgate a new constitution, Second Constituent Assembly elected in November 2013 completed the remaining tasks and completed the constitution writing process. On 20 September 2015, the New Constitution of Nepal was promulgated by the Second Constituent Assembly, which then got turned into Legislature Parliament.

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[7] Second Nationally Determined Contribution (SNDC), Government of Nepal Kathmandu, December 2020, https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Nepal%20Second/Second%20Nationally%20Determined%20Contribution%20(NDC)%20-%202020.pdf

[8] Nepal's Long-term Strategy for Net-zero Emissions, Government of Nepal, Kathmandu for October 2021, document downloaded from Internet platform of the United Nations Framework Convention on Climate Change (UNFCCC); https://unfccc.int/documents/307963

[9] Land area of 147,181 sq. km is based on official records. Upon publication of the new map on May 2020, the addition of 335 sq. km reported in the media is currently excluded from the above figure (https://myrepublica.nagariknetwork.com/news/nepal-s-new-map-covers-an-area-of-147-516-sq-km-10-000-copies-being-printed/)

[10] CIA World Factbook, Nepal; https://www.cia.gov/the-world-factbook/field/area/country-comparison/

[11] Government of Nepal, Ministry of Foreign Affairs; History Of Nepal; https://mofa.gov.np/about-nepal/history-of-nepal/

Nepal is strongly committed to the Paris Climate Agreement. The Government has stated that 'Nepal is among the most vulnerable countries to climate change. It is at high risk due to the country's fragile topography, the people's climate-sensitive livelihoods, and their limited adaptive capacity. Nepal is committed to acting on climate change in line with the Paris Agreement, despite the country's negligible emissions' (SNDC 2020)[12].

Nepal ranks 10th on the Climate Risk Index (CRI)[13] . This index measures "the level of exposure and vulnerability to extreme events, which countries should understand as warnings to be prepared for more frequent and/or more severe events in the future". These may be meteorological events, such as tropical storms and tornados, hydrological events, such as storm surges and flash floods, or climatological events, such as wildfires and droughts.

The Government of Nepal has undertaken or initiated a significant amount of research around the status and possible development of the energy sector, the sources of current GHG emissions from Nepal, and possible strategies to limit those emissions, as well as detailed assessments of the building sector, such as the Nepal Urban Housing Sector Profile, the United Nations Human Settlements Programme (UN-HABITAT), 2010, the Biomass Energy Strategy 2017 of the Government of Nepal, Ministry of Population and Environment, and the Nepal Energy Infrastructure Sector Assessment[14], published in March 2019 as a result of joint research by the World Bank, the Federal Ministry of Finance of Nepal, and a government working group representing all parts of the energy sector. However, these are only a few examples of a long list of research programs that the Government of Nepal and civil society have undertaken and which form the basis for our assumptions in this renewable energy research project. Nepal also works with the Climate Action Enhancement Package (CAEP), a partnership that supports developing countries to enhance quality of policy analysis, increase ambition, and implement NDCs[15].

II. Population development

With a population density of 205 people per square kilometre[16], Nepal is a medium densely populated country in South Asia, bordering China in the north and India in the south, east, and west. In 2021, Nepal had an estimated population of 29.1 million (CBS, 2021).

Through the 1960s and 1970s, the population growth rate in Nepal fluctuated around 2% per year, slowly increasing throughout the 1980s, with a peak of 2.77% in 1993. Since then, the population growth has decreased sharply to −0.27% in 2013. By 2019 and 2020, the annual population growth rate was 1.8%. The fertility rate is now 1.9 children born per woman[17], just under the global average of 2.4. Nepal has a young population, with 49% of people under 24 years old and about 12% of the population older than 55 years.

Nepal has seven provinces, which are further divided into 77 districts. For the power sector analysis (see Chapter 7), we used these seven provinces as modelling regions (Figure 1). This breakdown reflects the demand and supply centres of Nepal.

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[12] Second Nationally Determined Contribution (SNDC), Government of Nepal Kathmandu, December 2020, https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Nepal%20Second/Second%20Nationally%20Determined%20Contribution%20(NDC)%20-%202020.pdf

[13] Eckstein, D., Künzel, V., & Schäfer, L. (2021). Global Climate Risk Index 2021. Bonn: Germanwatch e.V.

[14] Singh, Bipulendu Narayan; Shah, Lopa; Wang, Xiaoping–GEE06; Ma, Yuge, Nepal–Energy Infrastructure Sector Assessment (English). Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/592481554093658883/Nepal-Energy-Infrastructure-Sector-Assessment

[15] https://ndcpartnership.org/caep

[16] World Population Review (2022), https://worldpopulationreview.com/country-rankings/countries-by-density

[17] CIA World Factbook, https://www.cia.gov/the-world-factbook/countries/nepal/#people-and-society

Table 1: Overview—Seven provinces of Nepal

Scenario Region	Provinces	Population [2021]	Area [km^2]	Population Density
1	Province 1	4,972,021	25,905	192v
2	Madhesh	6,126,288	9,661	634
3	Bagmati	6,084,042	20,300	300
4	Gandaki	2,479,745	21,504	115
5	Lumbini	5,124,225	22,288	230
6	Karnali	1,694,889	30,211	61
7	Sudurpaschim	2,711,270	19,539	139

Source: Population Census (2021)—Nepal Central Bureau of Statistics

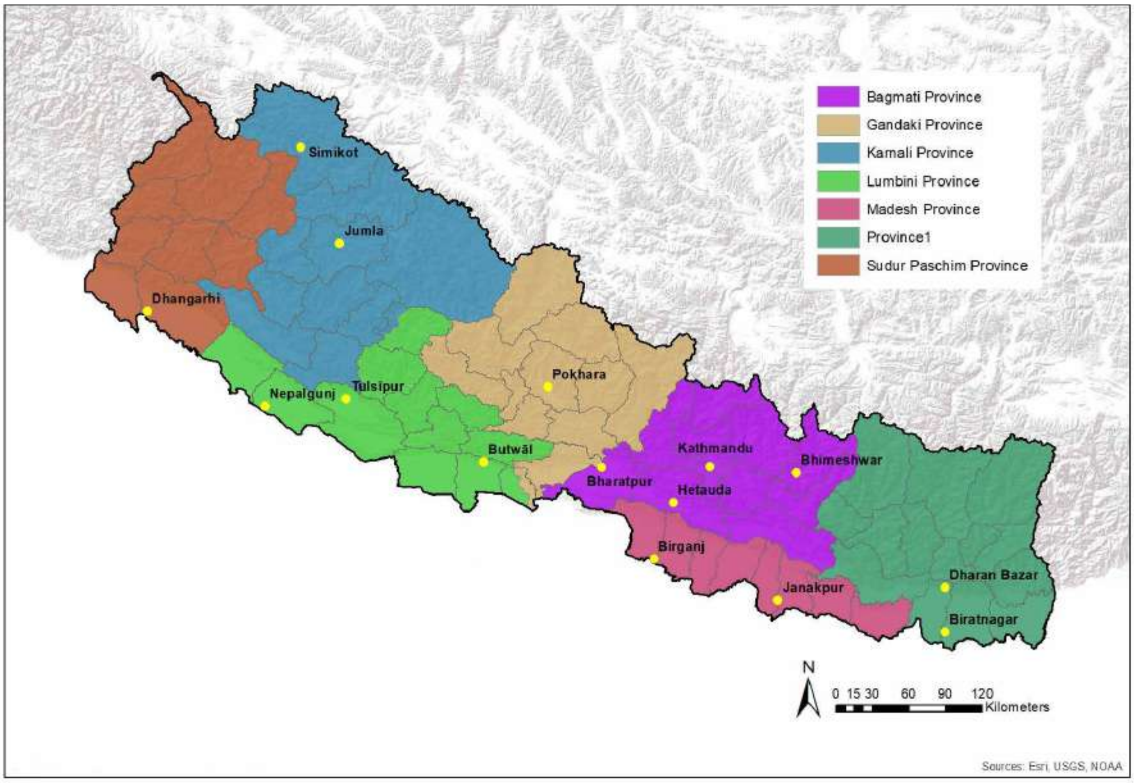

Figure 1: Nepal—Seven provinces with 77 districts

Source: OCHC services: Nepal—Subnational Administrative Boundaries (2022)

III. Economic context

According to the World Bank, Nepal has achieved respectable growth in the past, averaging 4.9% between 2009 and 2019. However, Nepal faces significant vulnerabilities in achieving inclusive and sustainable growth. The on-going disruptions caused by the COVID-19 pandemic have been compounded by structural constraints, such as slow domestic job creation, high vulnerability to natural disasters, climate change, environmental degradation, and large infrastructure gaps. Furthermore, the pandemic has recently triggered a surge in debt levels, which must be addressed (World Bank, 2022)[18]. However, strong economic growth is assumed for the development of the energy scenario.

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[18] World Bank 2022, Country Overview Nepal, viewed June 2022 https://www.worldbank.org/en/country/nepal/overview#1

Population and economic development projections until 2050

The population and gross domestic product (GDP) shown in Table 2 are based on projections of the Nepal Government, which have been used for the NDC and the long-term energy plan. The population is expected to grow from about 29 million in 2022 to 33.4 million by 2030 and to 35.3 million by 2050. The economy is assumed to increase from 3% to 4% during the pandemic, to reach a steady growth rate of 7.5% annually, leading to a more than five-fold increase in economic management, to around US$200 billion by 2050. The economic growth rates reflect those used for Nepal's Long-term Strategy for Net-zero Emissions published by the Government of Nepal, Kathmandu, in October 2021 (NLTS-NZ 2021).

Table 2: Nepal's population and GDP projections until 2050

Nepal	Units	2019	2025	2030	2035	2040	2045	2050
Population	[individuals]	28,608,710	31,757,446	33,389,537	34,299,735	34,889,691	35,220,968	35,326,631
Annual Population Growth	[%/a]	−0.7%	1.7%	1.0%	0.5%	0.3%	0.2%	0.1%
GDP	[US$ billion]	34.186,	40.627	55.863	76.812	105.616	145.223	199.681
Annual Economic Growth (data for 2030, 2040 and 2050 from LTLEDS)	[%/a]	3.1%	4.0%	7.5%	7.5%	7.5%	7.5%	7.5%
GDP/Person (calculated)	[US$/capita]		1,279	1,673	2,239	3,027	4,123	5,652

The Fifteenth Plan (Fiscal Year 2019/20–2023/24), Government of Nepal

The Government of Nepal has established socio-economic targets in its Fifteenth plan, which ends in mid-2024. The document defines various targets, some including targets until 2043/2044. The N-1.5 °C scenario includes the targets for various financial years (FY) shown in Table 3.

Table 3: Government of Nepal, 15th Plan 2019/2020 to 2023/2024

Indicator	Units	Status in FY 2018/19	Target for FY 2023/24	Target for FY 2029/30	Target for FY 2043/44
Contribution of the agriculture sector to GDP	%	27	23	17.1	9
Contribution of the industry sector to GDP	%	15.2	18.1	23.7	30
Contribution of the service sector to GDP	%	57.8	58.9	59.2	61
Electricity generation, installed capacity	MW	1,250	5,820	15,000	40,000
Renewable energy (solar, wind, micro-hydropower) installed capacity	MW	67.8	216.6	4,000	5,000
Households with access to electricity	%	88	100	100	100
Per capita electricity consumption	kWh	245	700	1,500	3,500
Ratio of renewable energy to total energy consumption	%	7	12	20	50
Hydropower	MW	1,128	5,000	-	-
Thermal plant	MW	53.4	53.4	-	-
Renewable energy	MW	67.8	216.6	-	-
Solar energy (private sector promoted)	MW	-	550	-	-
Electricity leakage	%	15.3	12.32	-	-
Total length of 66 kV (additional power line)	km	3,990	8,000	-	-
Total length of 33 kV (additional power line)	km	4,905	7,300	-	-
Total length of 11 kV (additional power line)	km		43,352	-	-

B. Electricity infrastructure and energy access

The Energy Progress Report (EPR 2021)[19], published in June 2021, identified Nepal as one of the leading countries of the global south, with the fastest-growing energy access rate. Over 94% of Nepalese have access to energy services: about 5.5% are connected to mini-grids and the remainder to the country's main power grid.

For this analysis, Nepal's power sector is divided into seven regions. The regional distribution of the population and the availability of the energy infrastructure correlate with the socio-economic situation in all regions. The following map provides an overview of the locations of power lines and power plants, a regional breakdown of energy pathways, and a power sector analysis (Chapter 7).

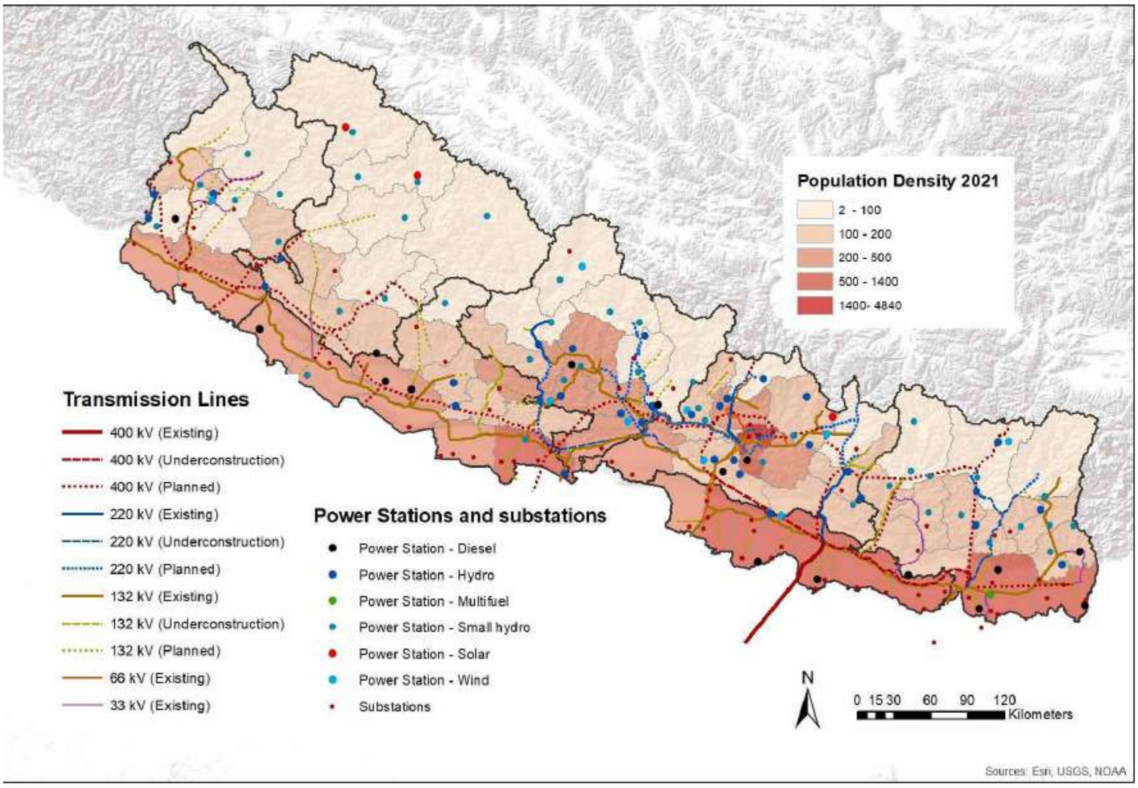

Figure 2: Distribution of population and the existing electricity infrastructure in Nepal

Source: Power stations and substations—World Bank Group (2018); transmission lines—Clean Cooking Alliance (CCA) generated a report for Nepal Electricity Authority (NEA), Government of Nepal; population—Population Census 2011, Nepal Central Bureau of Statistics

Figure 2 also shows the population density of Nepal. The highest population concentrations are shown in dark red and the lowest in white. The map clearly shows the high population densities in the metropolitan areas of Kathmandu (Bagmati Province) and districts near the southern border of the country.

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[19] IEA, IRENA, UNSD, World Bank, WHO. 2021. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC; World Bank. License: Creative Commons Attribution—NonCommercial 3.0 IGO (CC BYNC 3.0 IGO). https://www.irena.org/publications/2021/Jun/Tracking-SDG-7-2021

The existing constructed electricity infrastructure (power lines, power plants, and sub-stations), with their different types of grids, are shown as lines, and the differently coloured dots mark grid-connected power plants—each colour represents a specific technology, identified in the legend. The lines represent power transmission lines with different voltage levels. Over 95% of all power generation capacities in Nepal are hydropower plants, whereas there are also on- and off-grid-operated solar photovoltaic (PV) and wind power stations, mostly located in areas of lower population density. The figure visualizes the distribution of the grid, power plants, and population density, but does not claim to be complete.

The energy access rate of the rural population in Nepal is around 90%, although access to energy services does not necessarily mean that the supply is available at all times.

C. Energy demand—Development since 2005

It is necessary to analyse the development of the past energy demand in order to project that of the future. Therefore, the statistical data for Nepal's energy demand between 2005 and 2019 have been analysed (IEA 2022)[20].

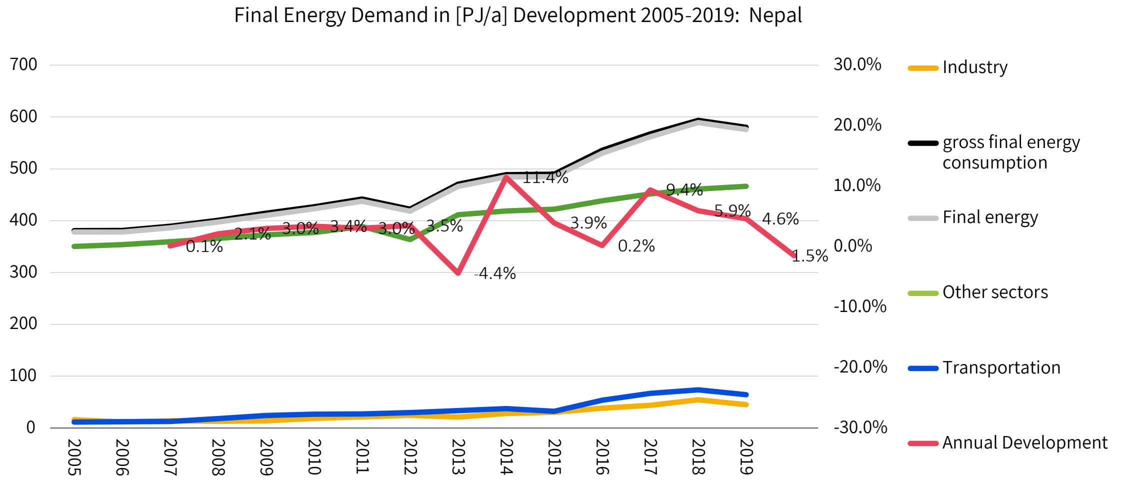

Figure 3: Final energy demand development in Nepal from 2005 to 2019

Source: Power stations and substations—World Bank Group (2018); transmission lines—Clean Cooking Alliance (CCA) generated a report for Nepal Electricity Authority (NEA), Government of Nepal; population—Population Census 2011, Nepal Central Bureau of Statistics

Figure 3 shows Nepal's final energy demand development between 2005 and 2019. The overall energy demand grew constantly, despite years of reduced demand due to reduced economic activity. The gross final energy demand has grown by about 50% since 2005 to around 600 petajoules per annum (PJ/a). The main energy demand is required in the residential sector, whereas only 8% of the energy is for industry use and 11% for the transport sector.

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[20] IEA 2022, Advanced World Energy Balances, Nepal.

The electricity demand has increased significantly faster than the final energy demand. By 2019, the annual electricity demand was close to 6.5 billion kilowatt-hours (6.5 TWh/a), up from 2 TWh/a in 2005 (Figure 4) growing by a factor of close to 3. Again, the residential sector grew fastest, followed by the industry sector, and the electricity demand for transport was almost negligible. However, with the increased electrification of vehicles, the energy demand for transport is expected to rise significantly.

However, Nepal's electricity demand, at 337 kWh per capita, is one of the lowest in the world[21], especially compared with those of South and East Asia and the Pacific islands states, with an average per capita consumption of 3677 kWh per year, whereas the global average consumption is 2,500 kWh per annum (World Bank 2019)[22].

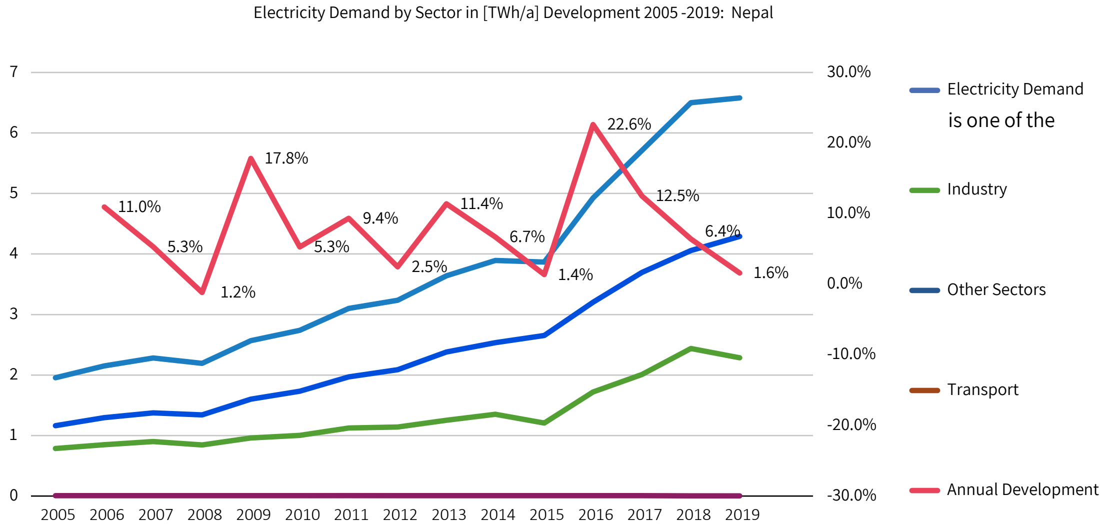

Figure 4: Electricity demand development in Nepal from 2005 to 2019

I. Energy demand—Future projections

To establish a stakeholder dialogue and develop energy demand and supply projections for Nepal, the trends in the energy demand and supply for the past 15 years (2005–2020) have been analysed, based on the International Energy Agency (IEA) World Energy Balances. Those rough trend calculations were used for the initial discussion of the future development of the energy sector. In the second step, the research results of government agencies of Nepal and international organizations, such as the IEA, the International Renewable Energy Agency (IRENA), and the World Bank, were reviewed. In the third step, a bottom-up demand analysis was performed, as documented in Section D.

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[21] D. K. Shahi, H. B. Rijal and M. Shukuya, "A study on household energy-use patterns in rural, semi-urban and urban areas of Nepal based on field survey," Energy and Buildings, vol. 223, no. 0378-7788, p. 110095, 2020.

[22] World Bank Database 2019, data referred to accessed via: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=IN-PK-BD-LK-NP-AF&name_desc=true

The trend analysis and government projections are presented below. Two projections have been calculated:

1. Trend projection: The energy demand and supply trends for the past 15 years will continue for the next 30 years, until 2050. The average growth rates for coal-, gas-, and oil-based electricity, heat generation, and the transport fuel supply will continue, and renewables will provide the remaining energy to meet the demand. In this projection, fossil fuels have priority over renewable energy—so the increased use of fossil fuels might push renewables out of the market. Renewables will only be deployed if the overall energy demand is not met by the projected growth in fossil fuels.

2. Target projection: The energy demand will develop according to the trend minus an assumed 1.5% efficiency gain, which is consistent with international projections and historical developments. Fossil fuels for electricity and heat generation and to supply the transport demand will be phased-out, with average annual decline factors (Table 4) that are based on a global 1.5 °C pathway[23]. The entire gap between the demand and (declining) fossil fuels will be supplied with renewables. A detailed breakdown of the renewable energy technologies available has not been calculated. The rate of fossil fuel decline is higher for industrialized countries than for countries of the global south. The resulting average for the entire G20 is shown in the table below.

An analysis of the historical development of the primary energy, heat, transport, and electricity demands and two projections of them have been undertaken. These demands are provided for the three main sectors: industry, transport, and 'other sectors'. The category 'other sectors' is dominated by buildings, and includes agriculture, forestry, and fisheries. The structure of this analysis is based on the IEA Advanced World Energy Balances[24].

Table 4: Projected average decline rates for fossil fuels necessary to remain within a 1.5 °C scenario

1.5 °C Scenario Carbon Budget 2020–2050: 400 GtCO$_2$	Average Annual Rate of Decline: 2021–2030	Average Annual Rate of Decline: 2031–2050	Average Annual rate of Decline: 2021–2030	Average Annual Rate of Decline: 2031–2050	Average Annual rate of Decline: 2021–2030	Average Annual Rate of Decline: 2031–2050
	Industrialized Countries		Developing Countries		G20 average	
Coal	−9.5%/a	−5.0%/a	−5.5%/a	−5.5%/a	−6.8%/a	−8.1%/a
Gas	−3.5%/a	−9.0%/a	−3.5%/a	−9.0%/a	−3.5%/a	−9.0%/a
Oil	−8.5%/a	−6.0%/a	−5.5%/a	−6.0%/a	−6.7%/a	−8.0%/a

In the last step, the energy-related CO$_2$ emissions for the historical and projected primary fossil-fuel demands were calculated with their emission factors (Table 5). **Neither projection is a scenario but only a trajectory calculated based on fixed annual percentages of growth and decline**.

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[23] Teske S, Niklas S (2021), Fossil Fuel Exit Strategy: An orderly wind down of coal, oil and gas to meet the Paris Agreement, June 2021

[24] IEA. IEA World Energy Statistics and Balances. IEA. 2021. Available online: https://doi.org/https://doi.org/10.1787/enestats-data-en (accessed on March 2022).

Table 5: Assumed emission factors for fossil fuels (UBA 2022)[25] in kilotonnes CO_2 per petajoule ($ktCO_2/PJ$).

Fuel	Units	Emission Factor
Lignite	[$ktCO_2/PJ$]	101
Hard coal	[$ktCO_2/PJ$]	93
Oil	[$ktCO_2/PJ$]	75
Gas	[$ktCO_2/PJ$]	56

This method was chosen to narrow the possible targets for renewable energies without calculating complete energy scenarios for the initial dialogue with stakeholders. Therefore, it is a mapping procedure and NOT a detailed procedure for developing energy scenarios.

Figure 5 shows the 'Trend' and 'Target' projections for Nepal's final energy demand. The energy demand increases in both cases. Whereas the demand more than doubles if the development of the past 15 years continues for the next 30 years, the demand under the 'Target' projection only increases by about one-third. The electricity demand forecast until 2030 by the Government of Nepal (IBN 2011) estimates an increase to just over 50 TWh/a by 2030, more than six times the current demand (Figure 7). Under the Trend projection, the electricity demand will increase to the demand (50 TWh) projected by the Government, but the increase will occur more slowly and will be reached by 2050. Under the Trend projection, the electricity demand will increase even more slowly and reach only 40 TWh by 2050 if no increased electrification of the heating and transport sectors occurs. Under the assumptions that 75% of Nepal's heating demand will be electrified (from currently 5%) and that oil will be replaced with electric drives in 100% of road vehicles, the electricity demand will jump to 195 TWh by 2050.

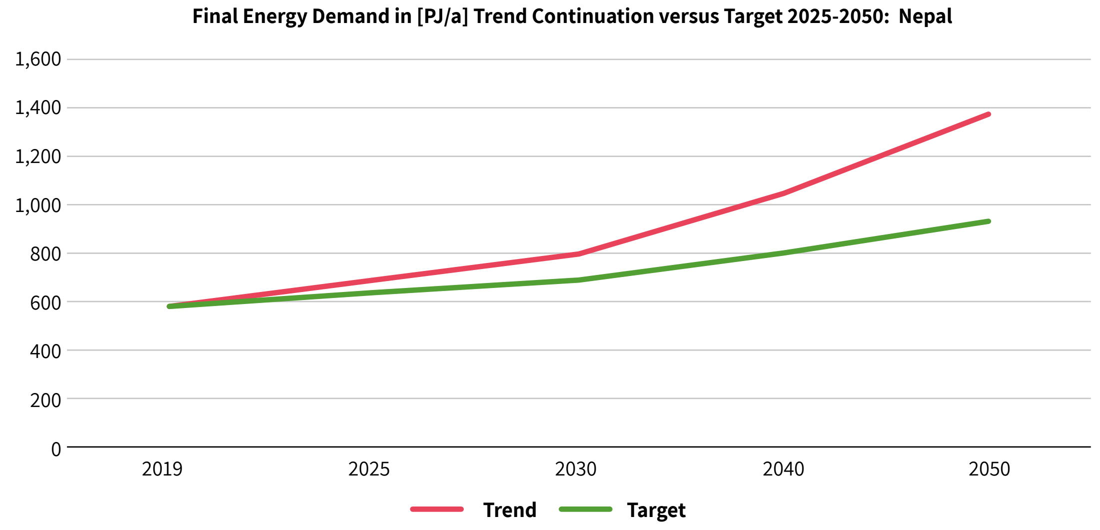

Figure 5: Nepal—Final energy demand Trend vs Target, 2020–2050

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[25] UBA (2022), CO_2 Emission Factors for Fossil Fuels, Update 2022, Kristina Juhrich German Environment Agency (UBA), section V 1.6 Emissions Situation), March 2022, ISSN 1862-4359, https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/cc_29-2022_emission-factors-fossil-fuels.pdf

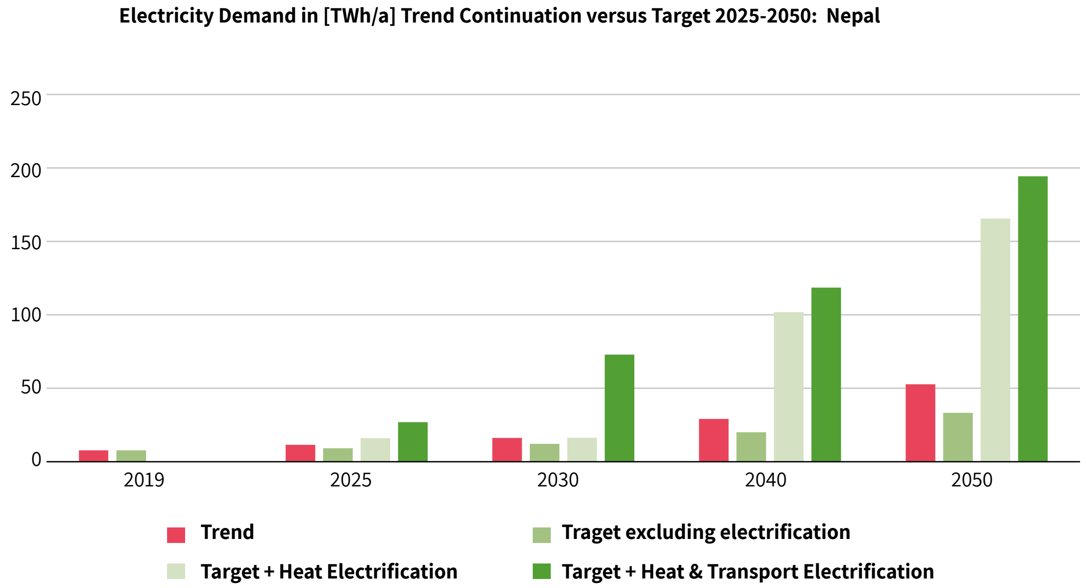

Figure 6: Nepal's electricity demand, Trend vs Target, 2020–2050

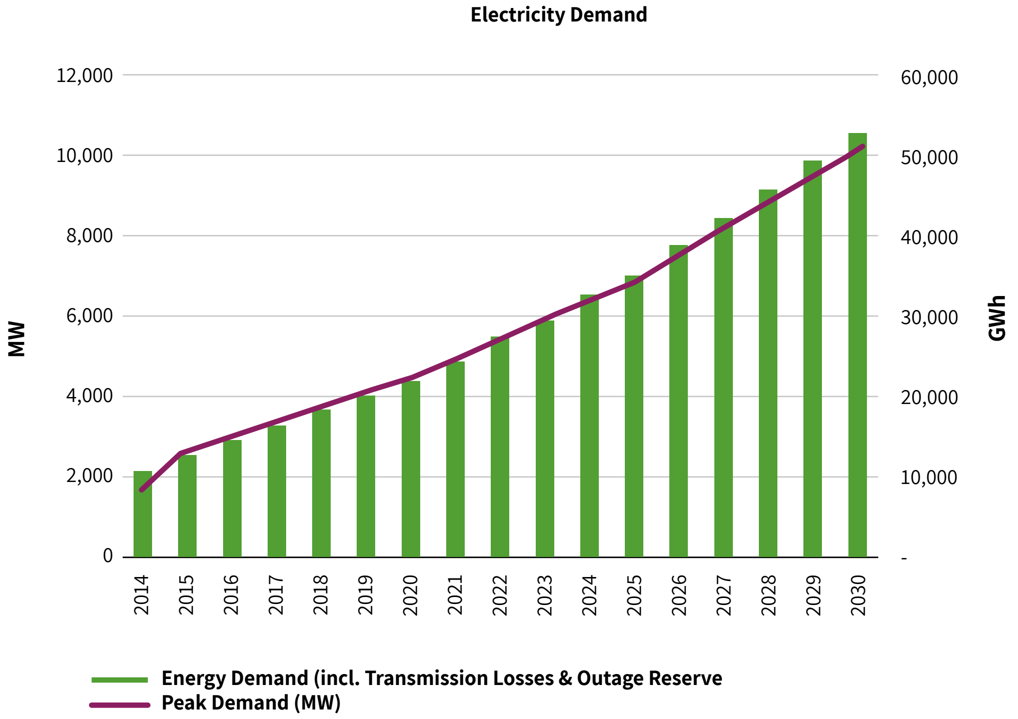

Figure 7: Nepal's electricity demand forecast until 2030. Government of Nepal, Investment Board (IBN 2011)

Table 6: Nepal's primary energy supply between 2005 and 2019 (IEA World Energy Balances 2021)

Primary Supply -	Units	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Annual development			0.0%	1.8%	3.1%	3.1%	2.9%	3.4%	-4.4%	11.1%	4.0%	-0.1%	9.2%	5.9%	4.9%	-1.1%
Primary energy	[PJ/a]	382	382	389	401	413	426	440	421	467	486	486	530	561	589	582
Net Export (–) / Import (+)	[PJ/a]	44	36	37	43	50	59	64	73	81	93	84	124	147	175	150
Fossil fuels	[PJ/a]	41	34	34	38	46	54	58	65	66	79	74	112	135	156	137
Coal	[PJ/a]	10	6	8	8	8	13	15	18	14	20	23	29	33	42	33
Lignite	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil	[PJ/a]	30	28	25	31	38	41	42	47	52	58	51	83	102	114	104
Gas	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nuclear	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Conventional Renewables	[PJ/a]	341	348	355	362	367	371	382	356	401	407	411	418	426	432	445
Biomass	[PJ/a]	332	338	345	352	356	360	370	343	389	394	399	403	409	415	422
Hydro	[PJ/a]	9	10	10	10	11	12	13	13	13	14	12	15	17	18	22
New renewables																
Solar (A)	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Conventional Renewables Share:	[%]	89%	91%	91%	90%	89%	87%	87%	85%	86%	84%	85%	79%	76%	73%	76%
New Renewables Share	[%]	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%

(A) Solar is not zero because it is used in various on- and off-grid applications. Similarly, wind is also not zero, because it is used in off-grid applications. However, the overall energy generation is < 0.1 PJ/a

II. Energy supply

The primary energy supply is dominated by biomass (over 65%), used mainly for cooking and heating, whereas electricity is almost entirely supplied by hydropower plants (99%), as shown in Table 6. If the primary energy supply continues according to its development over the past 15 years (by 3.5% annually), the primary energy demand will quadruple to 2,250 PJ/a by 2050.

Definition of renewable energy

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body assessing climate change. In its Special Report on Renewable Energy Sources and Climate Change Mitigation[26], the IPCC defines the term 'renewable energy' as follows:

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[26] Arvizu, D., T. Bruckner, H. Chum, O. Edenhofer, S. Estefen, A. Faaij, M. Fischedick, G. Hansen, G. Hiriart, O. Hohmeyer, K. G. T. Hollands, J. Huckerby, S. Kadner, Å. Killingtveit, A. Kumar, A. Lewis, O. Lucon, P. Matschoss, L. Maurice, M. Mirza, C. Mitchell, W. Moomaw, J. Moreira, L. J. Nilsson, J. Nyboer, R. Pichs-Madruga, J. Sathaye, J. Sawin, R. Schaeffer, T. Schei, S. Schlömer, K. Seyboth, R. Sims, G. Sinden, Y. Sokona, C. von Stechow, J. Steckel, A. Verbruggen, R. Wiser, F. Yamba, T. Zwickel, 2011: Technical Summary. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds), Cambridge University Press, Cambridge, UK and New York, NY, USA.

'RE is any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves, ocean thermal energy and wind energy. However, it is possible to utilize biomass at a greater rate than it can grow or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. On the other hand, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilization.'

The Alternative Energy Promotion Centre (AEPC), a Government of Nepal institution established on November 3, 1996, under the Ministry of Science and Technology to develop and promote renewable/alternative energy technologies in Nepal, distinguishes between *conventional renewables* (bio-energy and large hydropower) and *new renewables*, which include solar and wind energy systems and small hydropower stations.

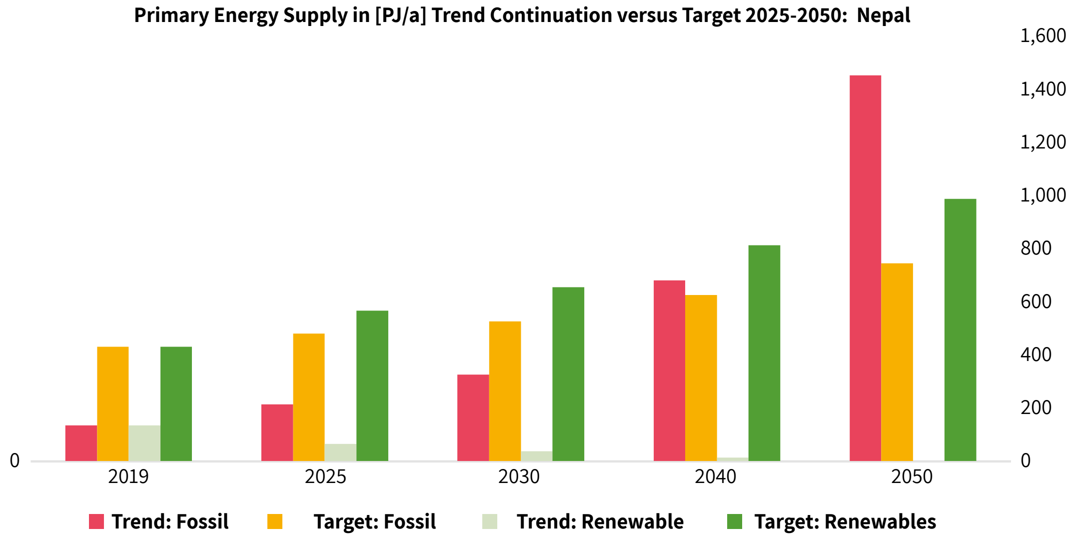


Figure 8: Nepal—Primary energy supply Trend vs Target, 2020–2050

Energy efficiency measures can reduce energy intensity. Energy intensity describes the energy demand required for each dollar of GDP or energy services, such as energy units per kilometre of passenger transport. When efficiency measures that lead to an efficiency gain of 1.5% annually are in place in Nepal—which has been the global average over the past two decades—the energy demand will still double under its assumed economic development. If the trends for fossil and renewable energy sources continue, fossil fuels will dominate the supply mix by 2040. This indicates that the current trends are insufficient to achieve net-zero emissions and therefore the target of 100% renewable energy. The fossil energy share projected in the Trend will decrease from 75% to 62% in 2030 and to only 34% in 2050.

The *Trend* projection is consistent with the *High Economic Growth Scenario - Nepal's Energy Sector Vision 2050*, published in November 2013, from a research project of the Government's Water and Energy Commission Secretariat of Nepal (Figure 9). This scenario envisages a high-economic-growth pathway, and the population growth is based on the census in 2011. The technology mix for the energy end-users is presumed to remain the same as in the base year. Energy consumption will increase to 663 PJ/a by 2030 and to 1,600 PJ/a by 2050.

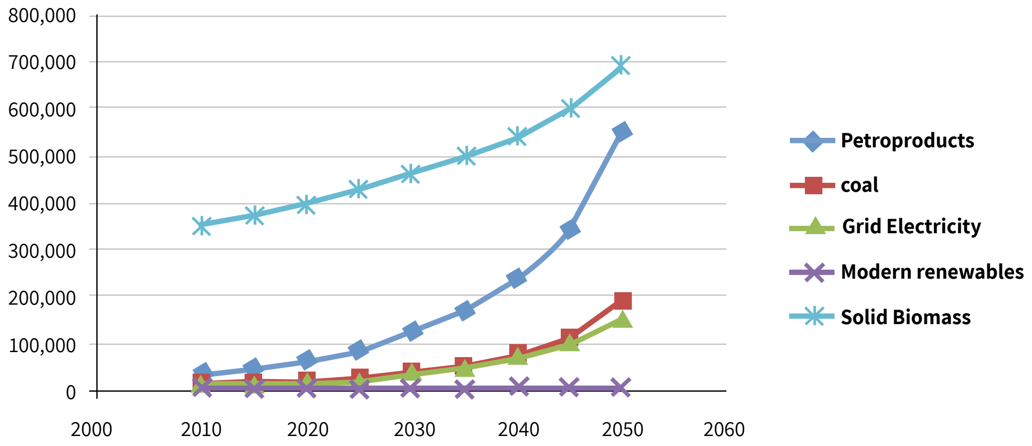


Figure 9: Nepal—Energy consumption by various energy carriers in the low-economic growth scenario

Source: Nepal's Energy Sector Vision 2050 A.D., Water and Energy Commission Secretariat, 2013.

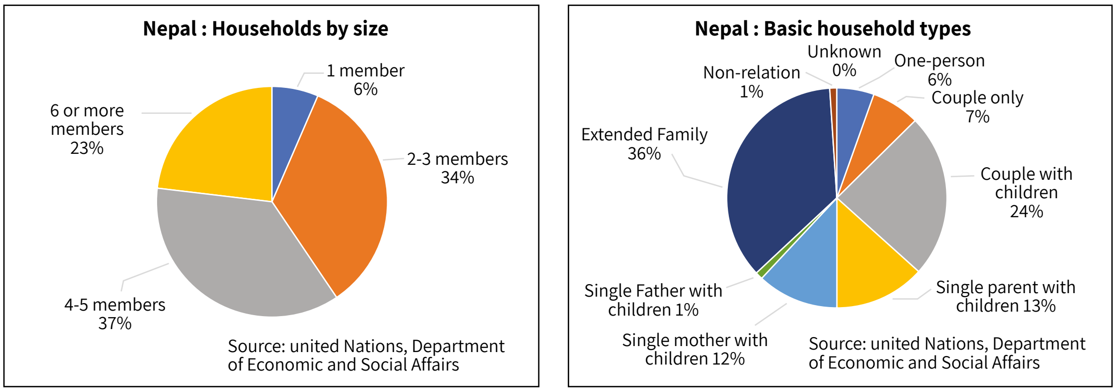
D. Development of the residential energy demand

To develop a projection for the residential electricity demand in Nepal over the coming 30 years to achieve the Nepal 1.5 °C (N-1.5 °C) scenario, a bottom-up electricity demand analysis was performed.

The N-1.5 °C aims to increase the access to energy—especially electricity—for all by 2050, while increasing the electrification and comfort standards to the levels of OECD countries. The growing economy requires a reliable power supply for small and medium businesses, industry, and the transport sector. It is assumed that households will use modern energy-efficient applications, according to the highest efficiency standards, to slow the growth of the power demand and to allow the parallel expansion of the energy infrastructure and the construction of renewable power plants. Electrification will be organized from the 'bottom up' in a new and innovative approach developed by UTS-ISF.

I. Household electricity demand

The current and future developments of the electricity demand for Nepal's households were analysed from the second half of 2021 onwards under the leadership of the Prakriti Resources Centre (PRC) and WWF Nepal in co-operation with the World Future Council (Germany), WWF Germany, and Brot für die Welt (Germany). The future development of the household demand has been discussed in a multiple-stakeholder dialogue with representatives from Nepal's academia, civil society, and government.



Source: united Nations, Department of Economic and Social Affairs

Source: united Nations, Department of Economic and Social Affairs

Figure 9: Nepal—Households by size and type

Table 7 shows the electricity demand and the electrical appliances used by households in Nepal in 2020 and the projected 'phases', with increased demand in the case of increased electrification. It is assumed that households with an annual consumption indicated under the household type in 'phase 1' will increase their demand to 'phase 2' or 'phase 3' values over time. There are currently three household types, separated according to their annual electricity demand: rural households, which have an average annual electricity demand of just under 340 kWh; semi-rural households, which consume around 500 kWh per year; and urban households, with an annual consumption of 840 kWh.

The electricity demand will gradually increase as the electric applications for each of the three household types progress from those households with very basic needs, such as light and mobile phone charging, to a household standard equivalent to that of industrialized countries. The different levels of electrification and the utilization of appliances are described with the affixes 'phase 1', 'phase 2', and 'phase 3' for rural households. In contrast, semi-urban and urban households have two groups: one for the basic level and one for the more-advanced stage of electrification. The households will develop over time, from the basic group towards the more advanced group.

The third phase of a rural household includes an electric oven, refrigerator, washing machine, air-conditioning, and entertainment technologies, and aims to provide the same level of comfort as households in urban areas in industrialized countries. Adjustments will be made to the levels of comfort in households in city and rural areas to prevent residents—especially young people—from leaving their home regions and moving to big cities. The phase-out of unsustainable biomass and liquefied pressurized gas (LPG) for cooking is particularly important in decarbonizing Nepal's household energy supply. A staged transition towards electrical cooking is assumed (see Section D ii).

Table 7: Household types used in all scenarios and their assumed annual electricity demands

Household Type	Group	NEPAL—Annual household electricity demands	Annual electricity demand [kWh/a]
Rural	Phase 1	Very-low-income rural household Low-income rural household	337[27]
	Phase 2	Lower-middle-income rural household	1021
	Phase 3	Upper-middle-income rural household	2210
Semi-Urban	Basic	Low-to-middle-income semi-urban household	501[27]
	Advanced	Middle-income semi-urban household	1763
Urban - Apartment	Basic	Low-to-middle-income urban household (apartment)	836[27]
	Advanced	Middle-income urban household (apartment)	2422
Urban House	Basic	Middle-income urban household (house)	2405
	Advanced	Middle-to-high-income urban household (house)	2477

The typical household electricity demands are compared with:

i) Regional countries in South Asia: India, Sri Lanka, Pakistan, and Bhutan;

ii) Example of an OECD country. The authors have chosen Switzerland for its well-documented electricity demands and good representation of energy-efficient but highly electrified households among the OECD countries.

Compared with the household annual energy and electricity demands of the regional and/or neighbouring countries such as India, Sri Lanka, Bhutan, and Pakistan (Figure 11, Figure 12, Figure 13, and Table 8, respectively), Nepal's household demand is the second lowest. Only Sri Lanka has a lower household electricity demand, of 111 kWh per year for rural households and 210 kWh per year for urban households, compared with 337 kWh/a (rural) and 836 kWh/a (urban), respectively, in Nepal. Rural households in India have an average annual electricity demand of around 300 kWh (approx. 1 GJ/a) per person. In comparison, Bhutan has the highest regional annual electricity consumption for rural households, at just over 3000 kWh, equal to that of an average household in the OECD.

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[27] D. K. Shahi, H. B. Rijal and M. Shukuya, "A study on household energy-use patterns in rural, semi-urban and urban areas of Nepal based on field survey," Energy and Buildings, vol. 223, no. 0378-7788, p. 110095, 2020.

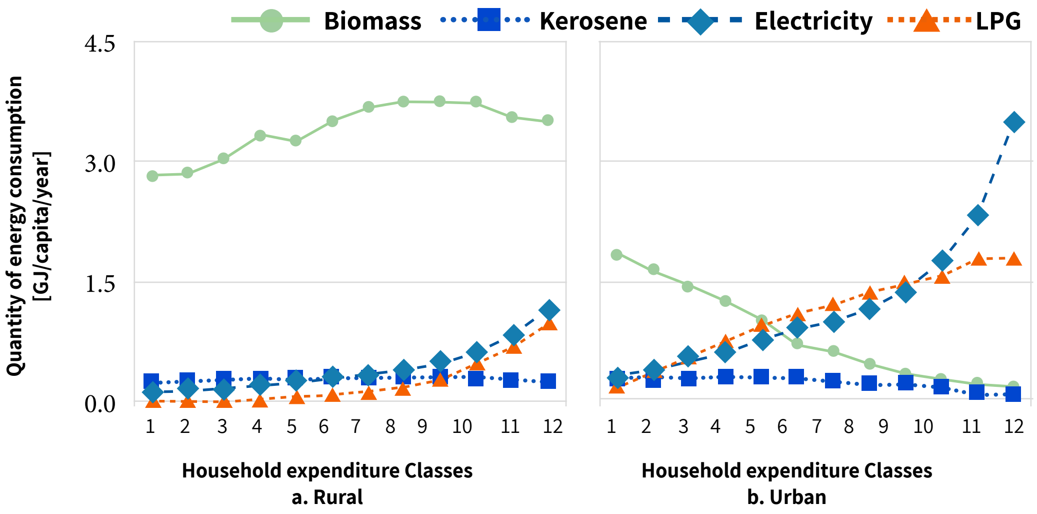

Figure 11: Reference example of household energy demands in South Asian countries: India

Source: Yawale et al. 2021[28]

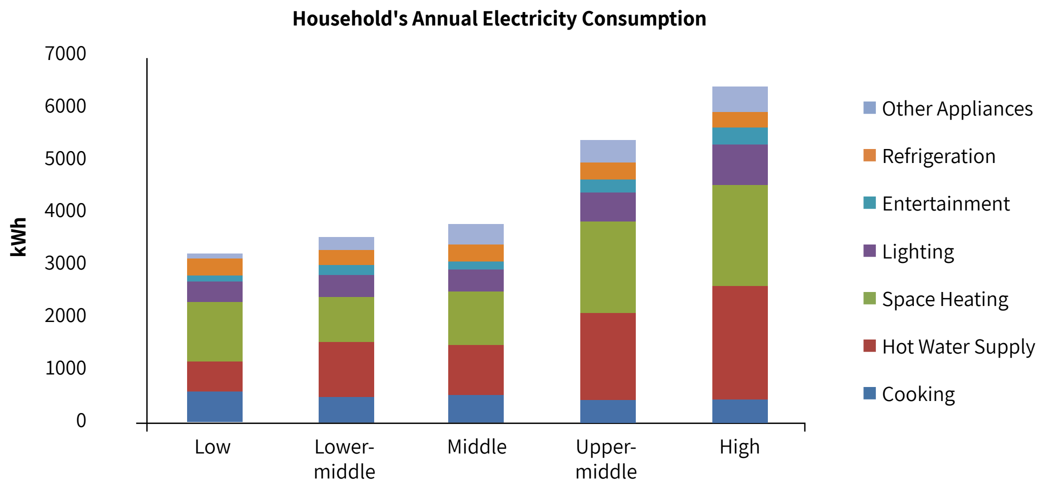

Figure 12: Reference example of household energy demands in South Asian countries: Bhutan

Source: Chhetri et al. (2018)[29]

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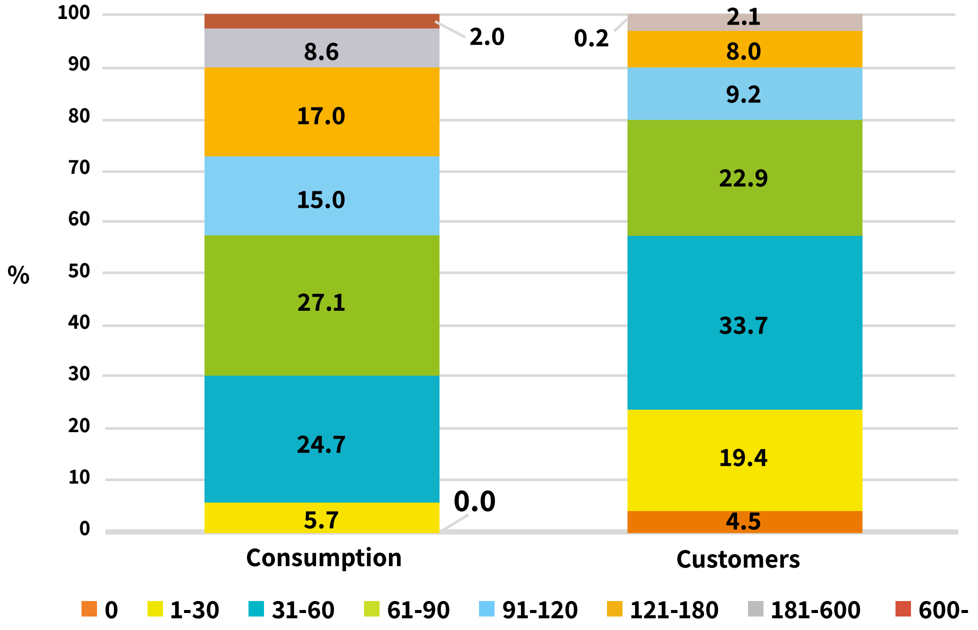
28. K. S. Yawale, T. Hanaoka and M. Kapshe, "Development of energy balance table for rural and urban households and evaluation of energy consumption in Indian states," Renewable and Sustainable Energy Reviews, p. 110392, 2021.
29. L. K. Chhetri and B. Sajjakulnukit, "A Study of Household Energy Consumption in Thimphu: Bhutan," Journal of Sustainable Energy & Environment, pp. 65–71, 2018.



CEB=Ceylon Electricity Board, kWh=Kilowatt-hour

Note: Legend blocks in household tarrif per household per month, in kwh, 4-5 households report zero consumption; 0.1% households in the 0-600 kwh/month category, sue 2% of electricity sold to households.

Source: information from CEB distribution licenses for July 2014

Variable	Rural households	Urban households
Quantity consumed (KWh / Per month)	111.73	209.16

Figure 13: Reference example of household energy demand in South Asian countries: Sri Lanka

Source: Karunarathna et al. (2019)[30]; ADB (2019)[31]

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[30] M. Karunarathna and W. Athukorala, "Determinants of Residential Electricity Consumption: A Comparison between Urban and Rural Households in Kandy District in Sri Lanka," Sri Lanka Journal of Economic Research, vol. 6, no. 2, pp. 1–15, 2019.

[31] Asian Development Bank, "Sri Lanka: Energy Sector Assessment, Strategy, and Road Map," Asian Development Bank, Manila, 2019.

Table 8: Reference example of household energy demand in South Asian countries: Pakistan (Amber 2021)[32]

	House Category			
	Category-1	Category-2	Category-3	Category-4
Electrical Appliances	**Non-AC House without UPS**	**Non-AC House with UPS**	**AC House without UPS**	**AC House with UPS**
Lights	✓	✓	✓	✓
Ceiling Fans	✓	✓	✓	✓
Electric Irons	✓	✓	✓	✓
TVs	✓	✓	✓	✓
Washing Machines	✓	✓	✓	✓
Fridges	✓	✓	✓	✓
Desktop Computers	✓	✓	✓	✓
Washing Machine and Dryer	✓	✓	✓	✓
Water Pump Motors	✓	✓	✓	✓
Water Cooler	✓	✓	×	×
UPS	×	✓	×	✓
Vacuum Cleaner	×	×	✓	✓
AC	×	×	✓	✓
Actual Average Electricity Consumption, KWh/year	1974	2409	2187	3207
Calculated Average Electricity Consumption, KWh/year	1996	2841	2808	3654
Difference, %	1.1%	17.9%	12.9%	13.9%

OECD household: Switzerland

Table 9 shows an example of the electricity demands of different household types in the OECD country of Switzerland. The example of Switzerland was chosen because of its well-documented electricity demands and its good representation of the energy-efficient and highly electrified households among the OECD countries. In predicting the future development of Nepal's electricity demand, we assume that the level of electrification and household appliances used will be similar to those in industrialized countries. Although the electricity demand of households in industrialized countries—excluding electric mobility—can be reduced through technical efficiency measures and more-efficient appliances by improving technical standards, the current demand provides an orientation for the future demands in developing countries.

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[32] K. P. Amber, R. Ahmad and M. Farmanbar, "Unlocking Household Electricity Consumption in Pakistan," Buildings, vol. 11, p. 566, 2021.

Table 9: Standard household demand in an industrialized country (Switzerland)

Standard Household—OECD	**Apartment**			**Separate House**			
Category	2 People	Additional person	4 People	2 People	Any additional person/s	4 People	Calculated Urban Family 2
	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]
Cooking/baking including special equipment, e.g., coffee maker	300	80	460	300	80	460	0
Dishwasher	250	25	300	250	25	300	
Refrigerator with or without freezer compartment	275	40	355	325	60	445	340
Separate freezer	275	25	325	350	25	400	
Lighting	350	90	530	450	125	700	198
Consumer electronics (TV, video, hi-fi, various players, etc.)	250	60	370	275	80	435	110
Home office (PC, printer, modem, comfort phone, etc.)	200	60	320	200	80	360	
Div. Nursing and small appliances including humidifier	250	45	340	325	60	445	272
Washing machine	225	65	355	250	78	405	127
Laundry dryer (about 2/3 of the laundry, with a tumbler)	250	85	420	275	88	450	
General (building services)	400		400+	900	150	1200	
Total	**3025**	**575**	**4175**	**3900**	**850**	**5600**	**1047**
Climatization							1,013
Total, including climatization	3025	575	4175	3900	850	5600	2060

Source: Der typische Haushalt-Stromverbrauch Energieverbrauch von Haushalten in Ein- und Mehrfamilienhäusern/Schweiz, https://www.werkezuerichsee.ch/dl.php/de/0dn3t-3gjac9/Typischer_Haushaltstromverbrauch-SEV0719.pdf

The development of the country-wide shares of the electricity demand in Nepal according to the various household types is presented in Table 10. Electrification starts with basic household types, such as rural, semi-urban, and urban (apartments or houses) and moves to better-equipped households. Thus, the proportion of fully equipped households grows constantly, while the proportion of basic households increases in the early years and decreases towards the end of the modelling period. By 2050, most households will have a medium-to-high level of comfort equipment. The authors of this report have deliberately chosen a high standard for Nepal's households to close the gap between households in OECD countries and countries in the global south, to achieve greater equity.

Table 10: Household types—Development of household shares of the electricity demand country-wide in Nepal

Household type	Country-wide electricity shares [%] (rounded)			
	2020	2030	2040	2050
No access to electricity	10.00%	4.00%	2.00%	0%
Rural —Phase 1	75.00%	72.00%	65.00%	55.00%
Rural—Phase 2	4.00%	8.00%	9.00%	15.00%
Rural—Phase 3	0.00%	3.00%	4.00%	10.00%
Semi-Urban—basic	10.00%	4.00%	3.00%	5.00%
Semi-Urban—advanced	0.00%	2.00%	0.00%	0.00%
Urban Apartment—basic	0.00%	0.00%	0.00%	0.00%
Urban Apartment—advanced	0.00%	4.00%	8.00%	10.00%
Urban House—basic	0.00%	2.00%	5.00%	1.00%
Urban House—advanced	1.00%	1.00%	4.00%	4.00%
Total	100%	100%	100%	100%

Source: CDP, REB, DESCO and UTS-ISF research

According to the most recent data in *The Energy Progress Report* published in June 2021 (EPR 2021)[33], over 90% of Nepalese households have access to electricity. However, only 72% of households have access to reliable and uninterrupted electricity (World Bank 2017)[34]. Rapidly expanding cities are problematic because the infrastructure for transport and energy supply and the requirements of residential apartment buildings cannot match the demand, often leading to social tensions. Mini-grids for remote areas have proven a successful technology option for bringing energy services to remote communities, helping villages develop local economies, and providing alternative opportunities for young people to establish careers outside the metropolitan areas.

Nepal—Leader in decentralized electrification

According to the Energy Progress Report 2021 of the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), the United Nations, and the World Bank, Nepal is among the leading countries of the global south in terms of decentralized electrification. This has been achieved with decentralized renewables-based solutions, which have grown significantly since 2010, and have accelerated in the last few years. The number of people connected to mini-grids that use solar, hydro, or biogas technologies doubled between 2010 and 2019, with 11 million people connected in 2019 (IRENA 2020)[35]. For measuring energy access, IRENA defines mini-grids as distribution networks that supply electricity to residential consumers and are not connected to a country's main grid.

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[33] (EPR 2021), IEA, IRENA, UNSD, World Bank, WHO. 2021. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC; World Bank. License: Creative Commons Attribution—Non-Commercial 3.0 IGO (CC BYNC 3.0 IGO). https://www.irena.org/publications/2021/Jun/Tracking-SDG-7-2021

[34] (World Bank 2017), Multi-Tier Framework for Measuring Energy Access 2017. NPL_2017_MTF_v01_M doi: https://doi.org/10.48529/r1sn-zg95, Energy Sector Management Assistance Program (ESMAP)

[35] IRENA 2020, Renewable Energy and Jobs: Annual Review 2020. Abu Dhabi: International Renewable Energy Agency; https://www.irena.org/publications/2020/Sep/Renewable-Energy-and-Jobs-Annual-Review-2020

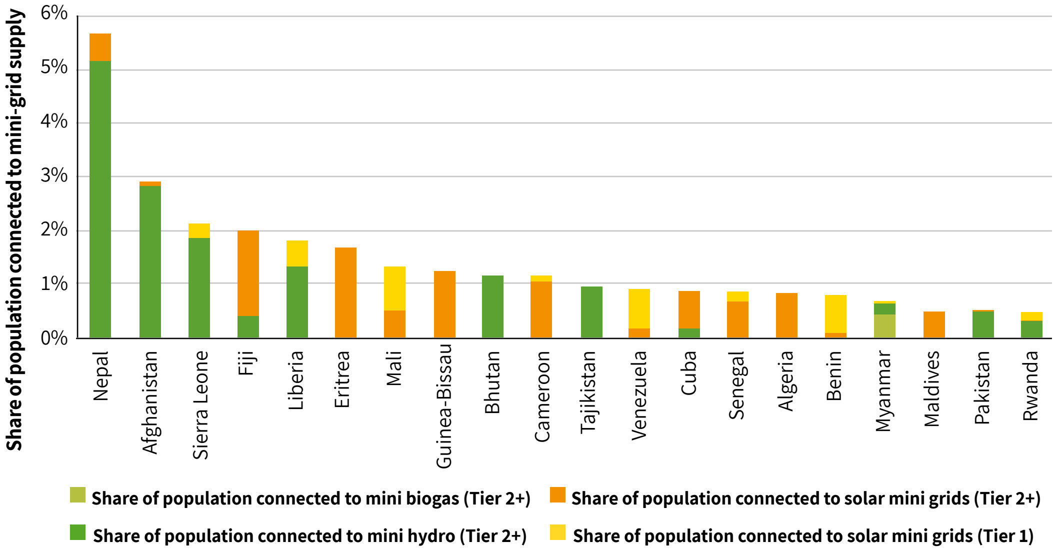

Figure 14: Twenty countries with the highest rates of access to mini-grid supply (Tier 1 or higher), 2019 (EPR 2019)

Source: IRENA 2020c.

In 2019, India, Nepal, and Afghanistan had the most people connected to mini-grids (regardless of technology), and Nepal, Afghanistan, and Sierra Leone had the highest proportions of the population served by mini-grids (Figure 14). Global connections to solar mini-grids have grown almost six-fold, to 3.4 million people. In 2019, 67% of those connected to solar mini-grids enjoyed Tier 2+ access. Indonesia, India, and Algeria had the largest number of people connected to solar mini-grids in 2019.

Table 11 shows Nepal's decentralized renewable energy systems in operation in 2021. Solar PV and mini-hydro systems dominated the generation technologies used, whereas small wind energy systems and bio-energy systems played only a minor role.

Table 11: Nepal—Decentralized renewable energy systems in operation in 2021

AEPC-Progress at Glance 2020/21: Cumulative RETs promotion (pg 37)					
Particulars		**Unit**	**Remarks: Assumed energy**	**Estimated annual energy (kWh)**	**Remarks**
Solar Home System	961,925	Nos	50 Wp	78,998,090	Assuming 4.5 peak-sun-hours
Micro/Mini Hydro	35,986	kW		197,023,350	Assuming 15hrs average runtime/day
Institutional Solar PV System	2,808	Nos	2 kWp	9,224,280	Assuming 4.5 peak-sun-hours
Urban Solar Home System	21,144	Nos	1 kWp	34,729,020	Assuming 4.5 peak-sun-hours
Solar/Wind Mini Grid System	1,261	kW		2,071,192	Assuming 4.5 peak-sun-hours without segregating wind system
			Total RET (kWh)	**322,045,932**	
			Total RET (TWh)	**0.322**	

I I. Household fuel demand—Cooking

The main energy demand for Nepalese households is for cooking (Bhandari et al. 2018). Firewood is the main energy source for rural households, whereas cylinders of LPG are the main source of energy for cooking in semi-urban and urban households.

Table 12 shows the variety of cooking fuels used for cooking. Firewood and LPG dominate greatly, whereas electricity is used in less than 1% of all Nepalese households. Table 13 provides an overview of the most important cooking technologies and their key technical and economic parameters (World Future Council 2019)[36]. The data are taken from a comprehensive analysis of cooking technologies and the sustainability and cost-effectiveness of electric cooking. One key finding of this analysis was that cooking with electricity (whether with solar home systems [SHS] or in a mini-grid context) using high-efficiency appliances could make cooking even cheaper than it is many households currently using firewood and charcoal. The World Bank's bottom-up research from across Sub-Saharan Africa indicated that households use on average US$1–31 per month on cooking fuels (World Bank 2014)[37]. With slow cookers and pressure cookers enabling household cooking costs of between USUS$15–21/month for SHS and US$3.56–9.53/month for mini-grids, the economics of cooking with high-efficiency cooking appliances is becoming increasingly compelling (World Future Council 2019).

Based on the current cooking energy usage, a transition scenario from fuel-based cooking to electric cooking (e-cooking) has been developed for the N-1.5 °C scenario (Table 14).

In the past, Nepal replaced inefficient stoves with more-efficient ones, which has had a positive effect on (indoor) air pollution and reduced the need for fuel for each cooking stove. However, with an increasing population and a growing number of households, the overall fuel demand is likely to remain at high levels, and a phase-out of emissions and fuel demand cannot be achieved with this measure.

Table 12 Distribution of cooking fuels in households

	Firewood	Cow Dung	Agricultural Residuals	LPG	Kerosene	Bio-Gas	Other	Total
Urban	33.0%	4.4%	0.7%	58.5%	0.2%	2.8%	0.4%	100%
Rural	72.5%	11.4%	3.3%	9.4%	0.0%	3.2%	0.2%	100%
Nepal	59.3%	9.0%	2.4%	25.8%	0.1%	3.1%	0.2%	100%

Source: Bhandari et. al. 2018[38]

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36. World Future Council 2019, Beyond fire—How to achieve electric cooking; Toby D. Couture (E3 Analytics); Dr. David Jacobs (IET– International Energy Transition GmbH), Eco Matser and Harry Clemens (Hivos), Anna Skowron (World Future Council) and Joseph Thomas (E3 Analytics), World Future Council, Lilienstrasse 5–9, 22095 Hamburg, Germany, May 2019–costs are converted from Euro to US$ with the exchange rate of 25th August 2022: 1 Euro = US$1
37. World Bank 2014, Clean and Improved Cooking in Sub-Saharan Africa: Second Edition. World Bank, Washington, DC. Available at: http://documents.worldbank.org/curated/en/164241468178757464/pdf/98664-REVISED-WP-P146621-PUBLIC-Box393185B.pdf
38. Bhandari et al. 2018, Bhandari, R., Pandit, S. Electricity as a Cooking Means in Nepal—A Modelling Tool Approach. Sustainability 2018, 10, 2841. https://doi.org/10.3390/su1008284

Table 13: Basic data on technologies and energy use

Appliance	Cost of the Stove (in EUR)	Cost of the Stove in NPR equivalents (based on EUR 1 = 134 NPR, August 2021 –August 2022 average)	Watts (range)	Approximate Daily Household Consumption (in Wh/day for electric options or in kg/day for solid and gas-based fuels)	Approximate Daily Household Consumption (in MJ)
Three Stones (Wood)	0	0	N/A	4.15–20.76 kg/day	68.48–342.54
Traditional Cooking Stove (Wood)	0–5	0–670	N/A	3.32–8.3 kg/day	54.78–136.95
Improved Cooking Stove (Wood)	5–65	670–8,715	N/A	2.08–5.53 kg/day	34.32–91.25
Three Stones (Charcoal)	0	0	N/A	1.92–4.81 kg/day	54.72–137.09
Traditional Cooking Stove (Charcoal)	0–10	0–1,341	N/A	1.6–4.01 kg/day	45.60–114.29
Improved Cooking Stove (Charcoal)	5–65	670–8,715	N/A	1.2–2.4 kg /day	34.20–68.40
Improved Cooking Stove (Wood-based Biomass Pellets)	16–80	2,145–10,726	N/A	1.76–3.96 kg/day	30.41–68.43
Improved Cooking Stove (Agro-waste Pellets)	16–80	2,145–10,726	N/A	2.42–5.44 kg/day	30.49–68.54
Single Burner Hot Plate	8–35	1,073–4,692	600–2000	1200–4000 Wh/day	4.32–14.40
Induction Hot Plate	45–95	6,033–12,737	1000–2300	2000–4600 Wh/day	7.20–16.56
Slow Cooker / Rice Cooker / Crock Pot	10–130	1,341–17,429	120–300	175–700 Wh/day	0.63–2.52
Electric Pressure Cooker	19–140	2,547–18,770	500–1000	160–340 Wh/day	0.58–1.22
Microwave Oven	50–100	6,704–13,407	600–1200	100–1200 Wh/day	0.36–4.32
Gas Stove (single burner)	20–60	2,681–8,044	N/A	0.3 kg/day	13.7
Gas Stove (double burner)	30–90	4,022–12,066	N/A	0.3 kg/day	13.7
Gas Stove (four burners)	40–100	5,363–13,407	N/A	0.3 kg/day	13.7

Source: (World Future Council 2019)

Table 14: Cooking energy demand by household type in 2021, Nepal

Household	Fuel	Demand per month [MJ/month]	Demand per year [MJ/year]	Persons per household	Demand per person & year [MJ/person/a]
Rural	Fire wood	2,100	25,200	5.9	4,271
Semi-urban	Fire wood	2,100	25,200	4.3	5,860
Urban	Firewood	2,100	25,200	3.5	720
Rural	LPG	300	3,600	5.9	610
Semi-urban	LPG	350	4,200	4.3	977
Urban	LPG	400	4,800	3.5	1,371

The monthly and annual energy demands for the two main fuel-based cooking technologies are shown in Table 14. Based on these, a scenario for transitioning from fuel-based cooking to electricity-based cooking was developed (Table 15).

On average, 3.3% of all fuel-based cooking applications will be gradually phased out per year and replaced with electric cooking appliances. The total phase-out of fuel-based systems will be for environmental and economic reasons. Fuel-based cooking requires fuel that generates emissions, and the fuel supply is, in most cases, not sustainable. Collecting fuel wood puts forests under pressure, is time-consuming, and has a negative economic impact on the country's productivity. Burning LPG causes CO_2 emissions, and its production is based on fossil gas, which must be phased-out by 2050 to remain within the global carbon budget to limit the global mean temperature rise to a maximum of +1.5 °C.

Table 15: Transition scenario from fuel-based to electricity-based cooking in Nepal under the N-1.5 °C pathway

Phase-out of Fuel-based Cooking 2020–2050											
	Share of Household with Fuel-based Cooking		**Rural— Phase 1**	**Rural— Phase 2**	**Rural— Phase 3**	**Semi-Urban 1**	**Semi-Urban 2**	**Urban Apartment 1**	**Urban Apartment 2**	**Urban House 1**	**Urban House 2**
2020	100%	[MJ/a HH]	25,920	25,920	25,920	16800	15960	4800	4800	4800	4800
2025	83%	[MJ/a HH]	21,513	21,513	21,513	14000	13300	4000	4000	4000	4000
2030	67%	[MJ/a HH]	17,366	17,366	17,366	11200	10640	3200	3200	3200	3200
2035	50%	[MJ/a HH]	12,960	12,960	12,960	8400	7980	2400	2400	2400	2400
2040	33%	[MJ/a HH]	8,553	8,553	8,553	5600	5320	1600	1600	1600	1600
2045	17%	[MJ/a HH]	4,406	4,406	4,406	2800	2660	800	800	800	800
2050	0%	[MJ/a HH]	0	0	0	0	0	0	0	0	0
Phase-in of Electric Cooking 2020–2050											
	Share of Households with Electric Cooking		**Rural— Phase 1**	**Rural— Phase 2**	**Rural— Phase 3**	**Semi-Urban 1**	**Semi-Urban 2**	**Urban Apartment 1**	**Urban Apartment 2**	**Urban House 1**	**Urban House 2**
2020	0%	[kWh$_{electric}$/a HH]	0	0	0	0	0	0	0	0	0
2025	17%	[kWh$_{electric}$/a HH]	122	122	122	122	122	122	122	122	122
2030	33%	[kWh$_{electric}$/a HH]	243	243	243	243	243	243	243	243	243
2035	50%	[kWh$_{electric}$/a HH]	365	365	365	365	365	365	365	365	365
2040	67%	[kWh$_{electric}$/a HH]	487	487	487	487	487	487	487	487	487
2045	83%	[kWh$_{electric}$/a HH]	608	608	608	608	608	608	608	608	608
2050	100%	[kWh$_{electric}$/a HH]	730	730	730	730	730	730	730	730	730

E-cooking can be supplied by renewable energy sources and will be emissions-free. A study in one municipality showed that cooking on induction stoves was almost 40% cheaper than cooking on LPG. Induction stoves consumed 1.22 kWh per day (World Future Council 2019)[39]. On average, a five-member middle-class family in Nepal (average rural household size) uses seven LPG cylinders in a year. After the adoption electric cooking, this decreased to three LPG cylinders a year (because they use both electricity and LPG for cooking). With a saving of four cylinders per year per household, the existing 515,000 e-cooking users[40] avoided the importation of 29,252 MT of LPG in the financial year 2018/19 (6.8% less than the actual LPG imported that year, 429,609 MT). Assuming an additional 10,00,000 households will adopt e-cooking by 2025, the country will avoid the importation of 86,052 MT of LPG in 2025.

However, there are some challenges to the introduction of electric cooking stoves:

- Firewood remains freely available.
- In relative terms, the initial investment and monthly costs are high.
- Concerns exist about the safety of the technology.
- (Initial) concerns exist around the learnability of new appliances.
- In the cold climate in mountainous regions, fire from cooking also heats the rooms.

There are already numerous electric cooking devices on the Nepalese market, including:

- Induction stoves
- Electric pressure cookers
- Electric ovens
- Hot plates
- Microwave ovens
- Electric and gas hobs
- Roti makers
- Infrared stoves
- Rice cookers
- Slow cookers
- Electric frying pans
- Air fryers
- Electric kettles

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39. World Future Council (2019), Beyond the fire—How to achieve electric cooking, Toby D. Couture (E3 Analytics); Dr. David Jacobs (IET - International Energy Transition GmbH), Eco Matser and Harry Clemens (Hivos), Anna Skowron (World Future Council), Joseph Thomas (E3 Analytics, World Future Council 2019, https://www.worldfuturecouncil.org/wp-content/uploads/2019/05/Beyond-Fire_-How-to-achieve-electric-cooking.pdf

40. '5.15 lakh cooking users' in the original source – 1 'lakh' equals 100,000 and is a unit in the Nepali numbering system.

Among these, the most viable energy-efficient appliances are:

- Induction stoves
- Infrared stoves
- Rice cookers
- Electric pressure cookers

As of February 2020, about 1,200 induction cooking stoves have been promoted under different pilot and research projects in Nepal. Moreover, private sector suppliers have sold about 50,000 induction stoves in the last 3 years.

The supply-side barriers to e-cooking are:

- Electric cooking stoves do not seem to be manufactured locally.
- After-sales service is poor (i.e., poor access to repairs and maintenance).
- Concerns exist around the quality and stability of the electricity supply.

Technical challenges of e-cooking for electric utilities and energy service companies:

The increase in the peak load during mealtimes will require an upgrade of the electricity distribution grid in terms of load management and the ability of the power grid to supply higher loads. The introduction of electric vehicles to replace fossil fuels will further increase the electric loads and require grid expansion and reinforcement to be implemented by electric grid operators.

Furthermore, current household electricity connections are often limited to 5-ampere meters, which significantly limits the load for each household, and the parallel operation of multiple appliances is not possible when electric stoves are used. Moreover, the technical standard of household wiring is low; cables are often not properly installed, or the lack of protective earthing compromises electrical safety.

Policy and social challenges in promoting electric cooking

Local-level governments in Nepal have not yet formulated policy frameworks, such as specific energy policies, acts, procedures, and/or guidelines, to support the increased utilization of electric cooking devices. These policies include support for additional renewable electricity generation to supply stoves. Therefore, the development of clean cooking programs is lagging behind the actual targets. Finally, the general awareness of the benefits of e-cooking—particularly in rural areas—is still low because the access to the necessary information is unavailable. Finally, this lack of information means that the acceptance of e-cooking devices in the supply chain—specialized kitchenware and hardware shops—is low. Therefore, awareness programs for retail staff are required

E. Industry and business demands

The analysis of Nepal's economic development is based on a breakdown of the fiscal year 2020/21 and assumes that the overall structure of the economy will not change, and that all sectors will grow at a rate equal to that of GDP over the entire modelling period.

Figure 15 shows that in the fiscal year 2020/21, wholesale and retail trade and vehicle and motorcycle maintenance services contributed most strongly to the growth of GDP (in the basic price), whereas water supply and sewage waste management and regeneration activities contributed least. The contribution of the manufacturing industry to the economic growth rate in that fiscal year (FY) was 5.33%, and the contribution of housing and food services was 3.29% (MoF-ES 2021)[41].

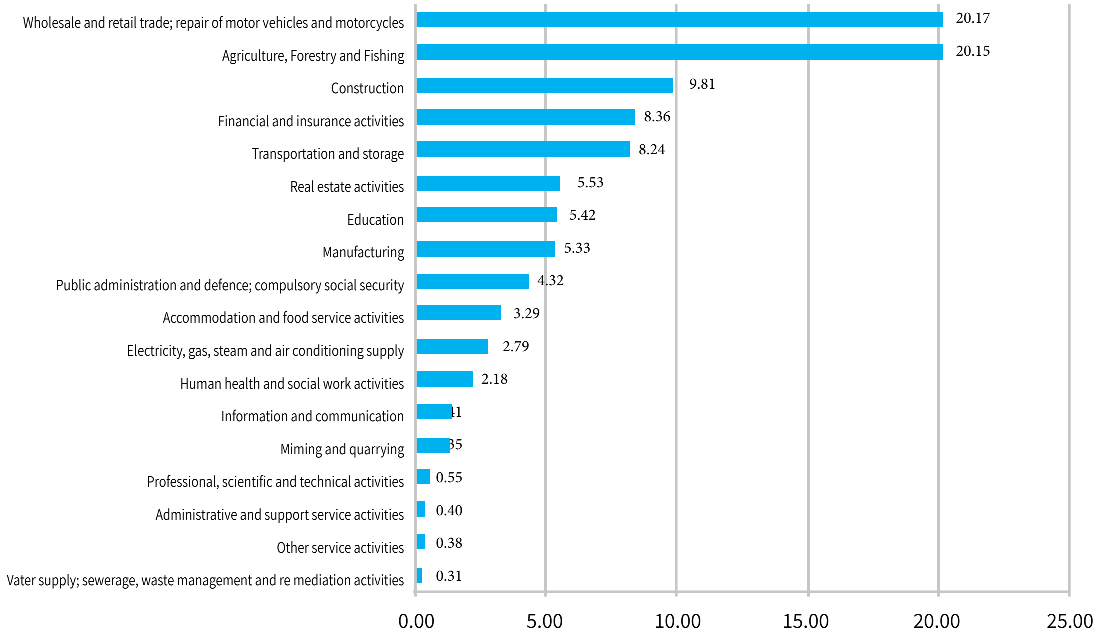

Figure 15: Contributions of sub-sectors to GDP growth, Economic Survey 2020/21, Government of Nepal Ministry of Finance, Singh Durbar, Kathmandu

Source: Central Bureau of Statistics, 2020/21

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[41] (MoF-ES 2021), Economic Survey 2020/21, Government of Nepal Ministry of Finance, Singh Durbar, Kathmandu.

According to the Ministry of Finance of Nepal, the contribution of the non-agricultural sector to the gross value added is increasing, whereas the agriculture sector's contribution is decreasing. In the fiscal year 2020/21, the agriculture sector's contribution to the gross value added was estimated to be 25.8% and that of the non-agricultural sector was 74.2%. In the fiscal year 2019/20, these contributions were 26.2% and 73.8%, respectively (Figure 16).

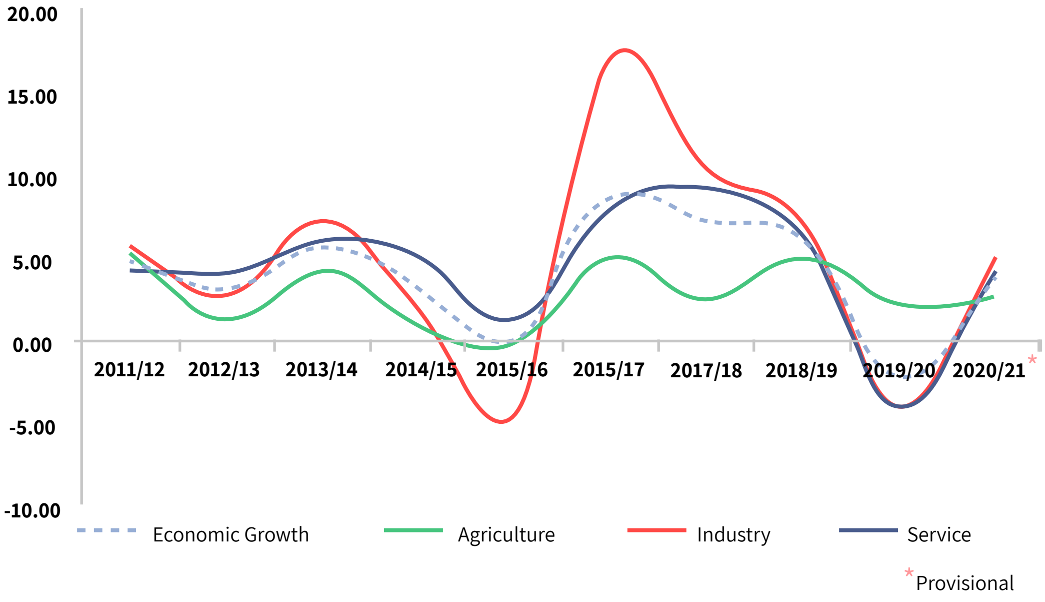

Figure 16: Gross domestic product (GDP) growth rate, Economic Survey 2020/21, Government of Nepal Ministry of Finance, Singh Durbar, Kathmandu

Source: Central Bureau of Statistics, 2021

Table 16 shows the assumed breakdown of GDP by sub-category used in the One Earth Climate Model 2.0 (OECM; Teske et al. 2022)[42]—which differs from that identified in the Economic Survey of Nepal. The value of 'wholesale and retail trade; repair of motor vehicles and motorcycles' identified by the *Economic Survey* has been added to the OECM sector *Manufacturing*. The sectors *Iron & Steel*, *Cement*, and *Chemicals* are not identified in the *Economic Survey* and have been assumed to be zero. However, the OECM does not cover some specific sectors, e.g., education (yet), and these values have been moved to *Services*. The identified sectors have been used to calibrate the bottom-up energy demand model with the current energy demand documented in the IEA Energy Balances statistics (IEA 2021)[43].

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[42] Teske et al. (2022), Teske, S., Guerrero, J. One Earth Climate Model—Integrated Energy Assessment Model to Develop Industry-Specific 1.5 °C Pathways with High Technical Resolution for the Finance Sector. Energies 2022, 15, 3289. https://doi.org/10.3390/en15093289

[43] IEA (2021): World Energy balances—IEA database.

Table 16: Development of GDP shares by industry sector, across all regions of Nepal

Industry (in brackets, the sector name used in the OECM)	Economic Survey Category	Input OECM	36.7%
Manufacturing	X	X	5.3%
Wholesale and retail trade; repair of motor vehicles and motorcycles (Manufacturing)	X		20.2%
Mining and quarrying	X	X	1.4%
Iron + Steel		X	0.0%
Cement		X	0.0%
Construction	X	X	9.8%
Chemical		X	0.0%
Services		**X**	**43.2%**
Water supply; sewerage, waste management and remediation activities (Water utilities)	X	X	0.3%
Other service activities (Services)	X		0.4%
Administrative and support service activities (Services)	X		0.4%
Professional, scientific, and technical activities (Services)	X		0.6%
Information and communication (Services)	X		1.4%
Human health and social work activities (Services)	X		2.2%
Electricity, gas, steam, and air-conditioning supply (Utilities)	X		2.8%
Accommodation and food service activities (Services)	X		3.3%
Public administration and defence; compulsory social security (Services)	X		4.3%
Education (Services)	X		5.4%
Real-estate activities (Construction)	X		5.5%
Transportation and storage (Road transport)	X		8.2%
Financial and insurance activities (Services)	X		8.4%
Agriculture			**20.1%**
Agriculture, forestry, and fishing	X	X	20.1%

F. Transport demand

Nepal's transport sector is currently dominated by motorcycles, which account for 78% of all registered vehicles, whereas cars, pick-up trucks, and vans represent only 8% of the vehicle fleet. The group of three-wheeler vehicles, such as electric rickshaws and 'tempos'[44], is 6.5%, almost as large as that of cars. Just over 1% of all registered vehicles are buses or mini-buses. The remaining 6% includes construction and industry vehicles, such as tractors, cranes, and excavators (Figure 17).

To develop a future transport scenario, the technical parameters of all vehicle options are required to project the energy demands. The following section provides an overview of the vehicular energy intensities for passenger and freight transport. Based on these, the actual utilization—in terms of annual kilometres per vehicle—**was estimated to calculate the energy demand over time until 2050.**

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44. Tempo three-wheeler originally developed from Vespa-scooter-based transport vehicles—used as freight transporters and for passenger transport.

Categories of vehicles registered with percentages of total no. registered (FY 2019/2020):

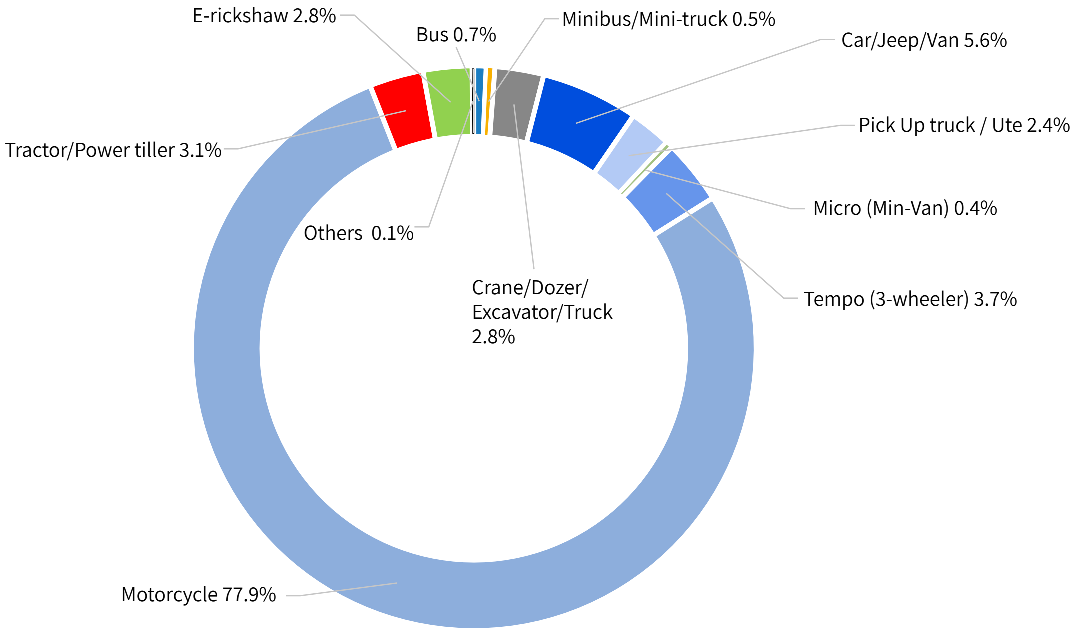

Figure 17: Gross domestic product (GDP) growth rate, Economic Survey 2020/21, Government of Nepal Ministry of Finance, Singh Durbar, Kathmandu

Source: Department of Transport Management (DTM 2020)[45]

The energy intensities for the different vehicle types and each available drive train play an important role in calibrating the transport modes and projections. Each transport mode has different vehicular options. Each of the vehicles has different drive-train and efficiency options. The technical variety of passenger vehicles, for example, is extremely large. The engine sizes for five-seater cars range between around 20 kW to > 200 kW.

Furthermore, drive trains can use a range of fuels, from gasoline, diesel, and bio-diesel to hydrogen and electricity. Each vehicle has a different energy intensity in megajoules per passenger kilometre (MJ/pkm). Therefore, the energy intensities provided in the following tables are average values.

I. Technical parameters—Individual transport

Passenger transport by road is the common and most important form of travel (TUMI 2021)[46] . There are numerous technical options to ‘move people with vehicles’: bicycles, motorcycles, tricycles, city cars, and four-wheel-drive SUVs. Each vehicle has a very different energy intensity per km. Although this research project aims for high technological resolution, simplifications are required. Table 17 shows the energy intensities for the main vehicle types (electric and with internal combustion engines [ICE]), and forms the basis for the energy scenario calculations.

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[45] Department of Transport Management, “Details of vehicles registered till mid-February of FY 2075/76,” Kathmandu, Nepal, 2075. https://www.dotm.gov.np/Files/NoticePDF/Vehicledatatill20762020-01-17_04-54-21-965.pdf?fbclid=IwAR0mDhFH12B1dfiY6NOc_Tkdu0LjIhp86T6HqgYZOCw-AWQ6aAPPWhbziK4

[46] TUMI (2021), Teske, S., Niklas, S., Langdon, R., (2021), TUMI Transport Outlook 1.5°C - A global scenario to decarbonize transport; Report prepared by the University of Technology Sydney for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH; Published by TUMI Management, Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH, Friedrich-Ebert-Allee 36 + 40, 53113 Bonn, Germany; https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf

Table 17: Energy intensities of individual transport—road transport

Individual Transport			Passengers		Vehicle Demand	Consumption per Passenger	Energy demand
			Average Passengers per Vehicle	Assumed Occupation Rate	Average	Average	Assumption for Scenario Calculation
		Fuels			litre/100 km	litre/100 pkm	[MJ/pkm]
Scooters & motorbikes	2-wheeler	Gasoline	1	1	3.0	3.0	1.21
		Electricity			kWh_{el}/100 km	kWh_{el}/100 pkm	[MJ/pkm]
E-bikes	2-wheeler	Battery	1	1	1.0	1.0	0.04
Scooters	2-wheeler	Battery	1	1	1.8	1.9	0.06
Motorbikes	2-wheeler	Battery	1	1	4.8	4.8	0.17
Rickshaw	3-wheels	Battery	3	2	8.0	4.0	0.14
		Fuels	0	0	litre/100 km	litre/100 pkm	[MJ/pkm]
Cars	small	ICE–oil	2	1.8	5.0	2.8	1.12
	medium	ICE–oil	4	2	7.5	3.8	1.51
	large	ICE–oil	5	2	10.5	5.3	2.11
	small	ICE–gas	2	1.8	4.5	2.5	0.63
	medium	ICE–gas	4	2	7.0	3.5	1.41
	large	ICE–gas	5	2	10.0	5.0	1.25
	small	ICE–bio	2	1.8	5.0	2.8	0.91
	medium	ICE–bio	4	2	7.5	3.8	1.51
	large	ICE–bio	5	2	10.5	5.3	1.72
	small	Hybrid–oil	2	1.8	4.0	2.2	0.89
	medium	Hybrid–oil	4	2.5	6.0	2.4	0.96
	large	Hybrid–oil	5	2.5	8.5	3.4	1.37
		Electricity			kWh_{el}/100 km	kWh_{el}/100 pkm	[MJ/pkm]
	small	Battery	2	1.8	16.0	8.9	0.32
	medium	Battery	4	2	25.0	12.5	0.45
	large	Battery	5	2	32.5	16.3	0.59
	large	Fuel Cell	4	2	37.5	18.8	1.36

II. Technical parameters—Public transport

There is a huge variety of public transport vehicles—from rickshaws to taxis and mini-buses to long-distance trains. The occupation rates for those vehicles are key factors in calculating the energy intensity per passenger per kilometre. For example, a diesel-powered city bus transporting 75 passengers uses, on average, about 27.5 litres per 100 kilometres. If the bus operates at full capacity during peak hour, the energy demand per passenger is as low as 400 ml per kilometre, lower than almost all fossil-fuel-based road transport vehicles. However, if the occupancy drops to 10%—e.g., for a night bus—the energy intensity increases to 3.7 litres, equal to that of a small energy-efficient car. Occupation rates vary significantly and depend on the time of day, day of the week, and season.

There are also significant regional differences, even within a province. Again, the parameters shown in Table 18 are simplified averages and are further condensed for the scenario calculations. Although high technical resolution is possible for the scenario model, it would pretend an accuracy that does not exist because the statistical data required for this resolution are not available at the regional level.

Table 18: Energy intensities for public transport—road & rail transport

Public Transport			Passengers		Vehicle Demand	Consumption per Passenger	Energy Demand
			Average Passengers per Vehicle	Assumed Occupation Rate	Average	Average	Assumption for Scenario Calculation
		Fuels			litre/100 km	litre/100 pkm	[MJ/pkm]
Buses	small	Diesel	12	40%	8.8	1.8	0.73
	small	Bio	12	40%	8.8	1.8	0.60
	12 m	Diesel	75	40%	27.5	0.9	0.37
	12 m	Bio	75	40%	27.5	0.9	0.30
	large	Diesel	135	40%	57.5	1.1	0.43
		Electricity	0	0	kWh$_{el}$/100 km	kWh$_{el}$/100 pkm	[MJ/pkm]
	small	Battery	12	40%	31	6.4	0.23
	small	Fuel Cell	12	40%	77	15.9	0.57
	12 m	Battery	75	40%	143	4.8	0.17
	12 m	Fuel Cell	75	40%	358	11.9	0.43
	large	Overhead lines	135	40%	263	4.9	0.18
		Fuels			litre/100 km	litre/100 pkm	[MJ/pkm]
Trains	Metros	Diesel	400	40%	150	0.9	0.38
	Metros	Bio	400	40%	150	0.9	0.31
	Commuter Trains	Diesel	600	40%	300	1.3	0.50
	Commuter Trains	Bio	600	40%	300	1.3	0.41
		Electricity	0	0	kWh$_{el}$/100 km	kWh$_{el}$/100 pkm	[MJ/pkm]
	Trams	Electric	300	40%	495	4.1	0.14
	Metros	Electric	300	40%	1,200	10.0	0.14
	Commuter Trains	Electric	600	40%	1,950	8.1	0.17

III. Technical parameters—Freight transport

The energy intensity data for freight transport are not as diverse as those for passenger transport because the transport vehicle types are standard and the fuel demands are well known. However, the utilization rates of the load capacities vary significantly, and consistent data are not available for the calculated regional and global levels. Therefore, the assumed utilization rate greatly influences the calculated energy intensity per tonne–km (tkm). The average energy intensities per tkm used in the scenario are shown in Table 19 and are largely consistent with those from other sources in the scientific literature (EEA, 2021)[47]. The assumed energy intensities for electric and fuel cell/hydrogen freight vehicles are only estimates because this technology is still in the demonstration phase. Therefore, none of the scenarios factor in large shares of electric freight transport vehicles before 2035.

Table 19: Energy intensities freight transport—road & rail transport

Freight Transport			Maximum Load Capacity (tonnes)	Assumed Utilization Rate	Vehicle Demand	Consumption per tonne	Energy Demand
					Average	Average	Assumption for Scenario Calculation
Trucks		Fuels			litre/100 km	litre/tkm	[MJ/tonkm]
	3.5 t	Diesel	3.5	40%	11	7.9	3.16
	3.5 t	Bio	3.5	40%	11	7.9	2.57
	7.5 t	Diesel	7.5	40%	20	6.5	2.61
	7.5 t	Bio	7.5	40%	20	6.5	2.13
	12.5 t	Diesel	12.5	40%	25	5.0	2.01
	12.5 t	Bio	12.5	40%	25	5.0	1.64
		Electricity			kWh_{el}/100 km	kWh_{el}/ton-km	[MJ/tonkm]
	3.5 t	Battery	3.5	40%	19	13.6	1.34
	3.5 t	Fuel Cell	3.5	40%	46	33.2	1.33
	7.5 t	Battery	7.5	40%	41	13.6	0.49
	7.5 t	Fuel Cell	7.5	40%	100	33.2	1.19
	12.5 t	Battery	12.5	40%	68	13.6	0.49
	12.5 t	Fuel Cell	12.5	40%	166	33.2	1.19
Trains		Fuels			litre/100 km	litre/ton-km	[MJ/tonkm]
	Freight–740 m	Diesel	1,000	40%	300	0.8	0.30
	Freight–740 m	Bio	1,000	40%	300	0.8	0.25
		Electricity			kWh_{el}/100 km	kWh_{el}/ton-km	[MJ/tonkm]
	Freight–740 m	Electric	1,000	40%	5,840	14.6	0.53

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[47] European Environment Agency, https://www.eea.europa.eu/publications/ENVISSUENo12/page027.html

IV. Utilization of vehicles

In the second step, the utilization of vehicles must be analysed to develop a projection into the future. No up-to-date surveys are available. However, a survey conducted in 2012 by the Japan International Cooperation Agency (JICA 2012)[48] found that 33.8% of people living in Kathmandu Valley worked for the population, and 31.9% were students.

Around 38.64% of trips were made for work purposes, 34.3% for education purposes, and 14.9% were made for personal business. Less than 4.29% of trips were made for shopping purposes. The average daily travel distance of private vehicles was 5 km. Although the survey data are already 10 years old, they still indicate the Nepalese transport demand.

The annual passenger–kilometres (pkm) and tonne–kilometres (tkm) for freight transport are calculated based on the current energy demand and the energy intensities of the vehicles in use. The average energy intensity across all passenger vehicles is assumed to have been 1.5 MJ per kilometre in 2020—which reflects the current vehicle fleet of motorcycles (average of 1.2–1.3 MJ/pkm), cars (average of 1.5 MJ/pkm), and SUVs and pick-up trucks with an energy demand of 2–6 MJ/pkm. The assumed average energy intensity for freight vehicles is calculated accordingly, assuming vans and mini-vans are the main transport vehicles. It is also assumed that internal combustion engines (ICEs) and not electric drives are in use.

Table 20: Nepal—Projected passenger and freight transport demand under the N-1.5 °C scenario

		2019	2020	2025	2030	2035	2040	2045	2050
Road: Passenger Transport Demand	[PJ/a]	45	41	51	43	33	34	36	36
Annual passenger kilometres	[million pkm]	30,292	27,869	35,381	40,030	45,291	51,242	57,976	65,595
Average energy intensity—passenger vehicles.	[MJ/pkm]	1.47	1.47	1.45	1.07	0.74	0.67	0.63	0.54
Annual demand variation:	[%/a]	10%	−8%	2%	3%	3%	3%	3%	3%
Kilometres per person per day	[km/person day]	2.9	2.6	3.1	3.3	3.6	4.0	4.5	5.1
Road: Freight Transport Demand	[PJ/a]	19	18	16	17	14	15	15	15
Annual freight kilometres	[million tkm]	12,698	11,682	13,843	15,284	16,875	18,631	20,570	22,711
Average energy intensity—freight vehicles	[MJ/tkm]	1.51	1.51	1.17	1.11	0.86	0.79	0.72	0.68
Annual demand Variations	[%/a]	10%	-8%	2%	2%	2%	2%	2%	2%

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[48] JICA 2012; Japan International Cooperation Agency (JICA), “Data Collection Survey on Traffic Improvement in Kathmandu Valley,” Kathmandu, Nepal, 2012.

The total amount of passenger and freight kilometres is the basis for the projection of the future transport demand. The contraction of the transport demand in 2020 due to COVID is expected to end. It is anticipated that the pre-COVID transport demand of 2019 will be reached by 2023, and the transport demand will increase with population growth and GDP. It is assumed that the annual passenger kilometres will increase by 3% annually until 2050, whereas the freight transport demand will increase by 2% annually. All assumptions and calculated energy demands are shown in Table 20. The energy intensities for all vehicles are assumed to decrease over time with the implementation of more-efficient engines, the phase-out of fossil-fuel-based drives, and their replacement with electric drives. To achieve the terms of the Paris Climate Agreement, all energy-related CO_2 emissions must be phased out by 2050. Therefore, all fossil-fuel-based vehicles must be phased out, and electric drives will dominate, supplemented with a limited number of biofuel-based vehicles.

However, it is assumed that the share of cars will grow at the expense of two-wheeler vehicles—which will increase the average energy intensity per kilometre. Although electric drives are significantly more efficient, the increased vehicle size combined with more public transport options—mainly buses—will limit the increase in the energy demand. On average—across all passenger vehicle types—the energy intensity will decrease from around 1.5 MJ per passenger kilometre to 1.07 MJ in 2030 and to 0.54 MJ in 2050.

The energy required by freight vehicles to move 1 tonne for 1 kilometre will decrease from around 1.5 MJ to 1.11 MJ by 2030 and to 0.68 MJ by 2050. Both reductions will only be possible with high shares of electric drives. Figure 18 and Figure 19 show the development of drive trains for passenger and freight transport vehicles over time. The electrification of large parts of these fleets is unavoidable if the transport sector is to be decarbonized. The supply of—sustainably produced—biofuels will be limited and will be directed to large commercial vehicles, buses, and the large trucks used in remote rural areas where the required charging infrastructure for electric vehicles is unlikely to be developed in the next two decades.

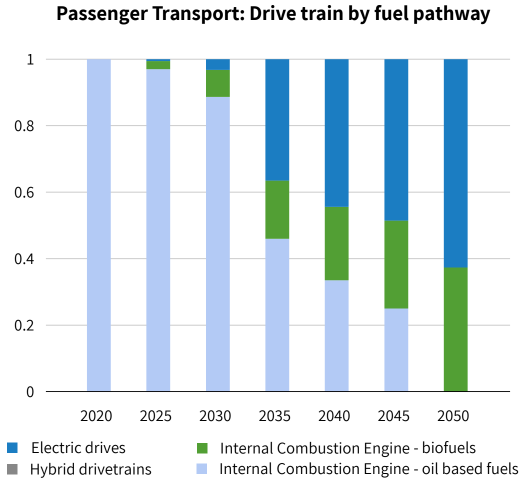

Figure 18: Passenger transport—drive trains by fuel

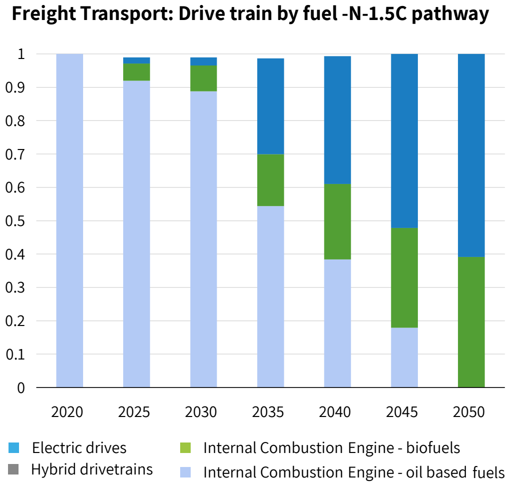

Figure 19: Freight transport—drive trains by fuel

The assumed trajectory for the transport sector (Figure 18 and Figure 19) is consistent with the NDC[49] of the Government of Nepal published in 2020, which identified the following three goals:

1. 25% of all vehicles will to be e-vehicles by 2025. This will include private two-wheeler vehicles and 20% of public four-wheeler vehicles.
2. By 2030, sales of e-vehicles will increase to include 90% of all private passenger vehicle sales, including two-wheelers, and 60% of all public four-wheeler passenger vehicle sales (the public passenger target does not consider electric rickshaws or electric tempos).
3. By 2030, 200 km of electric rail network will be developed to support public commuting and the mass transportation of goods.

The average lifespan of motorcycles and scooters in Nepal is 10 years, whereas cars are used for around 20 years (KP 8/2022)[50]. Based on these lifespans for motorcycles and cars, a country-wide overall market share of electric drives for the entire existing car fleet may not exceed 5% by 2030 for passenger and freight cars. Furthermore, it is assumed that the railway system will not be expanded beyond the current plans after 2030.

Supply-side barriers to e-vehicles

Currently, most e-vehicles are imported. The infrastructure required for electric mobility, in terms of maintenance and service centres and charging stations across urban and rural areas, is lagging. The resilience and reliability of the electricity supply—especially in rural areas—is still under development and faces challenges. Therefore, a rapid expansion of the charging infrastructure, which will increase the load even further, will depend on the progress of electricity services. However, the decarbonization of Nepal's energy sector will require increased electrification of the transport sector, and the expansion of a resilient power supply based on sustainable power generation technologies is essential.

G. Technology and fuel cost projections

All cost projections in this analysis are based on a recent publication by Teske et al. (2019)[51] . Section C in this chapter is based on Chapter 5 of that book, written by Dr. Thomas Pregger, Dr. Sonja Simon, and Dr. Tobias Naegler of the German Aerospace Center/DLR. The parameterization of the models requires many assumptions about the development of the characteristic technologies, such as specific investments and fuel costs. Therefore, because long-term projections are highly uncertain, we must define plausible and transparent assumptions based on background information and up-to-date statistical and technical information.

The speed of an energy system transition also depends on overcoming economic barriers. These largely involve the relationships between the cost of renewable technologies and of their fossil and nuclear counterparts. For our scenarios, the projection of these costs is vital to ensure a valid comparison of energy systems. However, there have been significant limitations to these projections in the past in terms of investment and fuel costs.

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[49] NDC Nepal 2020; Government of Nepal, "Second Nationally Determined Contribution (SNDC)," Kathmandu, Nepal, 2020.

[50] KP 8/2022; The Kathmandu Post, Trend of automobile ownership; 4th August 2022; https://kathmandupost.com/opinion/2018/02/11/trend-of-automobile-ownership

[51] Teske S (2019), Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2.0 °C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019.

Moreover, efficiency measures generate costs that are usually difficult to determine, which depend on technical, structural, and economic boundary conditions. Therefore, in the context of this study, we have assumed uniform average costs of 3 cents per kWh of electricity consumption avoided in our cost accounting.

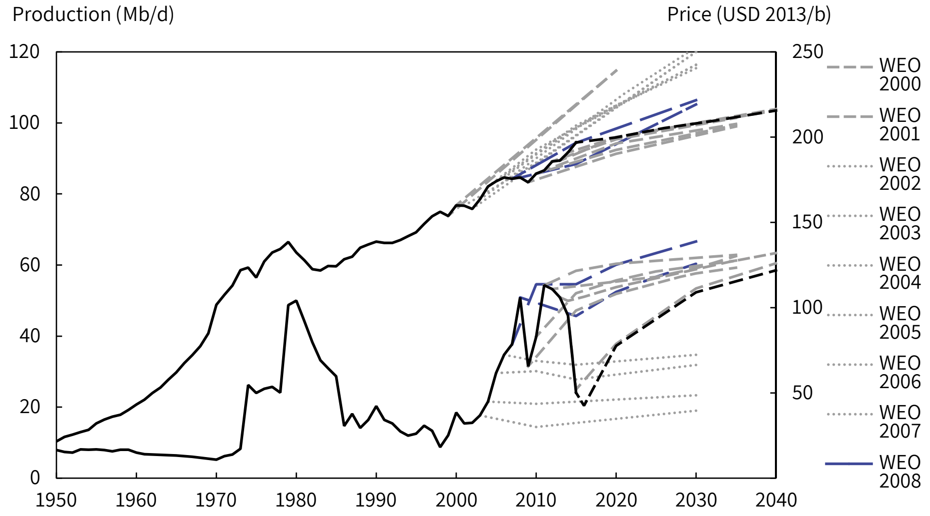

Figure 20: Historical development and projections of oil prices (bottom lines) and historical world oil production and projections (top lines) by the World Energy Outlook (WEO) published by the International Energy Agency (IEA), according to Wachtmeister et al. (2018)

During the last decade, fossil fuel prices have seen huge fluctuations. shows the oil prices since 1997. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices saw similar fluctuations (IEA 2017)[52] . Therefore, fossil fuel price projections have also seen considerable variations (IEA 2017[52]; IEA 2013[53]) and this has influenced the scenario results.

Although oil-exporting countries have provided the best oil price projections in the past, institutional price projections have become increasingly accurate, with the IEA leading the way in 2018 (Roland Berger 2018)[54]. An evaluation of the oil price projections of the IEA since 2000 by Wachtmeister et al. (2018)[55] showed that price projections have varied significantly over time. Whereas the IEA's oil production projections seem comparatively accurate, oil price projections showed errors of 40%–60%, even when made only 10 years ahead. Between 2007 and 2017, the IEA price projections for 2030 varied from US$70 to US$140 per barrel, providing significant uncertainty regarding future costs in the scenarios. Despite this limitation, the IEA provides a comprehensive set of price projections. Therefore, we based our scenario assumptions on these projections, as described below.

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52. IEA (2017): IEA (2017) World Energy Outlook 2017. International Energy Agency, Organization for Economic Co-operation and Development, Paris.
53. IEA 2013: IEA (2013) World Energy Outlook 2013. International Energy Agency, Organization for Economic Co-operation and Development, Paris.
54. Roland Berger (2018) 2018 oil price forecast: who predicts best? Roland Berger study of oil price forecasts. https://www.rolandberger.com/en/Publications/pub_oil_price_forecast_2015.html. Accessed 10.9.2018 2018.
55. Wachtmeister H, Henke P, Höök M (2018) Oil projections in retrospect: Revisions, accuracy and current uncertainty. Applied Energy 220:138-153. doi: https://doi.org/10.1016/j.apenergy.2018.03.013

However, because most renewable energy technologies provide energy without fuel costs, the projections of investment costs become more important than fuel cost projections, and this limits the impact of errors in the fuel price projections. It is only for biomass that the cost of feedstock remains a crucial economic factor for renewables. These costs range from negative costs for waste wood (based on credit for the waste disposal costs avoided), through inexpensive residual materials, to comparatively expensive energy crops. Because bio-energy has significant market shares in all sectors in many regions, a detailed assessment of future price projections is provided below.

Investment cost projections also pose challenges for scenario development. Available short-term projections of investment costs depend largely on the data available for existing and planned projects. Learning curves are most commonly used to assess the future development of investment costs as a function of their future installations and markets (McDonald and Schrattenholzer 2001[56] ; Rubin et al. 2015[57]). Therefore, the reliability of cost projections largely depends on the uncertainty of future markets and the availability of historical data.

Fossil fuel technologies provide a large cost data set featuring well-established markets and large annual installations. They are also mature technologies, so many cost-reduction potentials have already been exploited.

For conventional renewable technologies, the picture is more mixed. For example, like fossil fuels, hydropower is well established and provides reliable data on investment costs. Other technologies, such as solar PV and wind, are experiencing tremendous installation and cost-reduction developments. However, solar PV and wind are the focus of cost monitoring, and big data are already available on existing projects. However, their future markets are not readily predictable, as seen in the evolution of IEA market projections over recent years in the World Energy Outlook series (compare, for example, IEA 2007, IEA 2014, and IEA 2017). Small differences in cost assumptions for PV and wind lead to large deviations in the overall costs, also cost assumptions must be made with particular care.

Furthermore, many technologies have only relatively small markets, such as geothermal, modern bio-energy applications, and concentrated solar power (CSP), for which costs are still high and for which future markets are insecure. The cost reduction potential is correspondingly high for these technologies. This is also true for technologies that might become important in a transformed energy system but are not yet widely available. Hydrogen production, ocean power, and synthetic fuels might deliver important technology options in the long term after 2040, but their cost reduction potential cannot be assessed with any certainty today.

Thus, cost assumptions are a crucial factor in evaluating scenarios. Because costs are an external input into the model and are not internally calculated, we assume the same progressive cost developments for all scenarios. In the next sections, we present a detailed overview of our assumptions for power and renewable heat technologies, including the investment, fuel costs, and potential CO_2 costs in the scenarios.

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[56] McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. Energy Policy 29 (4):255–261. doi:https://doi.org/10.1016/S0301-4215(00)00122-1

[57] Rubin ES, Azevedo IML, Jaramillo P, Yeh S (2015) A review of learning rates for electricity supply technologies. Energy Policy 86:198–218. doi:https://doi.org/10.1016/j.enpol.2015.06.011

I. Power technologies

The focus of cost calculations in our scenario modelling is the power sector. We compared the specific investment costs estimated in previous studies (Teske et al. 2015)[58], which were based on a variety of studies, including the European Commission-funded NEEDS project (NEEDS 2009), projections of the European Renewable Energy Council (Zervos et al. 2010)[59], investment cost projections by the IEA (IEA 2014), and current cost assumptions by IRENA and IEA (IEA 2016c). We found that investment costs generally converged, except for PV. Therefore, for consistency, the power sector's investment and operation and maintenance costs are based primarily on the investment costs within WEO 2016 (IEA 2016c) up to 2040, including their regional disaggregation. We extended the projections until 2050 based on the trends in the preceding decade.

For renewable power production, we used investment costs from the 450-ppm scenario from IEA 2016c. For technologies not distinguished in the IEA report (such as geothermal combined heat and power [CHP]), we used cost assumptions based on our research (Teske et al. 2015). Because the cost assumptions for PV systems by the IEA do not reflect recent cost reductions, we based our assumptions on a more recent analysis by Steurer et al. (2018)[60], which projects lower investment costs for PV in 2050 than does the IEA.

The costs for onshore wind were adapted from the same source (Steurer et al. 2018) to reflect more recent data. Table 21 summarizes the cost trends for power technologies derived from the assumptions discussed above for Nepal. It is important to note that the cost reductions are, in reality, not a function of time but of cumulative capacity (production of units), so dynamic market development is required to achieve a significant reduction in specific investment costs. Therefore, overall, we might underestimate the costs of renewables in the REFERENCE scenario compared *with the With the Existing Measures* (WEM) scenario and the N-1.5 °C pathway (see Table 21).

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58. Teske S, Sawyer S, Schäfer O, Pregger T, Simon S, Naegler T, Schmid S, Özdemir ED, Pagenkopf J, Kleiner F, Rutovitz J, Dominish E, Downes J, Ackermann T, Brown T, Boxer S, Baitelo R, Rodrigues LA (2015) Energy [R]evolution - A sustainable world energy outlook 2015. Greenpeace International.
59. Zervos A, Lins C, Muth J (2010) RE-thinking 2050: a 100% renewable energy vision for the European Union. European Renewable Energy Council (EREC).
60. Steurer M, Brand H, Blesl M, Borggrefe F, Fahl U, Fuchs A-L, Gils HC, Hufendiek K, Münkel A, Rosenberg M, Scheben H, Scheel O, Scheele R, Schick C, Schmidt M, Wetzel M, Wiesmeth M (2018) Energiesystemanalyse Baden-Württemberg: Datenanhang zu techoökonomischen Kenndaten. Ministerium für Umwelt Klima und Energiewirtschaft Baden-Württemberg, STrise: Universität Stuttgart, Deutsches Zentrum für Luft- und Raumfahrt, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Stuttgart.

Table 21: Investment cost assumptions for power generation plants US Dollars (US$) and Nepalese Rupees (NPR/kW) by kW until 2050

Assumed Investment Costs for Power Generation Plants										
	2020		2025		2030		2040		2050	
Technology	[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]
Coal power plants	2,000	260,000	2,000	260,000	2,000	260,000	2,000	260,000	2,000	260,000
Diesel generators	900	117,000	900	117,000	900	117,000	900	117,000	900	117,000
Gas power plants	670	87,100	500	65,000	500	65,000	500	65,000	500	65,000
Oil power plants	950	123,500	930	120,900	890	115,700	860	111,800	820	106,600
Conventional Renewables										
Hydropower plants*	2,650	344,500	2,650	344,500	2,650	344,500	2,650	344,500	2,650	344,500
New Renewables										
PV power plants	2,000	260,000	980	127,400	730	94,900	560	72,800	470	61,100
Biomass power plants	2,134	277,420	2,111	274,430	2,089	271,570	1,998	259,740	1,916	249,080

*Values apply to both run-of-the-river and reservoir hydropower.

However, our approach is conservative when we compare the REFERENCE scenario with the more ambitious renewable energy scenarios under identical cost assumptions. Fossil-fuel power plants have limited potential for cost reductions because they are at advanced stages of technology and market development. The products of gas and oil plants are relatively cheap, at around US$670/kW and US$822/kW, respectively.

In contrast, several renewable technologies have seen considerable cost reductions over the last decade. This is expected to continue if renewables are deployed extensively. Hydropower and biomass have remained stable in terms of costs. Tremendous cost reductions are still expected for solar energy and wind power, even though they have experienced significant reductions already. Whereas CSP might deliver dispatchable power at half its current cost in 2050, variable PV costs could drop to 35% of today's costs.

II. Heating technologies

Assessing the costs in the heating sector is even more challenging than for the power sector. Costs for new installations differ significantly between regions and are interlinked with construction costs and industrial processes, which are not addressed in this study. Moreover, no data are available to allow the comprehensive calculation of the costs for existing heating appliances in all regions. Therefore, we have concentrated on the additional costs of new renewable applications in the heating sector.

Our cost assumptions are based on a previous survey of renewable heating technologies in Europe, which focused on solar collectors, geothermal energy, heat pumps, and biomass applications. Biomass and simple heating systems in the residential sector are already mature. However, more-sophisticated technologies that can provide higher shares of heat demand from renewable sources are still under development and rather expensive. Market barriers will slow the further implementation and cost reductions of renewable heating systems, especially for heating networks. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented, as projected in all scenarios.

Table 22 presents the investment cost assumptions for heating technologies, disaggregated by sector. Geothermal heating shows the same high costs in all sectors. In Europe, deep geothermal applications are being developed for heating purposes at investment costs ranging from €500/kW$_{\text{thermal}}$ (shallow) to €3000/kW$_{\text{thermal}}$ (deep), with the costs strongly dependent on the drilling depth. The cost reduction potential is assumed to be around 30% by 2050. No data are available for the specific situation in Nepal. However, geothermal power and heating plants are not assumed to be built under any scenario.

Heat pumps typically provide hot water or space heat for heating systems with relatively low supply temperatures, or they supplement other heating technologies. Therefore, they are currently mainly used for small-scale residential applications. Costs currently cover a large bandwidth and are expected to decrease by only 20% to US$1450/kW by 2050.

We assume the appropriate differences between the sectors for biomass and solar collectors. There is a broad portfolio of modern technologies for heat production from biomass, ranging from small-scale single-room stoves to heating or CHP plants on an MW scale. Investment costs show similar variations: simple log-wood stoves can be run for US$100/kW, but more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive to run. The running costs of log-wood or pellet boilers range from US$500–1300/kW, and large biomass heating systems are assumed to reach their cheapest cost in 2050 at around US$480/kW for industry. For all sectors, we assume a cost reduction of 20% by 2050.

In contrast, solar collectors for households are comparatively simple and will become cheap, at US$680/kW, by 2050. The costs of simple solar collectors for service water heating might have been optimized already, whereas their integration into large systems is neither technologically nor economically mature. For larger applications, especially in heat-grid systems, the collectors are large and more sophisticated. Because there is not yet a mass market for such grid-connected solar systems, we assume there will be a cost reduction potential until 2050.

Table 22: Specific investment cost assumptions (in US$2015) for heating technologies in the scenarios until 2050

Investment Costs for Heat Generation Plants									
		2020		2030		2040		2050	
		[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]	[US$/kW]	[NPR/kW]
Solar collectors	Industry	820	106,600	730	94,900	650	84,500	550	71,500
	In heat grids	970	126,100	970	126,100	970	126,100	970	126,100
	Residential	1,010	131,300	910	118,300	800	104,000	680	88,400
Geothermal		2,270	295,100	2,030	263,900	1,800	234,000	1,590	206,700
Heat pumps		1,740	226,200	1,640	213,200	1,540	200,200	1,450	188,500
Biomass heat plants		580	75,400	550	71,500	510	66,300	480	62,400
Commercial biomass heating systems	Commercial scale	810	105,300	760	98,800	720	93,600	680	88,400
Residential biomass heating stoves	Small scale / Rural	110	14,300	110	14,300	110	14,300	110	14,300

III. Renewable energy costs in Nepal in 2021

The following tables provide an overview of the specific renewable energy costs in Nepal. This information is based on reference price from Alternative Energy Promotion Centre (FY 2020/21).

Table 23: Cost of Solar Home Systems

Solar Home Systems	[NPR]	[$]	[US$/kW$_{peak}$]
10 W	5,944	46	4,572
20 W	11,237	86	4,322
50 W	20,709	159	3,186
55 W	22,536	173	3,152
60 W	23,858	184	3,059
80 W	27,337	210	2,629
100 W	32,439	250	2,495
Institutional Solar Power Systems	**[NPR]**	**[$]**	**[US$/kW$_{peak}$]**
1000 W	295,969	2,277	2,277
2000 W	496,080	3,816	1,908

Table 24: Cost of Solar Dryers

Solar Dryers [1 sqft = 0.0929 m^2]	[NPR]	[$]	[US$/m^2]
3–6 sqft (household)	33,537	258	617
10–15 sqft (household)	76,182	586	505
> 21 sqft (institutional)	117,719	906	464

Table 25: Cost of Solar Cookers

Solar Cookers	[NPR]	[$]
Parabolic—household	25,416	196
Parabolic—institutional	155,940	1,200

Table 26: Cost of Biomass Stoves

Biomass Stoves olar Cookers	[NPR]	[$]
Institutional improved stove—type 1	50,579	389
Institutional improved stove—type 2	52,991	408
Institutional improved stove—type 3	63,026	485
Natural draft stove	4,610	35
Forced draft stove	9,182	71
Improved metallic stove	12,599	97

IV. Fuel cost projections

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions up to 2040 on *World Energy Outlook 2017* (IEA 2017). Beyond 2040, we extrapolated the price developments between 2035 and 2040 and present them in Table 27. Although these price projections are highly speculative, they provide prices consistent with our investment assumptions. Fuel prices for nuclear energy are based on the values in the Energy [R]evolution report 2015 (Teske et al. 2015)[58], corrected by the cumulative inflation rate for the Eurozone between 2012 and 2015 of 1.82%.

Table 27: Development projections for fossil fuel prices in US$2015 (IEA 2017)

Development Projections for Fossil Fuel Prices										
All Scenarios	2019		2025		2030		2040		2050	
	[US$/GJ]	[NPR/GJ]	[US$/GJ]	[NPR/GJ]	[US$/GJ]	[NPR/GJ]	[US$/GJ]	[NPR/GJ]	[US$/GJ]	[NPR/GJ]
Oil	8.5	1,105	12.3	1,599	21.5	2,795	24.2	3,146	35.1	4,563
Gas	9.8	1,274	10.0	1,300	10.7	1,391	10.9	1,417	11.8	1,534
Coal	3.2	416	3.5	455	4.3	559	4.5	585	5.3	689

V. Biomass prices

Biomass prices depend on the quality of the biomass (residues or energy crops) and the regional supply and demand. The global variability is large. Lamers et al. (2015)[61] reported a price range of €4–4.8/GJ for forest residues in Europe in 2020, whereas agricultural products might cost €8.5–12/GJ. Lamers et al.61 modelled a range for wood pellets from €6/GJ in Malaysia to €8.8/GJ in Brazil. IRENA modelled a cost supply curve on a global level for 2030, ranging from US$3/GJ for a potential of 35 EJ/yr up to US$8–10/GJ for a potential of up to 90–100 EJ/yr (IRENA 2014) (and up to US$17/GJ for a potential extending to 147 EJ).

Table 28: Biogas plant prices—small quantities—in Nepal by region

Biogas	2 m^3		4 m^3		6 m^3		8 m^3	
	[NPR]	[$]	[NPR]	[$]	[NPR]	[$]	[NPR]	[$]
Household—in the Terai region	53,370	411	76,366	587	87,915	676	98,333	756
Household—in hilly region	61,198	471	83,045	639	96,095	739	105,681	813
Household—in mountainous region	71,650	551	91,968	707	106,779	821	114,039	877
Urban area	69,500	535						

Source: Alternative Energy Promotion Centre (FY 2077/78)

Table 29: Biogas plant prices—medium quantities—in Nepal by region

Biogas	2 m^3		4 m^3		6 m^3		8 m^3	
	[NPR]	[$]	[NPR]	[$]	[NPR]	[$]	[NPR]	[$]
Household—in the Terai region	282,259	2,171	813,090	6,255	1,079,534	8,304	1,574,586	12,112
Household—in hilly region	307,257	2,364	921,768	7,091	1,225,347	9,426	1,792,038	13,785
Household—in mountainous region	335,704	2,582	913,551	7,027	1,404,839	10,806	2,045,046	15,731

Source: Alternative Energy Promotion Centre (FY 2077/78)

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[61] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A (2015) Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. GCB Bioenergy 7 (4):618–634. doi:https:// doi.org/10.1111/gcbb.12162

4. Nepal: Renewable Energy Potential

Nepal's solar and wind potential was assessed as an input for energy scenario development. In this section, we assess the technical potential under space-constrained conditions.

A. The [R]E Space Methodology

The [R]E Space methodology is part of the One Earth Climate Model (OECM) methodology. GIS mapping was used to ascertain Nepal's renewable energy resources (solar and wind). It was also used in the regional analysis of geographic and demographic parameters and the available infrastructure that could be leveraged in developing the scenarios.

Mapping was performed with the software ESRI ArcGIS10.6.1, which allows spatial analysis and maps the results. It was used to allocate solar and wind resources and for the demand projections for the seven modelling regions. Population density, access to electricity infrastructure, and economic development projections are key input parameters in ta region-specific analysis of Nepal's future energy situation, to clarify the requirements for additional power grid capacities and/or micro-grids.

Open-source data and maps from various sources were collected and processed to visualize the country, its regions, and districts. Further demographic data related to the population and poverty were plotted on the maps together with transmission networks and power plants. The main data sources and assumptions made for this mapping are summarized in Table 30.

Table 30: Nepal—[R]E 24/7—GIS-mapping—data sources

Data	Assumptions	Source
Land cover	Land cover classes suitable for solar energy and wind energy production were identified from Copernicus Global Land Cover 2019.	Copernicus Global Land Cover - 2019
Digital Elevation Model (DEM)	For both wind and solar analyses, any land with a slope of > 30% was excluded from all scenarios.	Nepal Digital Elevation Model (DEM): US Geological Survey (USGS)
Population and Population Density	A population census was conducted in 2021 by the Nepal Central Bureau of Statistics, and a preliminary report is available.	Population Census 2021: Nepal Central Bureau of Statistics
Protected Areas	All protected areas designated national parks, wildlife reserves, hunting reserves, conservation areas, or buffer zones were excluded from all scenarios.	World Wildlife Fund (WWF) Nepal
Power Plants, Transmission Lines, and Network	Solar and wind potential of areas ≤ 10 km from transmission lines was considered (Scenario 2).	Clean Cooking Alliance (CCA)-generated report for the Nepal Electricity Authority (NEA), Government of Nepal
Solar Irradiance (direct normal irradiation : DNI)	The average yearly direct normal insolation/irradiation (DNI) values range from 1 to 5 MWh/m^2 per year (2.7–13.6 kWh/m^2 per day).	Global Solar Atlas (2017): Solar GIS/The World Bank
Wind Speeds	Wind speeds ≥ 5 m/s were considered at a height of 100 m.	Global Wind Atlas

The mapping procedure is summarised in Figure 21. The land areas available for potential solar and wind power generation were calculated and visualized at the national and provincial levels using ArcGIS. The land-cover map, elevation (digital elevation model: DEM), solar irradiation (direct normal irradiation: DNI) and wind speed data were obtained from the website cited above as raster data, and were all converted into binary maps (0 = area not suitable as a potential area, 1 = area suitable as a potential area) against all the assumptions in Table 30, and then combined into one binary map by overlaying all the raster data. This map integrates all the criteria listed cited above in one map with a value of 1 (land included in the potential area) or a value of 0 (land not included in the potential area).

Data on transmission lines and protected areas exist as vector data. All protected areas were excluded from the above value 1 area in the integrated raster data using a mask layer generated from the 'erase' function. For scenario 2 (see Figure 21), buffer layers were generated from transmission line (10 km) data, and then the raster data without protected areas were clipped by these buffer layers to generate potential area maps under Scenario 2. This input was fed into the calculations for the [R]E 24/7 model, as described below.

Disclaimer: The environmental criteria used to identify suitable areas for utility scale solar and wind projects do not reflect the current legislation in Nepal, and the potential provided is a conservative estimate and may ultimately be larger.

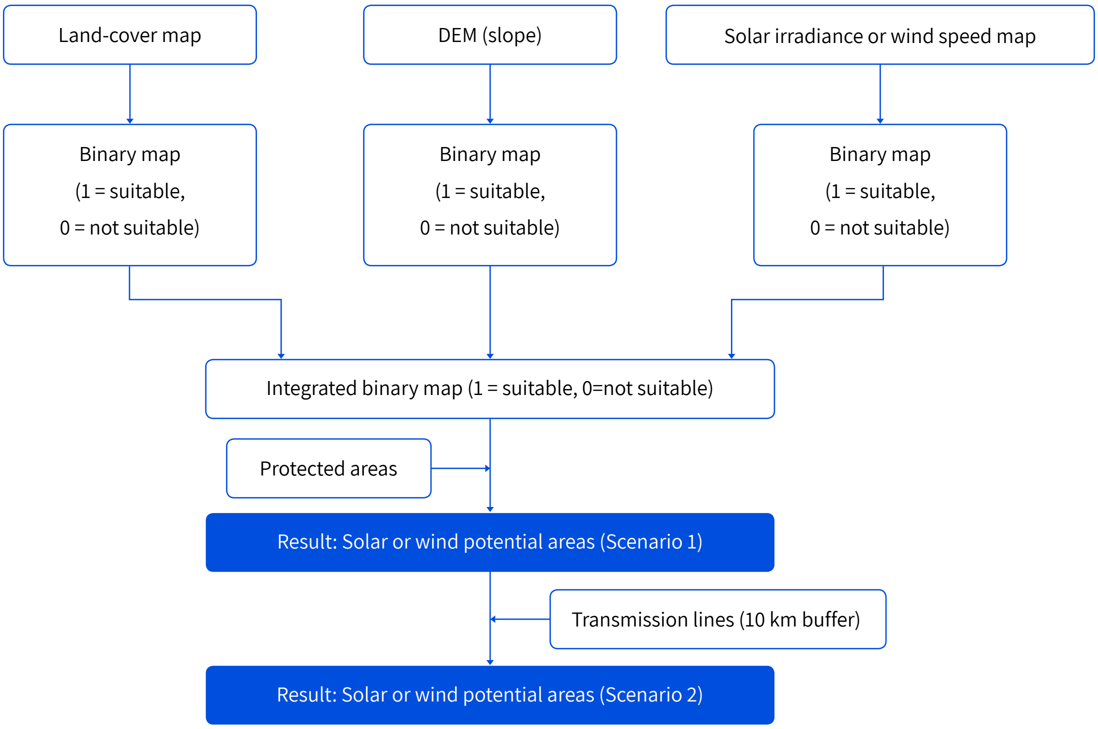

Figure 21: Methodology—Solar potential analysis and wind potential analysis

B. Mapping Nepal

Nepal has a largely untapped potential for renewable energy. Hydropower is utilized extensively and supplied almost 99% of the country's electricity in 2019 (IEA, 2022). Solar PV produced less than 1 GWh, and wind produced 7 GWh, both playing minor roles in 2019 compared with hydropower. However, Nepal's solar energy sector has transitioned over the past few years. In June 2020, the largest solar power plant, Nuwakot Solar Power Plant, launched the first phase of its first 25 MW solar power project. Solar panels are installed at six locations within Devighat Hydropower Station and are connected to the 66-kV sub-stations located approximately 15 km northwest of Kathmandu (Nepali Times, 2020). Various organizations have also assessed Nepal's wind resources. However, their potential is considered much lower than that of solar energy in Nepal, mostly because there are restrictions imposed by the geography (mountain regions), nature conservation (protected areas), and the limited access to existing energy infrastructure, especially in the northern part of the country.

I. Solar potential

The average annual solar irradiation (DNI) level in Nepal is 0.2– 8.5 kWh/m^2 per day, and the higher end of that range is in the northwest of the country, in the mountainous regions in Karnali Province (Solargis, 2017).

Nepal's solar potential has been mapped under two different scenarios.

Scenario 1. Available land—excluding protected areas (PA), extreme topography (slope > 30% [mountain areas], S30), and certain land-cover classes, including closed forests, wetlands, moss and lichen, snow and ice, and water (permanent water bodies) (LU).

Scenario 2. See 1, with additional restriction that excludes areas ≤ 10 km from existing transmission lines (PT10).

Table 31: Nepal's potential for utility-scale solar photovoltaic

Scenarios	**1. LU + PA + S30**		**2. LU + PA + S30 + PT10**	
Regions	**Solar Area (km^2)**	**Solar Potential (GW)**	**Solar Area (km^2)**	**Solar Potential (GW)**
Province 1	1,049.1	26.2	750.4	18.8
Madhesh	6,859.5	171.5	5,988.6	149.7
Bagmati	2,472.9	61.8	2,065.9	51.6
Gandaki	1,677.6	41.9	1,488.3	37.2
Lumbini	5,718.5	143.0	4,348.0	108.7
Karnali	3,405.1	85.1	856.1	21.4
Sudurpaschim	2,942.3	73.6	1,775.5	44.4
Total	**24,124.9**	**603.1**	**17,272.8**	**431.8**

Figure 22 shows the results of a spatial analysis indicating the solar potential areas under Scenario 1 (LU + PA + S30). The scenario provides 24,125 km^2 of areas with solar potential and a total potential for utility-scale solar PV capacity of 603.1GW. Scenario 1 excludes all protected areas and areas with slopes > 30%, because installing solar panels in steep mountainous areas is unrealistic. Open forests, shrubs, herbaceous vegetation, bare/spare vegetation, agricultural land, and urban/built-up land-cover classes in the Copernicus Global Land Cover 2019 dataset (Buchhorn et al., 2020) are included. However, certain land-cover classes (e.g., closed forests, wetlands, water bodies, snow and ice) are excluded in the scenarios selected for the consideration of solar energy potential. The potential solar areas overlap with productive agricultural areas, which are the most suitable lands for maize, rice, and tomato production (National Soil Science Research Centre, NARC). Because the resolution of the agricultural suitability maps is coarse, they are not considered in this analysis.

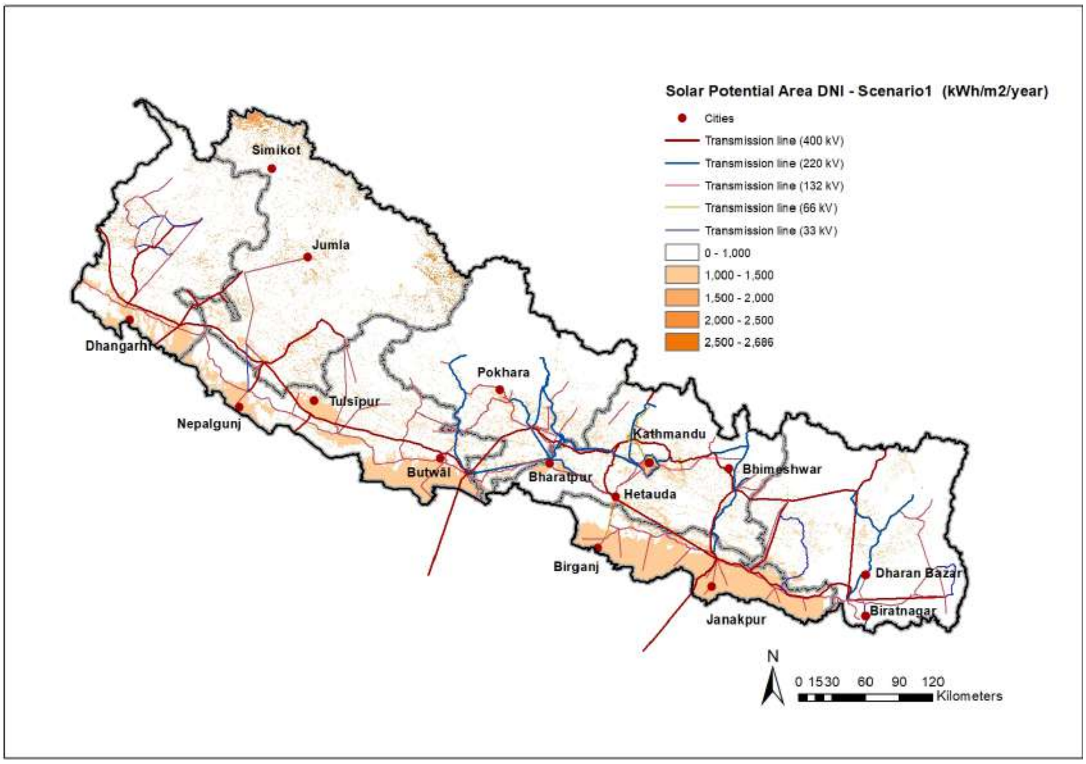

Figure 22: Nepal—Solar radiation and existing power transmission lines under [R]E-Space Scenario 1: LU + PA + S30

Figure 23 shows the solar potential areas for Scenario 2 (LU + PA + S30 + PT10). When the land area is restricted by its proximity to power lines (10 km), the potential solar areas decrease to 17,273 km^2. This is because most electricity and road infrastructure are currently developed in the country's southern provinces. Under Scenario 2, utility-scale solar farms in Nepal can potentially harvest 431.8 GW of solar PV.

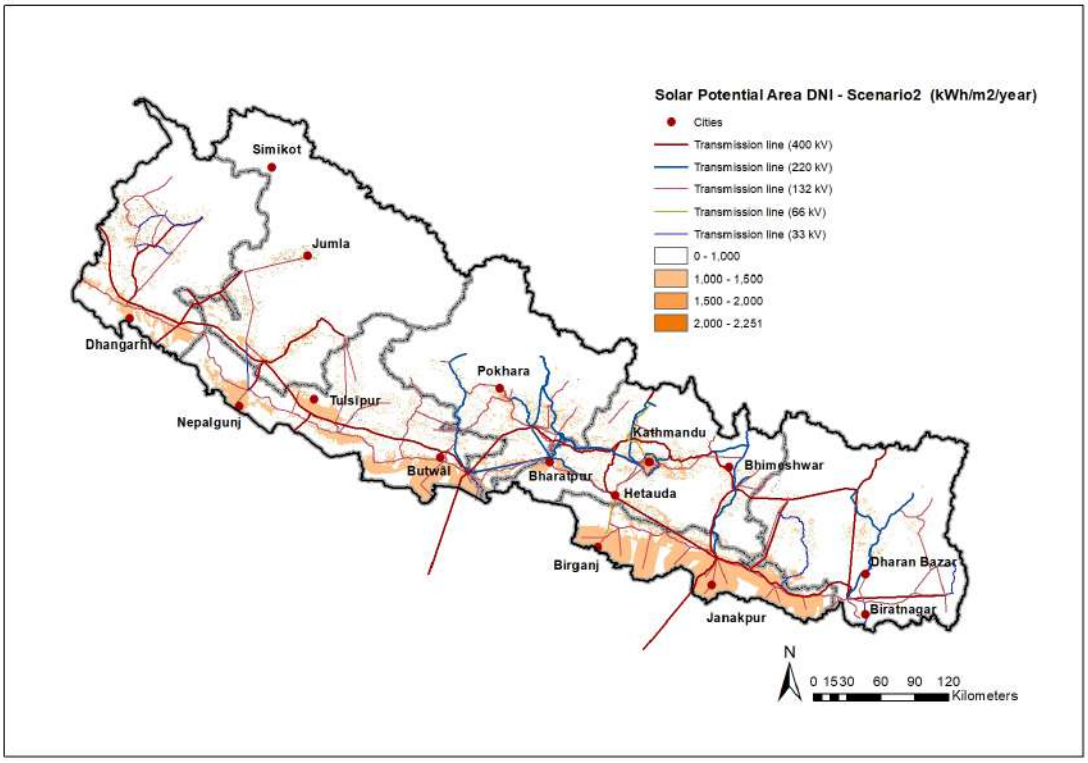

Figure 23: Nepal—Solar radiation and existing power transmission lines under [R]E-Space Scenario 2: LU + PA + S30 + PT10

II. Wind potential

The overall wind resources on land are significantly small in Nepal compared with the solar potential. The wind speeds in Nepal range from 0.06 to 28.3m/s at 100 m height, and high-wind-speed areas are predominantly located in the northern regions, in Karnali Province (Technical University of Denmark, 2019). The average annual wind speed in Nepal is 3.23 m/s. In this analysis, we have included only areas with an average annual wind speed of ≥ 5 m/s. Nepal's wind potential has been mapped under three different scenarios. The current use of wind energy in Nepal involves utility scale wind turbines in the range up to 10 kilowatts, operated both on- and off-grid as battery chargers.

'Scenario 1': Available land—restricted by protected areas (PA), topography (slope > 30% [mountain areas], S30), and existing land use, including forests and urban areas (LU).

'Scenario 2': See 1, with the additional restriction excluding areas ≤ 10 km from existing transmission lines (PT10).

Open forest, shrubs, herbaceous vegetation, bare/sparse vegetation, and agricultural land were included in the available land (LU) for the two wind scenarios, whereas the land-cover classes closed forests, wetland, moss and lichen, urban/built up areas, snow and ice, and permanent water bodies were excluded in this analysis of wind potential (Buchhorn et al., 2020).

Table 32 shows that the overall total wind potential under all restrictions is 5,932.8 MW (5.9 GW) for Scenario 1. Overall, the spatial analysis identified very limited wind potential in Nepal, especially under Scenario 2 (246.9 MW), because there are limited areas with an annual wind speed of ≥ 5 m/s and most of these areas are not located within close proximity to transmission lines (≤ 10 km).

Table 32: Nepal's potential for utility-scale wind power

Scenarios	**1. LU + PA + S30**		**2. LU + PA + S30 + PT10**	
Regions	**Wind Area (km²)**	**Wind Potential (MW)**	**Wind Area (km²)**	**Wind Potential (MW)**
Province 1	60.0	300.0	16.3	81.6
Madhesh	0.4	1.9	0.4	1.9
Bagmati	1.4	6.9	0.8	3.8
Gandaki	14.3	71.3	2.1	10.6
Lumbini	25.3	126.6	12.8	63.8
Karnali	1,012.0	5,060.0	12.4	62.2
Sudurpaschim	73.3	366.3	4.6	23.1
Total	**1,186.6**	**5,932.8**	**49.4**	**246.9**

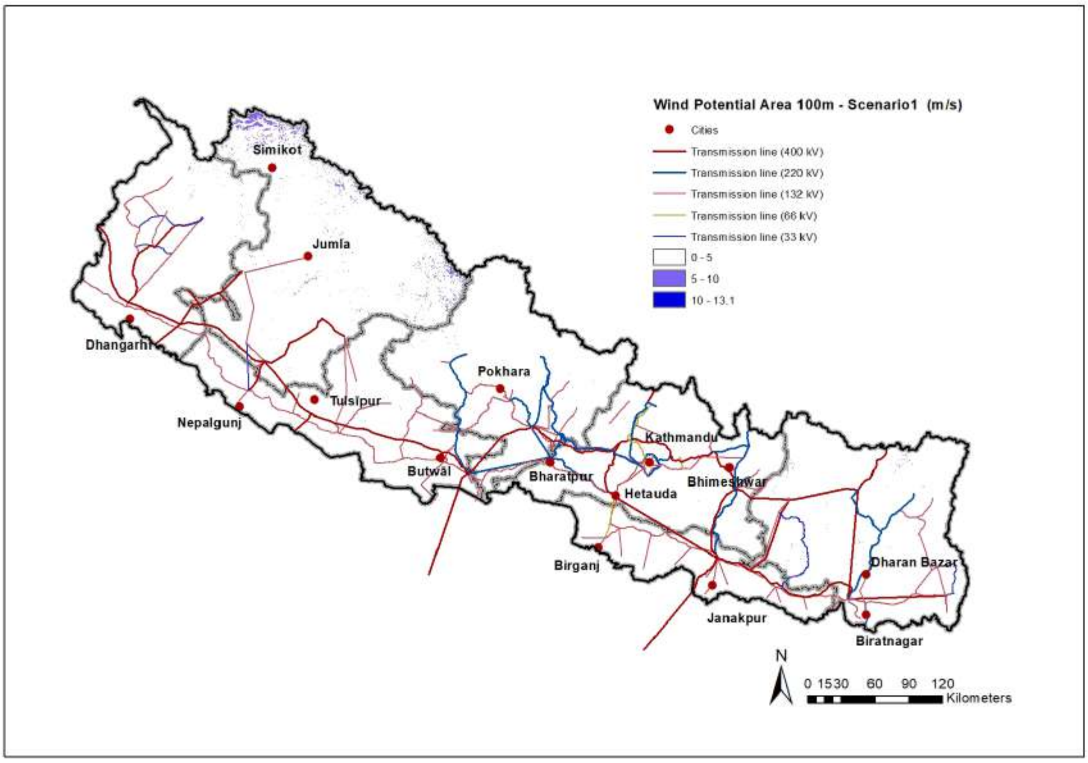

Figure 24: Nepal—Average wind speed and existing power transmission lines under [R]E-Space Scenario 1: LU + PA + S30

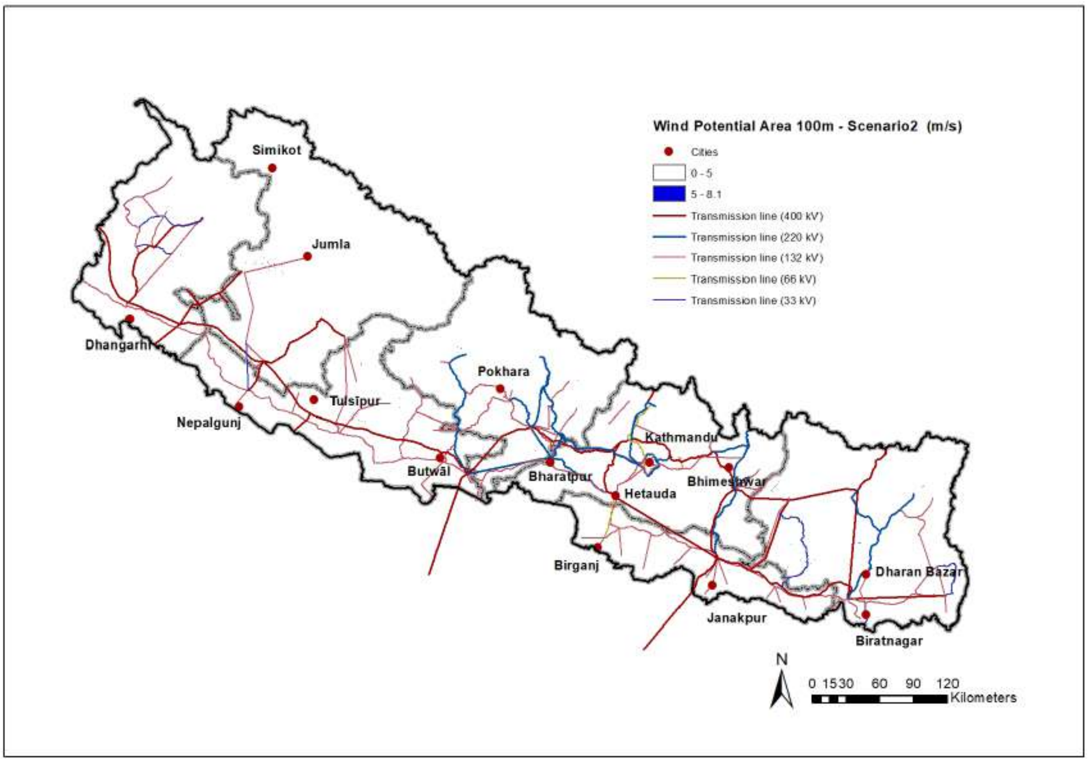

Figure 25: Nepal—Average wind speed and existing power transmission lines under [R]E-Space Scenario 2: LU + PA + S30 + PT10

Main challenge for utility-scale solar PV is the availability of land and policy stability

To use Nepal's utility-scale solar PV potential as efficiently as possible, further research is required, breaking down the utility-scale PV potential further into ground-mounted solar PV, agricultural solar PV, and floating solar PV.

- Utility-scale solar PV: Large-scale solar PV generators require space. Space is limited in Nepal and energy generation must often compete with other forms of land use. Therefore, space for solar power should be utilized as efficiently as possible, and multiple use options should be considered.
- Agricultural solar PV is a new development that combines agricultural food production techniques with solar PV equipment. The solar generator is mounted above the field—sometimes several meters high—to leave enough space for harvesting and to ensure light access.
- R&D is required into floating solar generators on lakes, especially the water storage reservoirs of hydropower stations with dams. Floating solar is a fairly new form of solar PV. In standardized floating devices for utility-scale projects, solar panels designed for ground-mounted systems are usually used.

Furthermore, policy changes regarding licensing and electricity rates for generated solar electricity have undergone changes in the past, which increases the risks to project development and the operation of systems. Higher risks lead to higher capital costs and lower economic advantages. Therefore, policy stability is a key driver of every technology, including utility-scale solar PV power plants.

Table 33: Nepal—Areas required for three types of renewable energy technologies under the most ambitious N-1.5 °C scenario

Technology		Units	2020	2030	2040	2050	% Landmass of Nepal (for 2050)
Solar PV	Total installed capacity	GW	0.00	1.37	7.38	24.57	≤ 1%
	Specific nominal capacity	MW/km²	80	80	80	80	
	Area	km²	0	17	92	307	
Wind onshore	Total installed capacity	GW	0.00	0.10	0.15	0.38	≤ 1%
	Average capacity	MW	3	3	3	3	
	Number of plants	#	1.5	32.3	48.4	127.7	
	Specific nominal capacity	MW/km²	5	5	5	5	
	Area	km²	1	19	29	77	

III. Bio-energy

The country has considerable biomass resources from agricultural residues. The Ministry of Population and Environment of the Government of Nepal published a comprehensive bio-energy resource analysis and developed a bio-energy strategy in 2017 (MoPE 2017)[62]. The Government identified biomass as one of the most important energy sources for Nepal's current and future energy supply. To promote the effective and efficient use of renewable energy, including biomass-derived energy, the Government of Nepal established the Alternative Energy Promotion Centre (AEPC) in 1996. AEPC provides financial and technical assistance for the promotion of biomass-derived energy, among other forms, through its programs.

The UTS authors of this energy analysis for Nepal based it on the energy scenario development documented in Chapter 3 regarding the implementation measures of the *Biomass Strategy 2017*.

The key targets of Nepal's bioenergy strategy for 2030 are:

- All the solid waste landfill sites to be established will be sanitary landfill sites, and provision will be made to collect and store biogas.
- Electricity will be generated through solid-waste management in those municipalities with more than 1 tonne of garbage production, and 10 MW of electricity will be generated from bio gasification.
- Clean cooking technologies of at least tier-3 will be provided to all households.
- Lands for energy cropping will be identified and used to cultivate energy crops.
- 10% of the total petrol and diesel consumed in Nepal will be replaced by biodiesel and bio-ethanol.

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[62] MoPE (2017), Ministry of Population and Environment, Government of Nepal, 'Biomass Energy Strategy 2017'; https://www.aepc.gov.np/uploads/docs/2018-07-29_Biomass%20Energy%20Strategy%202073%20BS%20(2017)%20English.pdf

The *Biomass Strategy* does not quantify Nepal's potential for sustainable bio-energy. However, the N-1.5 °C energy pathway is based on increased electric cooking and a significant reduction in biomass for cooking, which is currently the main use of biomass in Nepal. Under the N-1.5 °C scenario, the primary use of bio-energy will more than halve, from 422 PJ in 2019 to < 200 PJ in 2050.

IV. Hydropower

Nepal has significant potential for hydropower plants and has utilized its resources already. In 2020, hydropower plants supplied over 98% of Nepal's current electricity demand.

Table 34 shows the big and medium scale hydropower plants in Nepal as of FY 2021/22 obtained from Nepal Electricity Authority annual report. Big hydropower plants mean plant capacities ranging from 100MW to 1,000MW[63] and medium hydropower plants mean plant capacities ranging from 25 to 100MW[63].

Table 34: Big- and medium-sized hydropower plants in operation in Nepal

	Hydropower plants	**Province**	**Capacity (MW)**
	Big hydropower plants **600**		**Sub-total**
1	Upper Tamakoshi	Bagmati	456
2	Kaligandaki A	Gandaki	144
	Medium hydropower plants **675**		**Sub-total**
1	Middle Marsyandi	Gandaki	70
2	Marsyandi	Gandaki	69
3	Kulekhani I	Bagmati	60
4	Upper Trishuli 3A HEP	Bagmati	60
5	Khimti Khola	Bagmati	60
6	Likhu-IV	Bagmati	52
7	Upper Marsyangdi "A"	Gandaki	50
8	Upper Bhotekoshi Khola	Bagmati	45
9	Mistri Khola	Gandaki	42
10	Kulekhani II	Bagmati	32
11	Nyadi	Gandaki	30
12	Chameliya	Sudurpaschim	30
13	Singati Khola	Bagmati	25
14	Upper Madi	Gandaki	25
15	Kabeli B-1	Province 1	25
		Total	**1,275**

Note: Cumulative capacity of micro (up to 1MW) and small hydropower plants (1MW to 25MW): 806MW

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[63] R. P. Singh, H. P. Nachtnebel and N. Komendantova, "Deployment of Hydropower in Nepal: Multiple Stakeholders' Perspectives," Sustainability, vol. 12, no. 16, p. 6312, 2020.

Table 34 provides an overview of the big- and medium-sized hydro power plants in operation in 2022. Micro and small hydropower plants have not been listed. The total generation capacity was 3.2 GW with 1.27 GW in operation and around 2 GW of additional capacity in various planning stages or already under construction. The total generation capacity is expected to reach at least 5 GW by 2030.

Nepal has vast hydropower potential, which exceeds the current and future demand by an order of magnitude. According to Nepal's Water and Energy Commission Secretariat 2010 Synopsis report (WECS 2010), the estimated theoretical hydropower potential is around 83 GW, whereas the technical potential is estimated to be 45 GW, of which 42 GW is believed to be economically viable (Suman 2021)[64].

The sustainable potential for hydropower has not been quantified in the literature. Therefore, the N-1.5 °C pathway increases the hydropower capacity to 11 GW by 2050, only a quarter of the believed economic potential.

Table 35: Major river systems in Nepal and their hydropower potential

Major River Basin	Theoretical Potential	Technical Potential		Economic Potential	
	[MW]	Project sites	[MW]	Project sites	[MW]
Sapta Koshi	22,350	53	11,400	40	10,860
Sapta Gandaki	20,650	18	6660	12	5270
Karnali and Mahakali	36,180	34	26,570	9	25,125
Southern Rivers	4110	9	980	5	878
Total	**83,290**	**114**	**45,610**	**66**	**42,133**

ADB 2020[65]

V. Assumptions for hydrogen and synfuel production

In the Nepal 1.5 °C (N-1.5 °C) scenario, hydrogen and sustainable synthetic fuels will be introduced as a substitute for natural gas. Unsustainable biomass will only play a minor role and will be used almost exclusively by industry after 2030. Hydrogen is assumed to be produced by electrolysis, producing an additional electricity demand that will be supplied by extra renewable power production capacity, predominantly solar PV and hydropower. Renewable hydrogen and synthetic fuels are essential for a variety of sectors.

- In the industry sector, hydrogen is an additional renewable fuel option for high-temperature applications, supplementing biomass in industrial processes whenever the direct use of renewable electricity is not applicable.
- The transport sector will also rely increasingly on hydrogen as a renewable fuel, where battery-supported electric vehicles reach their limits and where limited biomass potential restricts the extension of biofuel use. However, future hydrogen applications may be insufficient to replace the whole fossil fuel demand, especially in aviation, heavy-duty vehicles, and navigation. The N-1.5 °C scenario introduces synthetic hydrocarbons from renewable hydrogen, electricity, and biogenic/atmospheric CO_2. These synthetic fuels will be introduced after 2030 and provide the remaining fossil fuel demand that cannot meet with biofuels because their potential is limited.

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[64] Suman (2021), A. Suman, Role of renewable energy technologies in climate change adaptation and mitigation: A brief review from Nepal, Renewable and Sustainable Energy Reviews, Volume 151, 2021, 111524, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.111524

[65] ADB (2020), Hydropower Development and Economic Growth in NepaL, Herath Gunatilake, Priyantha Wijayatunga, and David Roland-Holst, ADB South Asia Working Paper Series, No. 70, June 2020, https://www.adb.org/sites/default/files/publication/612641/hydropower-development-economic-growth-nepal.pdf

5. Areas of Forest Gain and Loss in Nepal

The Food and Agriculture Organization of the United Nations (FAO) is a specialized agency that leads international efforts to abolish hunger and improve nutrition and food security. The FAO has published extensive food production data and other data related to agriculture and forestry. According to the FAO, the forest area in Nepal in 2010 was 59,620.3 km^2 (including 57,410 km^2 of naturally regenerated forest), which is a 5.1% and 3.1% increase from 1990 and 2000, respectively (FAO, 2020). These increases resulted in negative carbon emissions from the forest sector (Table 36).

Table 36: Extent of forest areas and net emissions from forested land in Nepal (FAO)

	Extent of Forest		Net Emissions	
Year	**Areas (km^2)**	**Change from 1990**	**(kilotonnes)**	**Change from 1990**
1990	56,720.0	-	−4,304.1	-
2000	57,807.6	1.9%	−4,304.1	-
2010	59,620.3	5.1%	−7,173.6	− 66.7%
2020	59,620.3	5.1%	-	-

Source: FAO Stats.

The gain and loss of forest areas in Nepal were also visualized and calculated with ArcGIS. The spatial dataset Global Forest Change by Hansen et al. (2013) was used to highlight and calculate the areas of forest gain (2001–2012) and forest loss (2001–2021) using ArcGIS. The total area of forest gain in 2001–2012 was only 0.07 km^2, whereas the total forest loss in 2000–2021 was 699.64 km^2, equivalent to the release of 9,802 kilotonnes of forest carbon[66]. Although FAO data show any overall extension of forest areas in the country since 1990, Global Forest Change data show that forest has been cleared with the expansion of agricultural and urban areas during that period (Figure 26). Areas of forest loss are widespread across the country, whereas larger-scale forest loss has occurred in the southern provinces (e.g., Bagmati Province (Figure 27). Table 37 shows the areas of forest loss (km^2) by year since 2000 (the baseline year of this dataset).

Table 37: Nepal—Areas of forest loss (km^2) 2001–2019)

Years	Area (km2)
No forest loss—total forest area	147,730
2001–2005	132.4
2006–2010	213.6
2011–2015	138.1
2016–2021	215.6
Total areas of forest loss (2001–2021)	699.6

Source: Calculated with the Global Forest Change dataset (Hanse et al. 2013)

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[66] Forest carbon stock is assumed 140.1 tonnes/ha (carbon in living biomass is 79.0 tonnes/ha, carbon in dead wood and litter is 3.3 tonnes/ha, and carbon in soil is 57.8 tonnes/ha) (FAO, 2020).

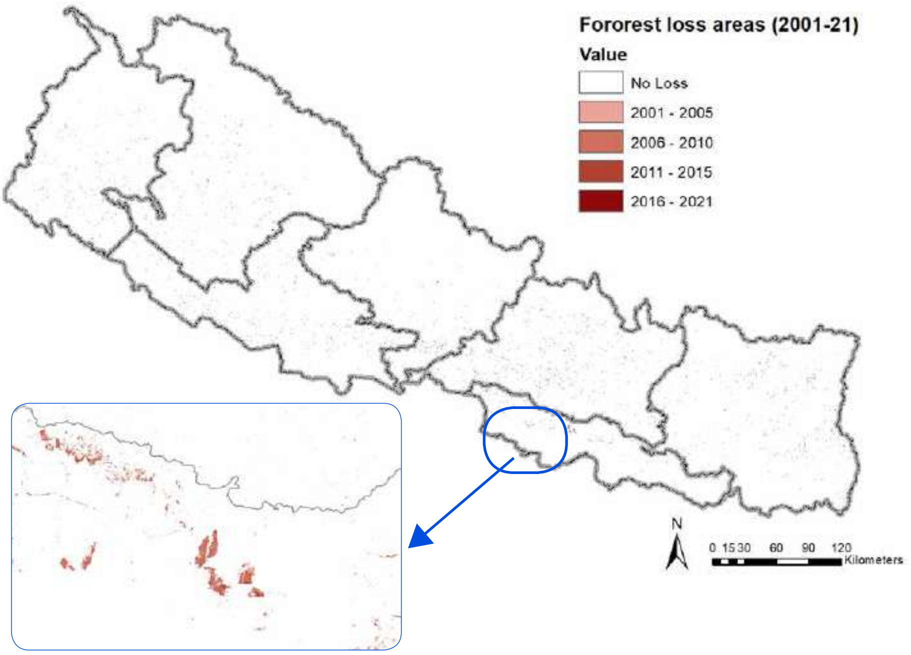

Figure 26: Areas of forest loss in Nepal 2001–2021)

Source: Global Forest Change

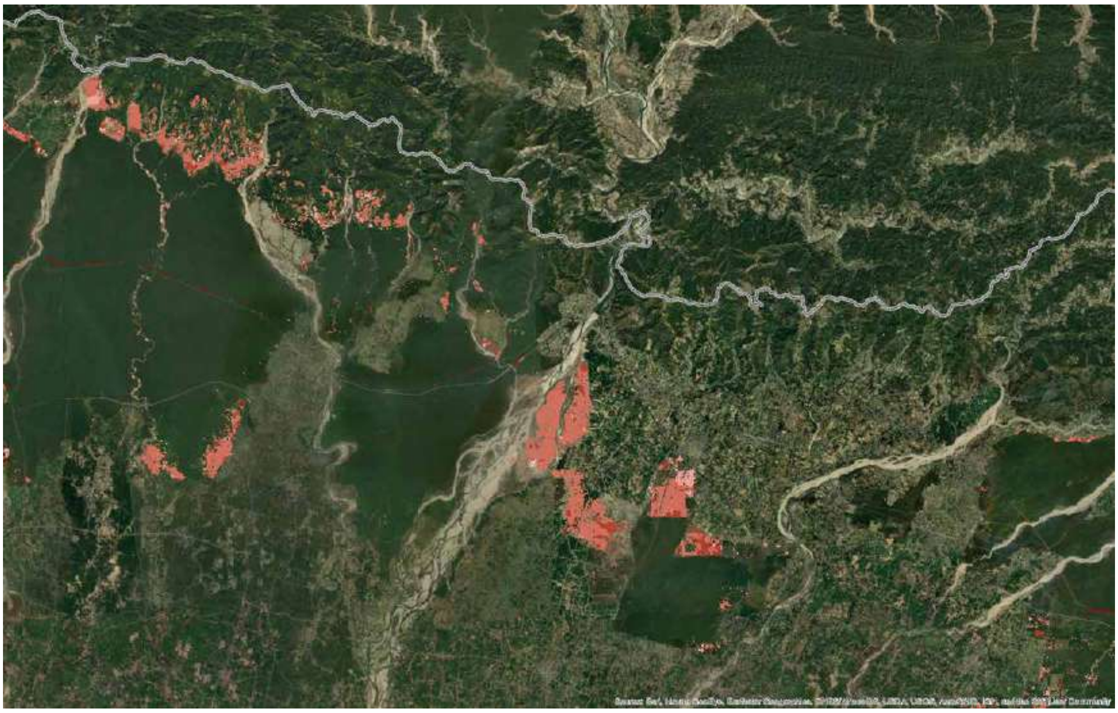

Figure 27: Example of areas of forest loss in Bagmati Province

6. Key Results: Long Term Scenario

Nepal must build up and expand its power generation system to increase the energy access rate to 100%. Building new power plants—no matter the technology—will require new infrastructure (including power grids), spatial planning, a stable policy framework, and access to finance.

With lower solar PV and onshore wind prices, renewables have become an economic alternative to building new hydro- and gas power plants. Consequently, renewables achieved a global market share of over 80% of all newly built power plants in 2021[67]. Nepal has significant solar resources, but only very limited wind potential. The costs of renewable energy generation are generally lower with stronger solar radiation and stronger wind speeds. However, constantly shifting policy frameworks often lead to high investment risks and higher project development and installation costs for solar and wind projects relative to those in countries with more stable policies.

The scenario-building process for all scenarios includes assumptions about policy stability, the role of future energy utilities, centralized fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that Nepal will establish a secure and stable framework for deploying renewable power generation. Financing a gas power plant or a wind farm is quite similar. In both cases, a power purchase agreement, which ensures a relatively stable price for a specific quantity of electricity, is required to finance the project. Daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions for any power plant with a technical lifetime of 20 years or longer.
- **Strengthened energy efficiency policies:** Existing policy settings, namely energy efficiency standards for electrical applications, buildings, and vehicles, must be strengthened to maximize the cost-efficient use of renewable energy and to achieve high energy productivity by 2030.
- **Role of future energy utilities:** With ‘grid parity’ of rooftop solar PV under most current retail tariffs, this modelling assumes that the energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** The three scenarios are based on the same population and GDP assumptions. Projections of population growth are taken from the *World Population Review*[68] whereas the GDP projection is taken from Nepal’s Second NDC[69], which assumes a long-term average growth rate of around 3% per year in 2020–2029 and 7.5% in 2030–2050, as documented in Chapter 3.
- **Firm capacity:** The scale of each technology deployed and the combination of technologies in the three scenarios target the firm capacity. Firm capacity is the “proportion of the maximum possible power that can reliably contribute towards meeting the peak power demand when needed[70].” Firm

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[67] REN21 – Global Status report 2021.

[68] World Population Review, online database, viewed August 2022, https://worldpopulationreview.com/countries/nepal-population

[69] NDC Nepal 2020; Government of Nepal, “Second Nationally Determined Contribution (SNDC),” Kathmandu, Nepal, 2020

[70] http://igrid.net.au/resources/downloads/project4/D-CODE_User_Manual.pdf

capacity is important to ensure a reliable and secure energy system. Note that variable renewable energy systems still have a firm capacity rating, and the combination of technology options increases the firm capacity of the portfolio of options (see also the 'security of energy supply' point in the REFERENCE scenarios).

- **Cost assumptions:** The same cost assumptions are used across all three scenarios. Because technology costs decline with the scale of deployment rather than with time, the reduction potential in renewable energy costs in both RENEWABLES scenarios may be larger than in the REFERENCE scenario due to larger market sizes. The reverse is true for the fuel cost assumptions because all three scenarios are based on low fossil fuel price projections. Whereas the WEM and the N-1.5 °C scenario have a significant drop in demand, the REFERENCE scenario assumes an increased demand, which may lead to higher fuel costs. Therefore, the costs should be considered conservative. The cost assumptions are documented in Chapter 3.


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A. Scenarios

I. The REFERENCE scenario

The REFERENCE scenario is taken from *Nepal's Long-term Strategy for Net-zero Emissions* (LTS-NZ 2021)[71], published by the government of Nepal in October 2021. The following paragraph is taken from the original document.

'The energy sector includes emissions from five economic sectors: residential, industrial, commercial transport, and agriculture. In the reference scenario, the major assumption is that the future trend will follow the current emissions trend. In this scenario, a GDP growth rate of 7% is assumed, and no technological interventions exist. Thus, the share of each demand technology remains the same in the future years. The non-energy sector includes agriculture, land use, land use change, forestry (LULUCF), waste, and IPPU sectors. In the agriculture and waste sectors, non-CO_2 greenhouse gases (i.e., methane and nitrous oxides) are the major sources of emissions. In agriculture, mitigation measures can be categorized into five emission sub-sectors: enteric fermentation, manure management, rice cultivation, biomass (Agri residue) burning, and soil management. The emissions in the waste sector are categorized into solid waste disposal, waste incineration and open burning, and wastewater treatment and discharge. In the industrial processes and product use (IPPU) sector, carbon dioxide is the major source of emissions attributed to the cement industry's calcination process. The emissions in LULUCF are assumed to follow the historical trend up to 2050. The LULUCF sector would remain as a net emitter in the reference scenario. The reference scenario assumes no technological intervention exists in the non-energy sub-sectors up to 2050. Scenarios with low (4.5%), medium (7%), and high (10.3%) economic growth rates were evaluated. The reference scenario was analysed at the medium economic growth rate.'

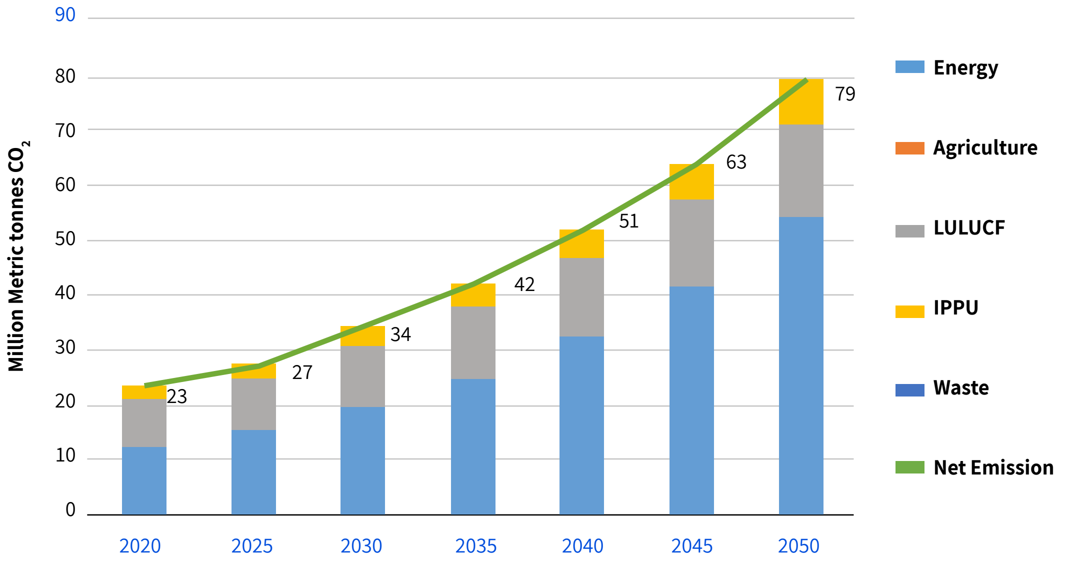

Figure 28: Carbon dioxide emissions in the REFERENCE scenario (LTS-NZ 2021)

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[71] (LTS-NZ 2021), Nepal's Long-term Strategy for Net-zero Emissions. Government of Nepal, Kathmandu, October 2021, https://unfccc.int/sites/default/files/resource/NepalLTLEDS.pdf

The information about the energy pathway behind the energy-related CO_2 emissions trajectory is not documented in detail. Therefore, the REFERENCE scenario results reported in this section are not identical to those of LTS-NZ 2021. With the measures described, the energy-related CO_2 emissions are unlikely to increase to just over 50 million tonnes by 2050, as indicated in the original graph (LTS-NZ 2021) in Figure 28. With the assumed GDP and population development, and the assumptions that the transport demand will almost quadruple and the overall primary energy demand will double, energy-related CO_2 emissions will triple to 36 million tonnes of CO_2 by 2050. Therefore, given the lack of data, the REFERENCE scenario is not identical to the one presented in LTS-NZ 2021.

II. The 'WEM' scenario

Like the REFERENCE scenario, the With the Existing Measures (WEM) scenario is taken from LTS-NZ 2021. The government document describes the WEM scenario as follows:

'The WEM scenario is estimated using the same methodology as the reference scenario but focusing on the intervention measures specified in the plans and policies implemented and adopted up to 2020. The year 2019 serves as the reference year in this scenario. It assumes the GDP growth rate to be the same as that of the reference scenario. The mitigation measures in the WEM sector were assumed for implementing low carbon technologies considered by the NDC 2020, the NPC's roadmap for achieving the SDGs by 2030, and other government plans and policies. Mitigations in the energy sector included electrification in major end-uses in all economic sectors, such as efficiency improvement and alternative clean fuel intervention in the industrial process heat, substituting traditional brick kilns with 100% Zigzag brick kilns and biomass fuel mix in the brick industry, fuel switching to modern fuels, electricity, LPG, and renewable energy technologies like solar, and biogas, and modal shift to mass electric mobility in the transport sector. Strategic action in the agriculture and waste sectors includes measures that reduce CO_2 and non-CO_2 greenhouse gases. The mitigation measures in the agriculture sector include biogas digester in manure management, improved water management in rice cultivation, and low- or no-tillage practices in soil management. In the waste sector, the mitigation options include implementing methane recovery, anaerobic digester, and waste incinerator. However, the WEM scenario assumes that the implementation level is low. In LULUCF, mitigation measures include a reduction in forest degradation and deforestation along with increased plantation and sustainable management of forests. There are no interventions in the IPPU sector in the WEM scenario.'

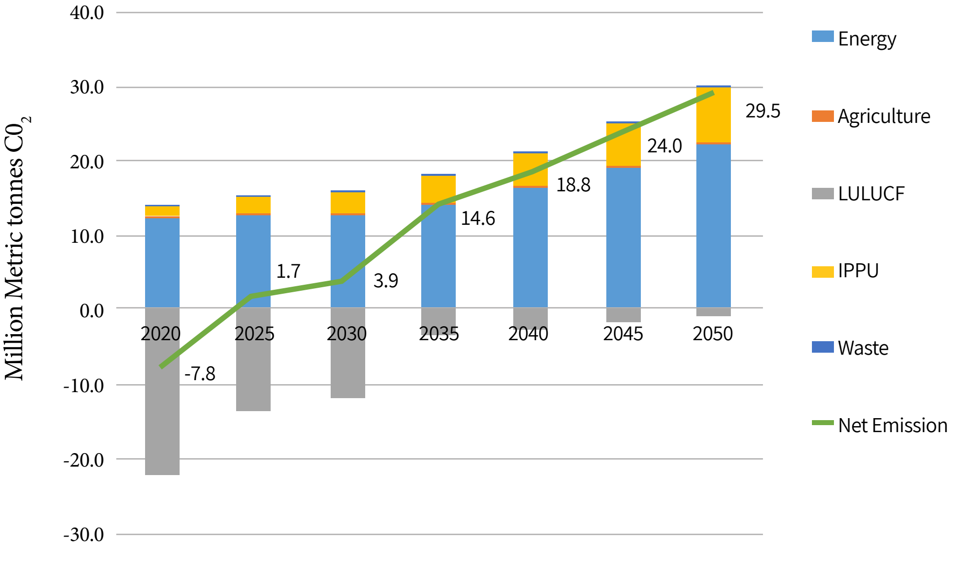

Figure 29: Carbon dioxide emissions in the WEM scenario (LTS-NZ 2021)

The WEM scenario presented in this section arrives at similar energy-related CO_2 emissions. Therefore, the N-1.5°C scenario, developed as an additional option for discussing the supply future of Nepal's energy, can be directly compared with the WEM scenario.

III. Assumptions for the Nepal 1.5 °c scenario

The Nepal 1.5 °C (N-1.5 °C) scenario is built on a framework of targets and assumptions that strongly influence the development of individual technological and structural pathways for each sector. The main assumptions considered in this scenario-building process are detailed below.

- **Emissions reductions:** The main measures taken to meet the CO_2 emissions reductions in the N-1.5 °C scenario include strong improvements in energy efficiency, which will double energy productivity over the next 10–15 years, and the dynamic expansion of renewable energy across all sectors.
- **Growth of renewables industry:** Dynamic growth in new capacities for renewable heat and power generation is assumed based on current knowledge of the potential, costs, and recent trends in renewable energy deployment. Communities will play a significant role in the expanded use of renewables, particularly in terms of project development, the inclusion of the local population, and the operation of regional and/or community-owned renewable power projects.
- **Fossil-fuel phase-out:** The operational lifetime of gas power plants is approximately 30 years. In both scenarios, coal power plants will be phased out early, followed by gas power plants.
- **Future power supply:** The capacity of large hydropower remains flat in Nepal over the entire scenario period, whereas the quantities of bio-energy will increase within the nation's potential for sustainable biomass (see below). Solar PV is expected to be the main pillar of the future power supply, complemented by the contributions of bio-energy and wind energy. The figures for solar PV combine rooftop and utility-scale PV plants, including floating solar plants.
- **Security of energy supply:** The scenarios limit the share of variable power generation and maintain a sufficient share of controllable, secured capacity. Power generation from biomass and gas-fired backup capacities and storage are considered important for the security of supply in a future energy system, and are related to the output of firm capacity discussed above. Storage technologies will increase after 2030, including battery electric systems, dispatchable hydropower, and hydro pump storage.
- **Sustainable biomass levels:** Nepal's sustainable level of biomass use is assumed to be limited to 425 PJ—precisely the amount of bio-energy used in 2020. However, low-tech biomass use, such as inefficient household wood burners, is largely replaced in the N-1.5 °C scenario by state-of-the-art technologies, primarily highly efficient heat pumps and solar collectors.
- **Electrification of transport:** Efficiency savings in the transport sector will result from fleet penetration by new highly efficient vehicles, such as electric vehicles, but also from assumed changes in mobility patterns and the implementation of efficiency measures for combustion engines. The scenarios assume the limited use of biofuels for transportation, given the limited supply of sustainable biofuels.
- **Hydrogen and synthetic fuels:** Hydrogen and synthetic fuels generated by electrolysis using renewable electricity will be introduced as a third renewable fuel in the transportation sector, complementing biofuels, the direct use of renewable electricity, and battery storage. Hydrogen generation can have high energy losses; but the limited potential of biofuels, and probably battery storage, for electric mobility means it will be necessary to have a third renewable option in the transport sector. Alternatively, this renewable hydrogen could be converted into synthetic methane and liquid fuels, depending on the economic benefits (storage costs versus additional losses) and the technological

and market development in the transport sector (combustion engines versus fuel cells). Because Nepal's hydrogen generation potential is limited, it is assumed that hydrogen and synthetic fuels will be imported. Furthermore, hydrogen utilization will be limited to the industry sector only, and is not expected to contribute more than 5% of industry's energy supply by 2050. Nepal, particularly Kathmandu University, has started R&D on green hydrogen, which it is believed will play a role in the future energy supply for transport and agriculture (KU 2022)[72].

Nepal's 1.5 °C scenario (N-1.5 °C) takes a more ambitious approach than the other scenarios to transforming Nepal's entire energy system to an accelerated new renewable energy supply. The consumption pathways remain similar to those of the WEM scenario. However, under the N-1.5 °C scenario, a much faster introduction of new technologies will lead to the complete decarbonization of energy for stationary energy (electricity), heating (including process heat for industry), and transportation. In the latter, there will be a strong role for storage technologies, such as batteries, synthetic fuels and hydrogen.

The resulting final energy demand for transportation is lower than that under the WEM scenario, based on the assumptions that:

- future vehicles and particularly electric vehicles, will be more efficient; and
- there will be a greater improvement in the public transport system in N-1.5 °C.

Under the N-1.5 °C scenario, the share of electric and fuel cell vehicles will increase. This scenario also relies on a greater production of synthetic fuels from renewable electricity, for use in the transport and industry sectors. Renewable hydrogen will be converted into synthetic hydrocarbons, which will replace the remaining fossil fuels, particularly in heavy-duty vehicles and air transportation—albeit with low overall efficiency typical of the synthetic fuel system. Because renewable synthetic fuels require a (gas) pipeline infrastructure, this technology is not widely used in Nepal's energy plan because the costs in the early development stages are relatively high. It is assumed that synthetic fuels and hydrogen will not enter Nepal's energy system before 2040. Compensating for the high energy losses associated with producing synthetic fuels will require fundamental infrastructure changes, which seem too costly for a developing country. Electricity and hydrogen will play larger roles in the heating sector (mainly heat for industry), replacing fossil fuels. In the power sector, natural gas will also be replaced by hydrogen. Therefore, electricity generation will increase significantly under this scenario, assuming that power from renewable energy sources will be the future's main 'primary energy'.

The N-1.5 °C scenario also models a shift in the heating sector towards the increased direct use of electricity because of the enormous and diverse potential for renewable power and the limited availability of renewable fuels for high-temperature process heat in industry. Increased implementation of a district heating infrastructure (interconnections of buildings in central business districts), bio-energy-based heat generation, and solar collectors and heat pumps for office buildings and shopping centres in larger cities are assumed, leading to a growth in electricity demand that partly offsets the efficiency savings in these sectors. A rapid expansion of solar and geothermal heating systems is also assumed.

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[72] KU (2022), Kathmandu University, https://iopscience.iop.org/article/10.1088/1755-1315/1037/1/012064/pdf and https://iopscience.iop.org/article/10.1088/1755-1315/1037/1/012061/pdf

The increasing shares of variable renewable power generation, principally by solar PV, will require the implementation of smart grids and the fast interconnection of micro- and mini-grids with regional distribution networks, storage technologies such as batteries and pumped hydro, and other load-balancing capacities. Other infrastructure requirements will include an increasing role for on-site renewable process heat generation for industries and mining, and the generation and distribution of synthetic fuels.

B. Energy pathway until 2050

The following section provides an overview of the key results of three different energy scenarios for Nepal. The energy scenarios by no means claim to predict the future; instead they provide useful tools to describe and compare potential development pathways from the broad range of possible ‘futures’. The N-1.5 °C scenario was designed to demonstrate the efforts and actions required to achieve the ambitious objective of a 100 per cent renewable energy system and to illustrate the options available to change our energy supply system into one that is truly sustainable. The scenarios may serve as a reliable basis for further analyses of possible concepts and actions needed to implement technical pathways to achieve measurable results.

I. Final energy demand

The projections for population development, GDP growth, and energy intensity are combined to project the future development pathways for Nepal’s final energy demand. These are shown in Figure 31 for the REFERENCE, WEM, and N-1.5 °C scenarios. In the REFERENCE scenario, the total final energy demand increases by 67% from 600 PJ/a to 1000 PJ/a in 2050. In the WEM scenario, the final energy demand will increase at a much lower rate (by 33%) compared with current consumption and is expected to reach 800 PJ/a by 2050. The N-1.5 °C scenario will reduce final energy demand further due to a higher proportion of electric cars.

As a result of the projected continued annual GDP growth of 5% on average until 2025 and 7.5% thereafter until 2050, the overall energy demand is expected to grow under all three scenarios (Figure 30). The residential sector will remain dominant in Nepal’s energy demand, but the energy demand of the industry sector will increase constantly. By 2050, industry will consume at least four times more energy than in 2020, making this sector the second highest consumer after transport in all three scenarios.

The energy demand of the transport sector will quadruple by 2050 under the REFERENCE scenario, whereas it will stabilize under WEM and the N-1.5 °C scenario. The main reason for the significant difference in growth projections is the high rates of electrification in the latter two pathways.

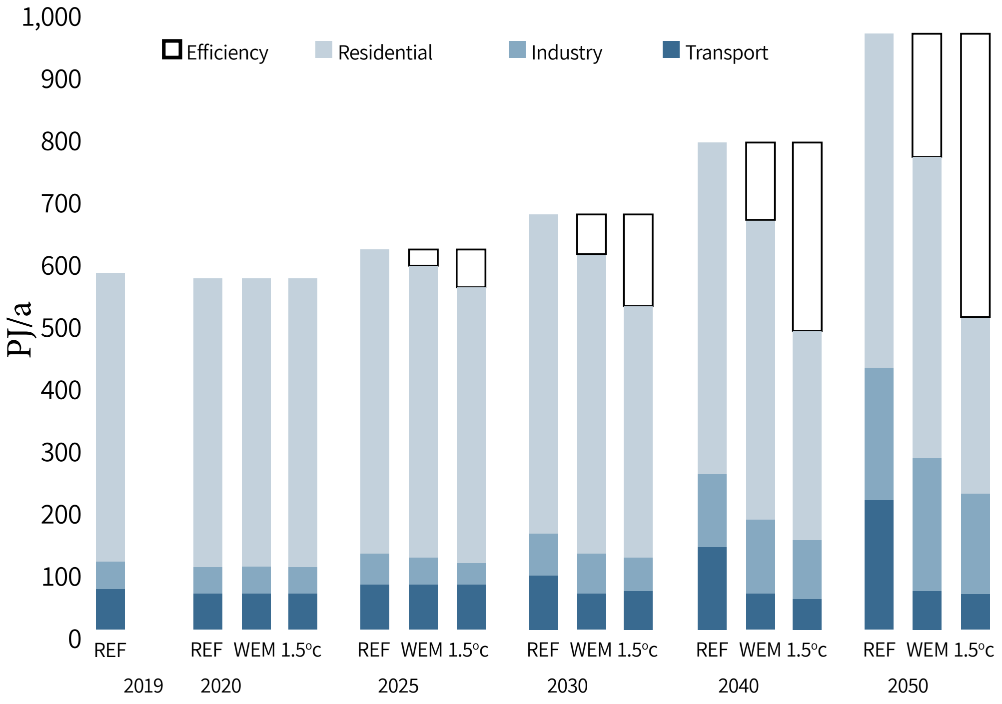

Figure 30: Projection of the total final energy demand by sector (excluding non-energy use and heat from CHP auto producers)

The large efficiency gains achieved in the N-1.5 °C pathway is attributable to the high electrification rates, mainly in the cooking and transport sectors, because combustion processes with high losses are significantly reduced.

The increased projected electrification of the heating, cooking, and transport sectors, especially under the N-1.5 °C scenario, will lead to a significantly increased electricity demand. Under the WEM scenario, the total electricity demand will increase from about 10 TWh/a to 60 TWh/a in 2050. Compared with the REFERENCE scenario, efficiency measures in the industry, residential, and service sectors will avoid the generation of about 4 TWh/a under WEM. However, increased electrification under the WEM scenario will be 10 TWh above that under the REFERENCE scenario.

The N-1.5 °C pathway will accelerate the electrification of the heating, cooking, and transport sectors compared with those of the WEM pathway, and aims to replace more fossil and biofuels with electricity. Therefore, the electricity demand will already be twice as high as under the REFERENCE scenario by 2030 (31 TWh/a). By 2050, Nepal's electricity demand will increase to 62 TWh per year, compared with 60 TWh under WEM and 50 TWh under the REFERENCE scenario.

Electricity will become the major renewable 'primary' energy, not only for direct use for various purposes, but also for the generation of a limited amount of synthetic fuels to substitute for fossil fuel in providing industrial process heat. Under N-1.5 °C, around 10 TWh will be used for electric vehicles and rail transport in 2050.

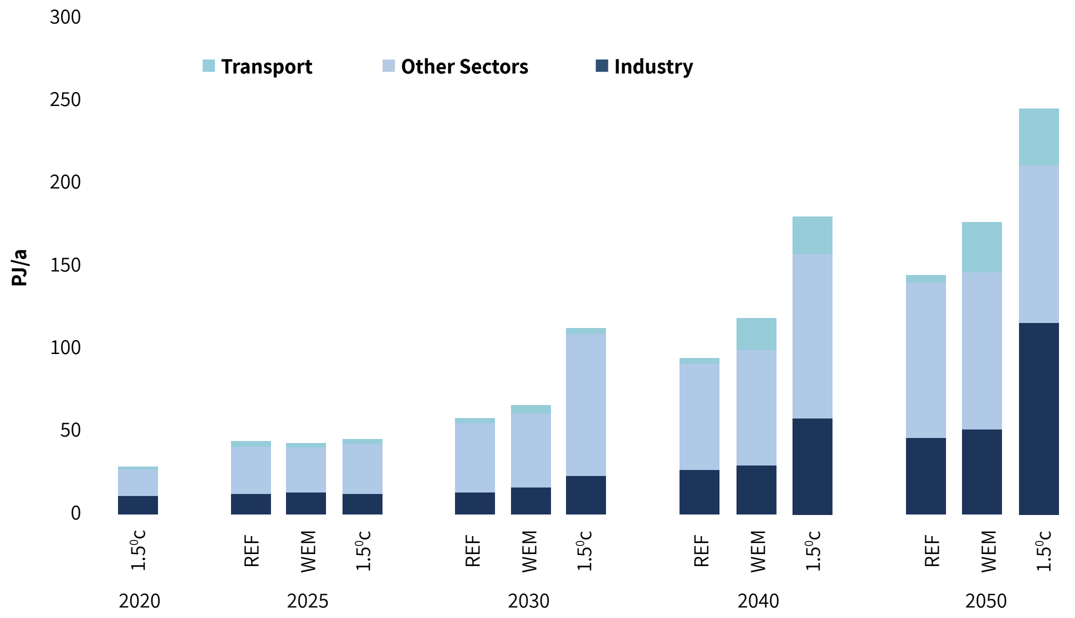

Figure 31: Development of electricity demand by sector under all three scenarios

The energy demand for process heat, space heating of residential and commercial buildings, and cooking will continue to grow under all three scenarios. The main driver will be a combination of population growth and the increased role of the industry sector in Nepal's GDP. The main differences between the REFERENCE and N-1.5C pathways are the increased role of electrification in the heating supply (with heat pumps) and the implementation of electric cooking.

As a result, the N-1.5 °C pathway will lead to an annual heat demand of around 350 PJ/a, whereas the REFERENCE and WEM scenarios will consume 550 PJ/a.

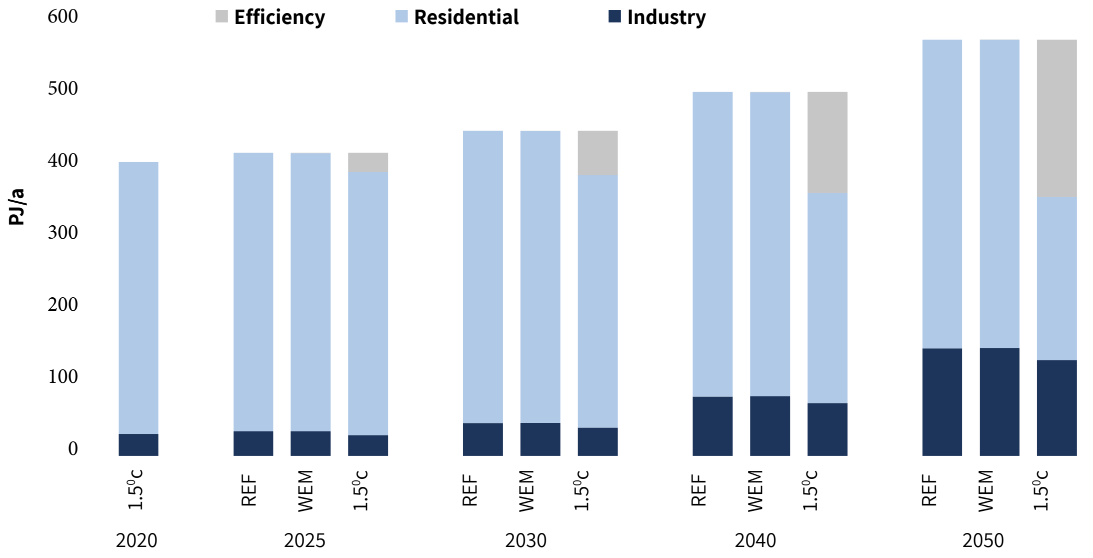

Figure 32: Development of the final energy demand for heat by sector in all three scenarios

The projected development of the road transport sector differs significantly between scenarios. Under the REFERENCE scenario, the kilometres travelled per person will increase by 4%–5% throughout the entire projection period until 2050. The energy demand projection of WEM suggests lower growth rates of around 3%–3.5% per year until 2025, and 2.5% thereafter. The N-1.5˚C pathway has similar growth rates to WEM until 2025, with slightly reduced annual growth until 2050, decreasing by around 3%–2.5% per year. However, the calculated energy demands based on the assumed transport vehicle fleet for both alternative (renewable) scenarios are within the same order of magnitude, and the road transport demand will stabilize at around 55 PJ per year. More details of the assumptions made for the transport sector projections, broken down into freight and passenger transport, are documented in Chapter 3 Section F.

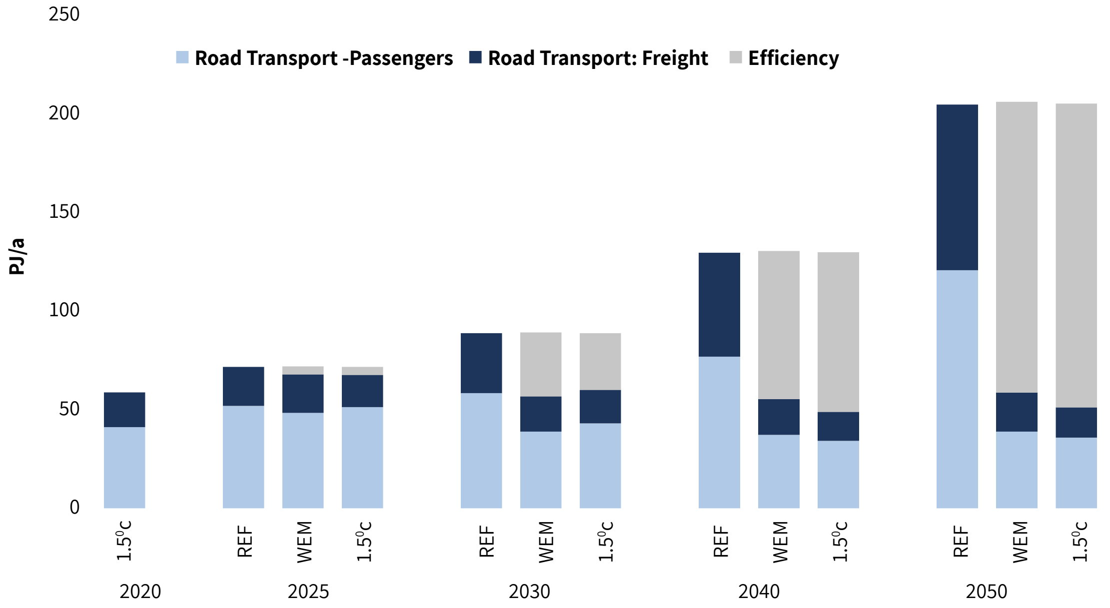

Figure 33: Development of the road transport energy demand for passengers and freight

II. Electricity generation

The development of the electricity supply sector is characterized by a dynamically growing renewable energy market and an increasing share of new renewable electricity, mainly from solar PV. The additional electricity demand caused by accelerated electric cooking and electric vehicles under the N-1.5 °C scenario will greatly benefit new renewables, whereas hydropower will continue to generate bulk electricity for industry and export.

By 2050, 100% of the electricity produced in Nepal will come from conventional and new renewable energy sources under the WEM scenario. 'New' renewables—mainly decentralized and utility-scale solar PV, but also a limited amount of wind power—will contribute 20% of the total electricity generation in 2040. By 2025, the share of new renewable electricity production will reach 6% and increase to 44% by 2050 under the N-1.5 °C scenario. The installed capacity of new renewables will reach about 3.5 GW in 2030 under all three scenarios and increase to 13.2 GW by 2050 under the REFERENCE scenario. Both the WEM and the N-1.5 °C scenarios will lead to higher capacities.

A 44% electricity supply from new renewable energy resources under the N-1.5 °C scenario will lead to around 35.4 GW of installed generation capacity in 2050, about twice the capacity achieved under WEM and 2.7 times higher than that achieved under the REFERENCE scenario.

Table 38 shows the comparative evolution of Nepal's power generation technologies over time. Hydro will remain the main power source. However, just after 2040, solar PV will overtake hydropower in installed capacity. After 2045, the continuing growth of solar PV and additional wind power capacities will lead to a total capacity of 25 GW, compared with 10 GW hydropower under the N-1.5 °C scenario. It will lead to a high share of variable power generation and demand-side management, and the management of electric vehicle charging and other storage capacities, such as stationary batteries and pumped hydropower. The development of smart grid management will be required from 2025 onwards to increase the power system's flexibility for grid integration, load balancing, and a secure supply of electricity.

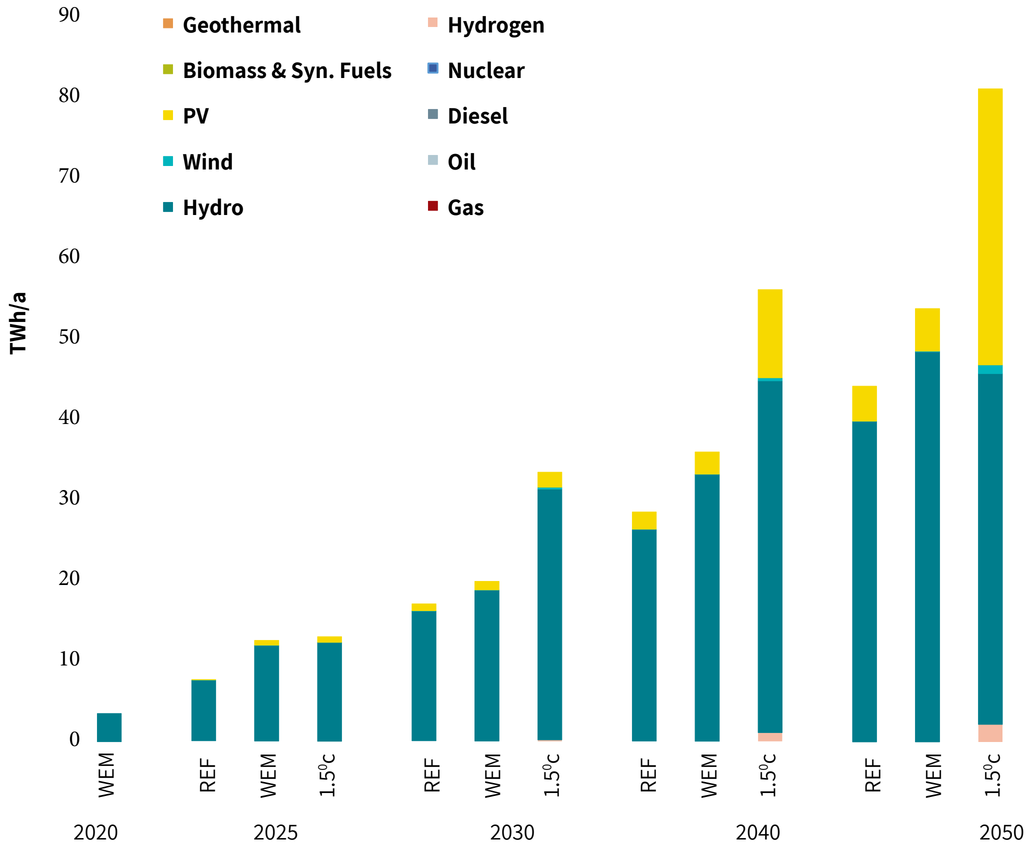

Figure 34: Breakdown of electricity generation by technology

Table 38: Projection of renewable electricity generation capacities

Generation Capacity [GW]		2020	2030	2035	2040	2050
Hydro	REF	1.755	2.790	3.676	5.993	9.071
	WEM	1.755	2.704	4.277	7.557	11.047
	N-1.5 °C	1.755	2.757	7.019	9.916	9.928
Biomass	REF	0.000	0.000	0.000	0.000	0.000
	WEM	0.000	0.000	0.000	0.000	0.000
	N-1.5 °C	0.000	0.000	0.000	0.000	0.000
Wind	REF	0.003	0.008	0.010	0.017	0.026
	WEM	0.003	0.008	0.012	0.021	0.032
	N-1.5 °C	0.003	0.005	0.145	0.145	0.383
PV	REF	0.317	0.634	0.878	2.146	4.356
	WEM	0.317	0.614	1.071	2.760	5.305
	N-1.5 °C	0.317	0.545	1.371	7.379	24.572
Total	**REF**	**2.072**	**3.432**	**4.564**	**8.156**	**13.453**
	WEM	**2.072**	**3.326**	**5.360**	**10.338**	**16.383**
	N-1.5°C	**2.072**	**3.308**	**8.536**	**17.441**	**34.884**

III. Energy supply for cooking and industrial process heat

Today, bio-energy meets around 86% of Nepal's energy demand for fuel-based cooking and heating. Dedicated support instruments are required to ensure dynamic development, particularly of electric cooking stoves, renewable heating technologies for buildings, and renewable process heat production. In the N-1.5 °C scenario, fuel-based cooking (mainly firewood and LPG) will be replaced by electric cooking stoves. The increased electricity used for e-cooking will increase the electricity demand but will replace a significant amount of bio-energy (firewood) because its efficiency is low. Under N-1.5 °C, the use of heat pumps as one of the leading new heating supply technologies will accelerate, and direct electric heating, such as radiators, will be introduced, but only as an interim measure between 2025 and 2030. These will be exchanged for heat pumps at the end of their lifetimes.

- Energy efficiency measures will help to reduce the currently growing energy demand for heating, especially building standards.
- In the industry sector, solar collectors, geothermal energy (including heat pumps), and electricity and hydrogen from renewable sources will increasingly substitute for fossil-fuel- and biofuel-fired systems.

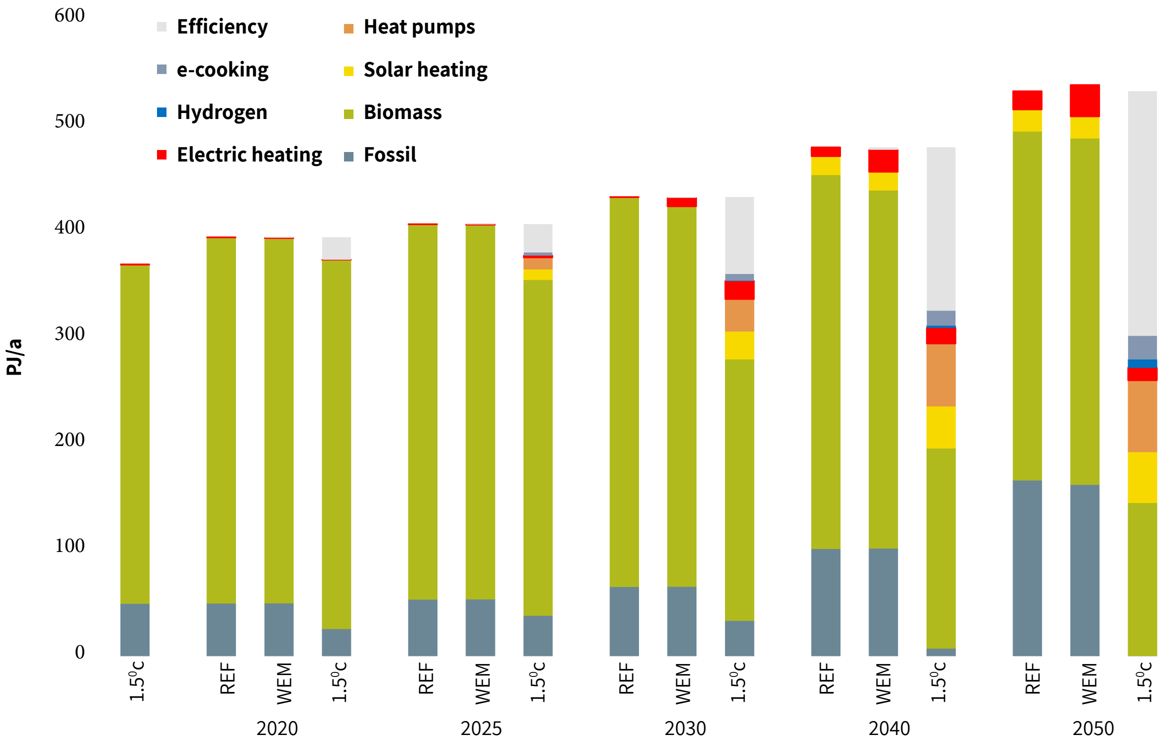

Figure 35: Projection of heat supply by energy carrier (REFERENCE, WEM, and N-1.5°C scenarios)

Table 39: Projection of renewable heat supply (cooking and process heat)

Supply (in PJ/a)		2019	2025	2030	2040	2050
Biomass	REF	344	352	366	351	327
	WEM	343	352	357	336	325
	N-1.5 °C	347	316	245	186	139
Solar Heating	REF	0	0	0	17	21
	WEM	0	0	0	17	21
	N-1.5 °C	0	10	26	39	48
Heat Pumps (electric & geothermal)	REF	0	0	0	0	0
	WEM	0	0	0	0	0
	N-1.5 °C	0	11	31	61	72
Direct Electric Heating	REF	0	0	0	9	17
	WEM	0	0	8	21	30
	N-1.5 °C	0	2	17	15	12
Total	**REF**	**344**	**353**	**366**	**377**	**365**
	WEM	**343**	**352**	**365**	**374**	**375**
	N-1.5 °C	**347**	**338**	**319**	**301**	**271**

Table 39 shows the development of different renewable technologies for heating in Nepal over time. Biomass will remain the main contributor, with increasing investments in highly efficient modern biomass technology. After 2030, a massive increase in solar collectors and growing proportions of geothermal and environmental heat, as well as electrical heat and some limited renewable hydrogen for industrial process heat, will compensate for the phase-out of fossil fuels. The N-1.5 °C scenario includes many efficient heat pumps, which can also be used for demand-side management and load flexibility (see also Section F ii).

Table 40: Installed capacities for renewable heat generation

Capacities (in GW)		2020	2025	2030	2040	2050
Biomass	REF	63	65	68	65	60
	WEM	63	65	66	62	60
	N-1.5 °C	63	58	45	33	24
Geothermal	REF	0	0	0	0	0
	WEM	0	0	0	0	0
	N-1.5 °C	0	1	2	3	3
Solar heating	REF	0	0	0	5	6
	WEM	0	0	0	5	6
	N-1.5 °C	0	3	8	12	15
Heat pumps (electric and geothermal)	REF	0	0	1	2	5
	WEM	0	0	1	2	2
	N-1.5 °C	0	1	8	10	10
Total	**REF**	**63**	**65**	**68**	**72**	**72**
	WEM	**63**	**65**	**67**	**69**	**69**
	N-1.5 °C	**63**	**64**	**62**	**58**	**52**

IV. Transport

A key target in Nepal is to introduce incentives for people to support the transition towards electric mobility, especially in urban and semi-urban regions. It is also vital that transport use shifts to efficient public transport modes, such as rail, light rail, and buses, especially in the large expanding metropolitan areas. Together with rising prices for fossil fuels, these changes will reduce the further growth in private vehicle sales projected under the REFERENCE scenario. With the increasing population, GDP growth, and higher living standards, the energy demand of the transport sector is expected to increase under the REFERENCE scenario by around 209%, to 210 PJ/a in 2050. Under the WEM scenario, efficiency measures and modal shifts will save 71% (150 PJ/a) in 2050 relative to the REFERENCE scenario.

Additional modal shifts and a technology switch to electric mobility will lead to even higher energy savings of 75% (150 PJ/a) in 2050 under the N-1.5 °C scenario relative to the REFERENCE scenario. Highly efficient propulsion technology, with plug-in hybrid and battery-electric power trains, will bring large efficiency gains. By 2030, electricity will provide 8% of the transport sector's total energy demand under the WEM scenario, whereas in 2050, the share will be 49% (61% under the N-1.5 °C scenario). The N-1.5 °C scenario will achieve the total decarbonization of the transport sector in Nepal by 2050. More details about the assumptions made to calculate the transport demand and supply development are documented in Section C.

Table 41: Projection of transport energy demands by mode

Transport mode		Unit	2020	2025	2030	2040	2050
Rail		[PJ/a]	0.01	0.01	0.01	0.01	0.01
	WEM	[PJ/a]	0.01	0.01	0.01	0.01	0.01
	N-1.5 °C	[PJ/a]	0.01	0.01	0.01	0.01	0.01
Road	REF	[PJ/a]	58.71	71.58	88.66	129.41	204.36
	WEM	[PJ/a]	58.15	67.75	56.61	55.23	58.56
	N-1.5 °C	[PJ/a]	59.19	67.52	59.99	48.83	51.13
Domestic Aviation	REF	[PJ/a]	0.55	0.66	0.78	1.15	1.77
	WEM	[PJ/a]	0.54	0.47	0.41	0.36	0.31
	N-1.5 °C	[PJ/a]	0.54	0.64	0.74	0.98	1.21
Total	**REF**	**[PJ/a]**	**59.27**	**72.25**	**89.44**	**130.57**	**206.15**
	WEM	**[PJ/a]**	**58.70**	**68.22**	**57.04**	**55.61**	**58.88**
	N-1.5 °C	**[PJ/a]**	**59.74**	**68.17**	**60.74**	**49.82**	**52.35**

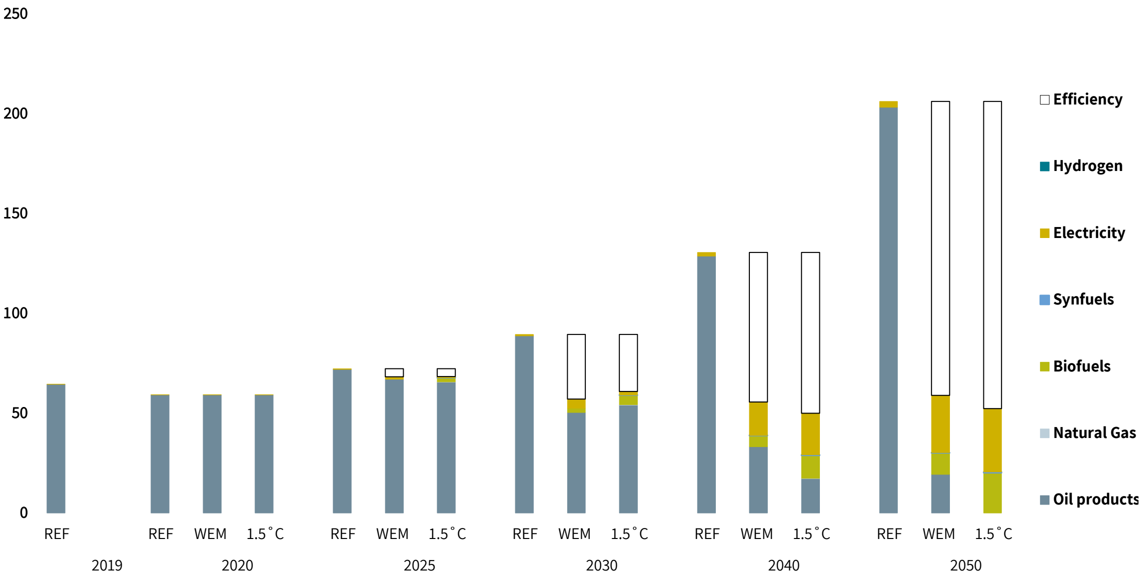

Figure 36: Final energy consumption by transport under the three calculated scenarios

V. Primary energy consumption

Based on the assumptions discussed above, the resulting primary energy consumption under the three documented pathways is shown in Figure 37. Under the WEM scenario, the primary energy demand will increase by 79% from today’s 560 PJ/a to around 1000 PJ/a in 2050. Compared with the REFERENCE scenario, the overall primary energy demand will be reduced by 41% in 2050 under the WEM scenario. The N-1.5 °C scenario will result in primary energy consumption of around 500 PJ in 2050, 49% less than under the REFERENCE scenario.

The N-1.5 °C scenario aims to phase-out oil in the transport sector and oil for industrial use as fast as is technically and economically possible, through the expansion of renewable energies. The fast introduction of very efficient vehicle concepts in the road transport sector will replace oil-based combustion engines. This will lead to an overall renewable primary energy share of 82% in 2030 and 73% in 2050 under the WEM scenario and of more than 73% in 2050 under the N-1.5 °C scenario (including non-energy consumption).

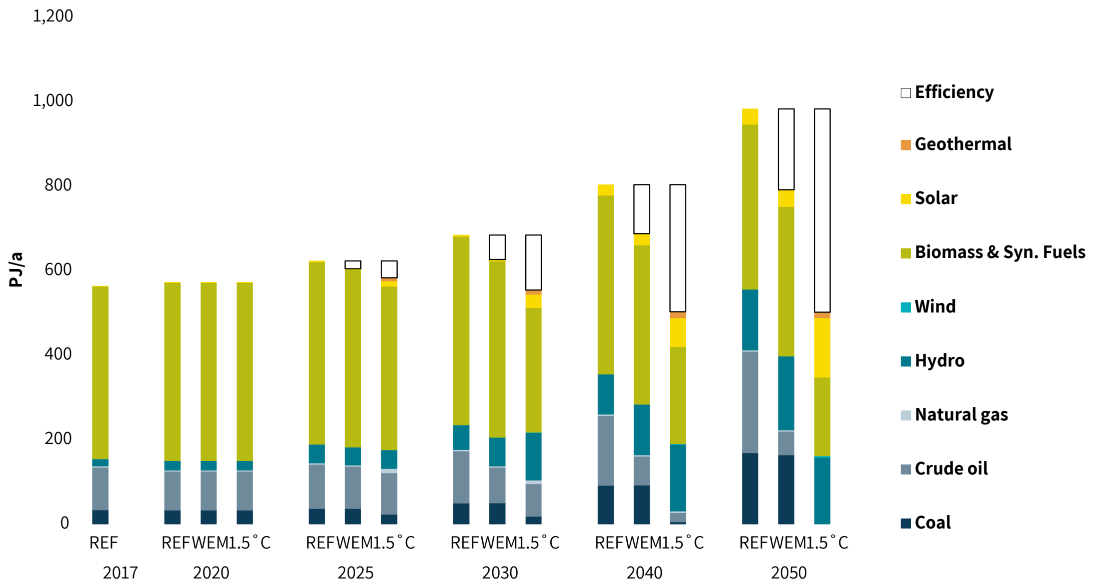

Figure 37: Projection of total primary energy demand by energy carrier (including electricity import balance)

VI. CO_2 emissions trajectories

Under the REFERENCE scenario, Nepal's annual energy-related CO_2 emissions will increase from 12.9 million tonnes in 2018 to 15 million tonnes in 2030 and 36 million tonnes in 2050. In comparison, the WEM scenario will stabilizes the energy-related CO_2 emissions until 2035 and limit the increase to 20 million tonnes in 2050. Most of the increased CO_2 emissions in the REFERENCE and WEM scenarios will be based on the increased use of coal for industrial processes. Furthermore, the significant increase in the oil demand projected in the REFERENCE scenario will add more energy-related CO_2 emissions until 2050 than the total energy emissions from Nepal in 2019. The WEM scenario already addresses this by reducing the demand and increasing the electrification of the transport sector.

The N-1.5 °C scenario will reverse the trend of increasing energy-related CO_2 emissions after 2025, leading to a reduction of about 20% relative to 2020 by 2030 and of about 50% by 2040. In 2050, full decarbonization of Nepal's energy sector will be achieved under the N-1.5 °C scenario. Under the REFERENCE scenario, the cumulative CO_2 emissions from 2020 until 2050 will sum to 0.6 Gt. In contrast, under the WEM and N-1.5 °C scenarios, the cumulative emissions will sum to 0.4 Gt and 0.2 Gt, respectively.

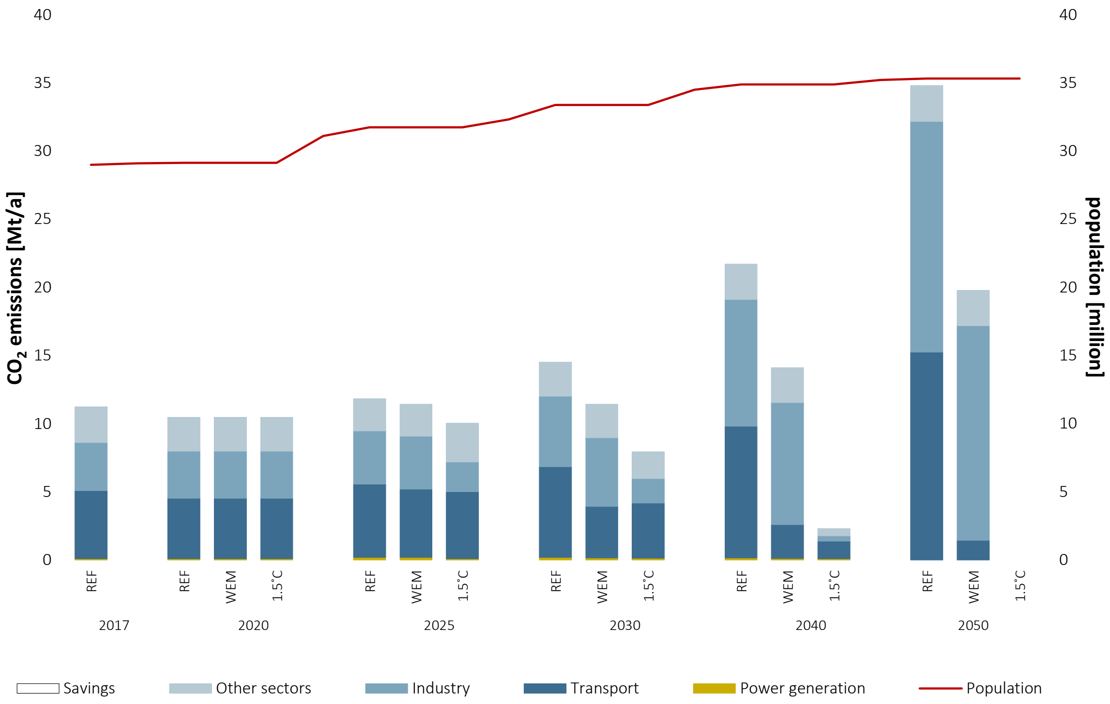

Figure 38: Development of CO_2 emissions by sector under the three scenarios (‘efficiency’ = reduction relative to the REFERENCE scenario)

VII. Cost analysis

Future costs of electricity generation

Figure 39 shows that introducing new-generation capacities will increase the average electricity generation due to new investments, and consequently, additional capital costs will be required under all three scenarios. Under the REFERENCE and WEM scenarios, new electricity capacities will be built, primarily based on hydropower, with solar PV complementing the generation mix.

The N-1.5 °C pathway will increase hydropower to around 10 GW by 2050—between the projected capacities for the REREFENCE (9 GW) and WEM scenarios (11 GW). The additional hydropower capacity will include decentralized mini and micro hydropower plants, which are excellent for powering remote areas in Nepal. However, the solar PV capacity will increase five-fold under the N-1.5 °C scenario relative to those under the other two scenarios. The reason for the significantly higher generation capacity is the far-reaching electrification strategy to replace fossil fuel with electricity for cooking, heating, and transport.

In comparison to the two government scenarios, the N-1.5 °C will lead to around 10% higher electricity generation costs for the first 7 to 10 years before cost advantages will be reached due to accelerated investment in renewable electricity: The difference in the full cost of generation relative to the REFERENCE scenario by 2030 will be around 208 NPR/kWh (US$1.6 cent/kWh) under the WEM scenario and about 546 NPR/kWh (US$4.2 cent/kWh) under the N-1.5 °C scenario, when no consideration is given to the integration costs for storage or other load-balancing measures. However, the higher average generation costs under the N-1.5 °C scenario will only be temporary and are expected to fall rapidly around 2035, leading to lower generation around 2040 than under both other scenarios. By 2050, the N-1.5 °C scenario will lead to average electricity generation costs of 208 NPR/kWh (1.6 US$ cent/kWh) below those under the REFERENCE scenario and 143 NPR/kWh (US$1.1. cent/kWh) below those under WEM. The reason for the cost peaks under the WEM and N-1.5 °C scenarios is the higher investment in solar PV and increased electrification, which require additional power generation capacities. However, those investments will be regained later through fuel cost savings.

Nepal's total electricity supply costs will increase with the increasing electricity demand across all three scenarios. The N-1.5 °C pathway has the highest total electricity costs, but these will directly replace bio-energy and oil fuel costs.

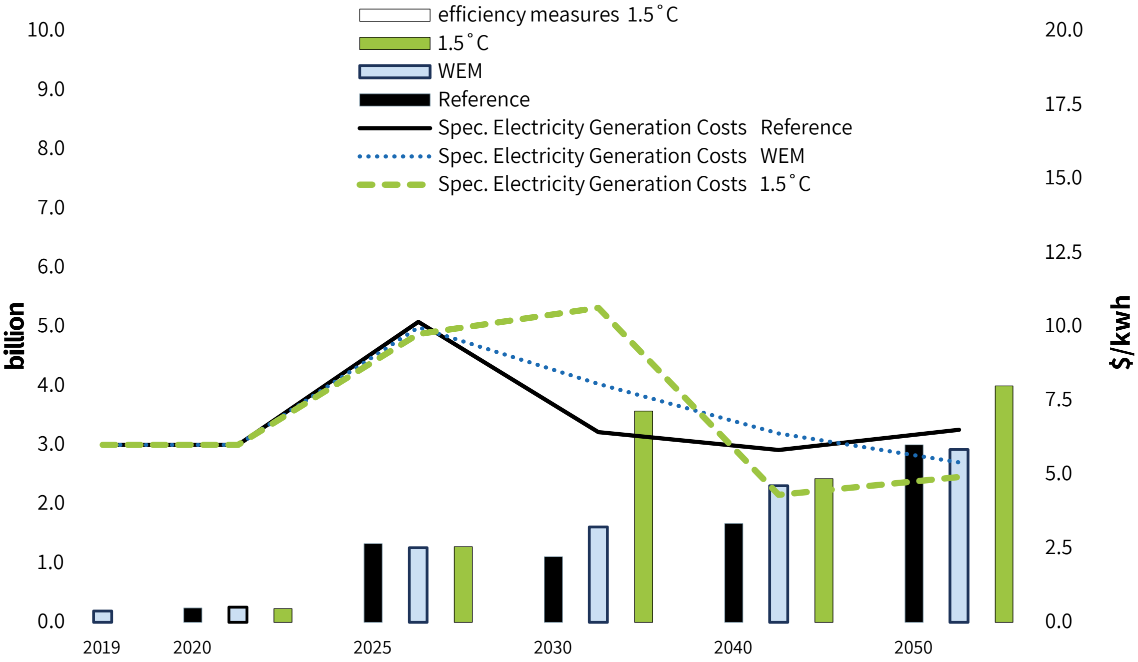

Figure 39: Development of total electricity supply costs and specific electricity generation costs in the scenarios

Investments in power generation

Nepal will invest in new power generation—mainly hydropower (including decentralized mini- and micro-hydro)—over the next decades under all three scenarios. The main difference between the N-1.5˚C scenario and the REFERENCE and WEM scenarios is the investment in other technologies—primarily solar PV. The wind potential of Nepal is very limited because the average wind speeds are low around the urban areas and the geographic situation in rural areas is not suitable, with high mountains, steep slopes, and remote villages with limited or no road access, which are also often not connected to Nepal's power grid network. The electrification of remote villages under the N-1.5 °C pathway is mainly based on solar PV power mini-grids with (battery) storage systems. However, wind energy systems can and should play a role in some limited locations. The generation pattern is different from that of solar and will therefore reduce the energy storage requirements because electricity generation is distributed throughout the day and is not limited to daylight hours.

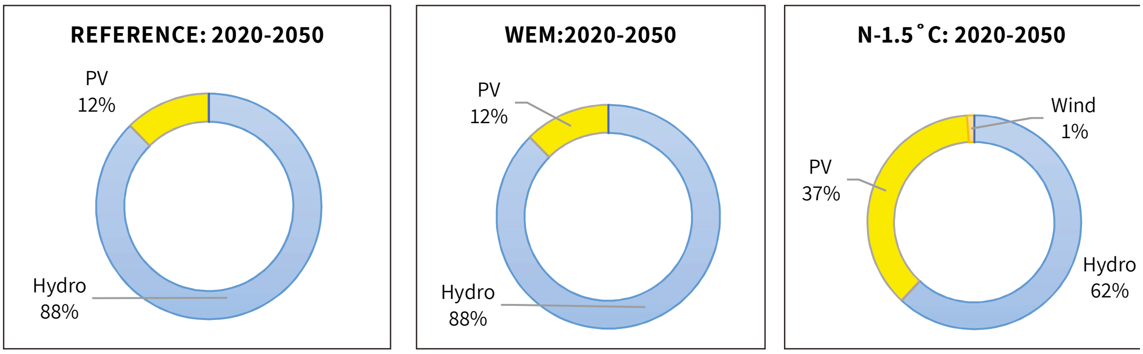

Figure 40: Shares of cumulative investment in power generation under the WEM, N-1.5°C, and REFERENCE scenarios

The additional investment in solar PV under the N-1.5 °C scenario will amount to around 1.5 trillion NPR (US$10 billion) over 30 years. Compared with the WEM scenario, the additional electricity generated with solar PV will be 1 billion kWh (1 TWh/a) by 2030 and 29 billion kWh/a (29 TWh/a) by 2050. This electricity will primarily be used to replace biomass for cooking and heating and to charge various electric vehicles, from two- and three-wheeler vehicles to cars and small delivery trucks.

Table 42: Investment costs in new power generation under the REFERENCE, WEM, and N-1.5 °C scenarios (exchange rate: US$1 = 130 NPR, 1st October 2022)

REFERENCE	**2020–2050**	
	[trillion NPR]	**[billion US$]**
Hydro	2.88	22.17
Biomass	0.00	0.00
PV	0.40	3.10
Wind	0.00	0.00
Fossil & other	0.00	0.00
Total	**3.29**	**25.27**

WEM	**2020–2050**	
	[trillion NPR]	**[billion US$]**
Hydro	3.48	26.74
Biomass	0.00	0.00
PV	0.49	3.79
Wind	0.00	0.00
Fossil & other	0.00	0.00
Total	**3.97**	**30.53**

1.5˚C	**2020-–050**	
	[trillion NPR]	**[billion US$]**
Hydro	3.09	23.75
Biomass	0.00	0.00
PV	1.85	14.19
Wind	0.05	0.41
Fossil & other	0.00	0.00
Total	**4.99**	**38.36**

Future investments in the heating sector

The main difference between the N-1.5 °C pathway and the REFERENCE and WEM pathways is the significant reduction in bio-energy use and the diversification of heating technologies. Electrical heat pumps, geothermal heat pumps, and solar thermal applications for space and water heating and drying will lead to a considerable reduction in the use of biogas and solid biomass, and therefore reduce the fuel costs. Figure 41 shows the shares of cumulative investments in the heating sector between 2020 and 2050 in the three scenarios.

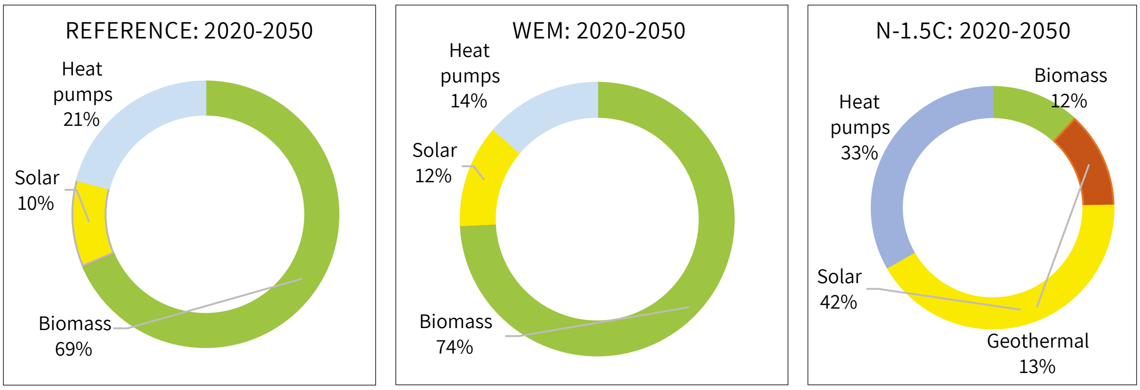

Figure 41: Cumulative investment in the heating technologies (generation) under the WEM, N-1.5 °C, and REFERENCE scenarios

Table 43 shows the cumulative investment and fuel costs in the heating sector under the three scenarios and the resulting overall cost for each pathway. Whereas the investment costs under the N-1.5 °C will be 47% higher than under the REFERENCE scenario, the fuel costs will be 57% lower. The overall heat sector costs—investment and fuel costs—over the entire scenario period until 2050 will be 2.3 trillion Nepalese Rupees lower under the N-1.5 °C scenario than under the REFERENCE scenario and 1.1 trillion Nepalese Rupees lower than under the WEM scenario.

Table 43: Nepal—heating: cumulative investment and fuel costs in 2020–2050 under the three scenarios

	Reference		Wem		N-1.5 °C	
	[trillion NPR]	[billion US$]	[trillion NPR]	[billion US$]	[trillion NPR]	[billion US$]
Cumulative investment: 2020–2050	3.7	28.3	3.2	24.5	5.4	41.6
Cumulative fuel costs: 2020–2050	9.2	70.9	8.6	65.8	5.2	40.2
Total cumulative costs: 2020–2050	**12.9**	**99.2**	**11.7**	**90.4**	**10.6**	**81.8**

VIII. Investment and fuel cost savings

Finally, the fuel costs of all three scenarios in the power, heating and transport sectors are compared.

The REFERENCE scenario has the highest fuel costs of all the scenarios, mainly due to the high reliance on biomass for heating and cooking, and on oil for the transport sector. All three sectors have very low fuel costs for the power sector because generation is based on hydro and solar power—the remaining fuel costs are for diesel generators. Increased electrification will lead to higher investment costs in power generation and higher overall electricity supply costs for Nepal. Under the most ambitious electrification strategy of the N-1.5 °C pathway, investment will be 1.7 trillion RS (US$13 billion) higher over the 30 years until 2050 than under the REFERENCE pathway.

Fuel cost savings in the heating sector until 2040 alone will be able to re-finance the additional investments in power generation. Table 44 shows all the accumulated fuel costs by sector and scenario and the calculated fuel cost savings in 10-year intervals between 2020 and 2050 in Nepalese rupees; Table 45 shows them in US dollars. Additional power generation investments will be compensated by fuel costs savings in the decade that they are made. Across the entire scenario period, fuel cost savings under the N-1.5 °C scenario will be 6.47 trillion Nepalese rupees (US$51.8 billion), more than three times higher than the additional investment in power generation until 2050. Whereas fuel cost predictions are subject to a great deal of uncertainty, the distinct result makes the cost-effectiveness of electrification very clear.

Table 44: Accumulated fuel costs for heat generation under the REFERENCE, WEM, and N-1.5 °C scenarios in Nepalese rupees (NPR)

REFERENCE: Accumulated fuel costs

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	Total	trillion NPR/a	35	3	28	11	74	2
Heat	Total	trillion NPR/a	2,933	293	2,983	2,947	8,863	295
Transport	Total	trillion NPR/a	1,010	101	1,347	1,711	4,068	136
	Summed Fuel Costs	**trillion NPR/a**	**3,978**	**397**	**4,358**	**4,669**	**13,005**	**433**

WEM: Accumulated fuel costs

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	Total	trillion NPR/a	32	3	21	8	60	2
Heat	Total	trillion NPR/a	2,839	284	2,751	2,637	8,227	274
Transport	Total	trillion NPR/a	826	83	566	336	1,728	58
	Summed Fuel Costs	**trillion NPR/a**	**3,697**	**370**	**3,338**	**2,981**	**10,015**	**334**

N-1.5 °C: Accumulated fuel costs

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	Total	trillion NPR/a	26	3	16	1	44	1
Heat	Total	trillion NPR/a	2,415	242	1,477	1,130	5,023	167
Transport	Total	trillion NPR/a	871	87	462	263	1,596	53
	Summed Fuel Costs	**trillion NPR/a**	**3,312**	**332**	**1,955**	**1,394**	**6,663**	**221**

Fuel Cost Savings by Sector

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	REF vs WEM	trillion NPR/a	3	0	7	3	14	0
	REF vs N-1.5 °C	trillion NPR/a	8	1	12	10	30	1
Heat	REF vs WEM	trillion NPR/a	94	9	232	310	636	21
	REF vs N-1.5 °C	trillion NPR/a	518	52	1,506	1,817	3,840	128
Transport	REF vs WEM	trillion NPR/a	184	18	781	1,375	2,340	78
	REF vs N-1.5 °C	trillion NPR/a	139	14	885	1,448	2,472	82
Summed Fuel Cost Savings	**REF vs WEM**	**trillion NPR/a**	**281**	**27**	**1020**	**1688**	**2990**	**99**
	REF vs N-1.5 °C	**trillion NPR/a**	**665**	**67**	**2403**	**3275**	**6342**	**211**

Table 45: Accumulated fuel costs for heat generation under the REFERENCE, WEM, and N-1.5 °C scenarios in US dollars (US$)

REFERENCE: Accumulated fuel costs

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	Total	billion $/a	0.28	0.03	0.22	0.09	0.59	0.02
Heat	Total	billion $/a	23.46	2.35	23.87	23.57	70.91	2.36
Transport	Total	billion $/a	8.08	0.81	10.78	13.69	32.54	1.08
	Summed Fuel Costs	**billion $/a**	31.82	3.19	34.87	37.35	104.04	3.46

WEM: Accumulated fuel costs

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	Total	billion $/a	0.25	0.03	0.16	0.06	0.48	0.02
Heat	Total	billion $/a	22.71	2.27	22.01	21.10	65.82	2.19
Transport	Total	billion $/a	6.61	0.66	4.53	2.69	13.82	0.46
	Summed Fuel Costs	**billion $/a**	**29.57**	**2.96**	**26.70**	**23.85**	**80.12**	**2.67**

N-1.5 °C: Accumulated fuel costs

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	Total	billion $/a	0.21	0.02	0.13	0.01	0.35	0.01
Heat	Total	billion $/a	19.32	1.93	11.82	9.04	40.18	1.34
Transport	Total	billion $/a	6.96	0.70	3.69	2.11	12.77	0.43
	Summed Fuel Costs	**billion $/a**	**26.49**	**2.65**	**15.64**	**11.16**	**53.3**	**1.78**

Fuel Cost Savings by Sector

			2021–2030	2021–2030 average per year	2031–2040	2041–2050	2021–2050	2020–2050 average per year
Power	REF vs WEM	billion $/a	0.02	0.00	0.06	0.03	0.11	0.004
	REF vs N-1.5 °C	billion $/a	0.07	0.01	0.09	0.08	0.24	0.008
Heat	REF vs WEM	billion $/a	0.75	0.08	1.86	2.48	5.09	0.170
	REF vs N-1.5 °C	billion $/a	4.14	0.41	12.05	14.53	30.72	1.024
Transport	REF vs WEM	billion $/a	1.47	0.15	6.25	11.00	18.72	0.624
	REF vs N-1.5 °C	billion $/a	1.11	0.11	7.08	11.58	19.78	0.659
Summed Fuel Cost Savings	**REF vs WEM**	**billion $/a**	**2.24**	**0.23**	**8.17**	**13.51**	**23.92**	**0.79**
	REF vs N-1.5 °C	**billion $/a**	**5.32**	**0.53**	**19.22**	**26.19**	**50.74**	**1.69**

7. Nepal: Power Sector Analysis

In this chapter, we summarize the results of the hourly simulations of the long-term scenarios (Chapter 6). The One Earth Climate Model (OECM) calculates the demand and supply by cluster. Because of its geographic position, the electricity market in Nepal includes large shares of electricity imported from and exported to India, predominantly from hydropower plants. The *Electricity Grid Modernization Project enjoys* high priority in Nepal. The Asian Development Bank, for example, supports the financial investment in electricity grid modernization in both the transmission and distribution systems in Nepal, under the following outputs (ADB 2020)[73] :

A. Electricity transmission capacity in project areas will be strengthened and modernized. The project will finance:
    - the automation of 40 grid sub-stations throughout the country;
    - the construction of units of modern 132/11 kV grid sub-stations with automation (each with 2 × 45 megavolt ampere [MVA] capacity) together with 16 km of 132 kV double-circuit underground transmission line along Chobhar–Lagankhel–Sinamangal, and 5 km of 66 kV double-circuit underground transmission line along Sinamangal–Chabahil in the Kathmandu Valley;
    - the upgrading 237 km of 132 kV transmission lines with more-efficient high-temperature low-sag conductors; and
    - the commissioning of a transmission system consisting of four automated grid sub-stations with a capacity of 290 MVA and 48 km of transmission lines in the Myagdi and Dhading districts.

B. The electricity distribution system in project areas will be modernized. This will include:
    - the construction of a distribution control centre in Kathmandu;
    - the installation of 350,000 additional smart meters in Kathmandu Valley;
    - the construction of eight sub-stations with automation, and the reinforcement and extension of the distribution system in Dhading, Dharan, Morang, Nepalgunj, Parasi, Sindhupalchowk, and Surkhet; and
    - the new connection of 150,000 households to the national grid.

C. The capacity of the Nepal Electricity Authority (NEA) and electricity users in the project areas will be increased. Considering the importance of continued support to NEA and users, the project will support increasing the knowledge of:
    - at least 40 eligible NEA staff (including 30% eligible women) about the automation of grid sub-stations;
    - at least 30 eligible NEA staff (including 30% women) about NEA’s organizational development;
    - at least 20 eligible NEA staff (including 30% women) about putting in place improved billing and collection measures; and
    - at least 2,000 electricity consumers in project areas (40% women and disadvantaged groups) about the safe and efficient energy use at distribution centres. The project will also support the implementation of key actions of NEA's gender equity and social inclusion (GESI) strategy and operational guidelines in its regional offices, to complement the corporate-level activities covered under a forthcoming project.
    - These outputs will result in improved access to an efficient grid electricity supply in Nepal.

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[73] ADB (2020), Asian Development Bank, Nepal: Electricity Grid Modernization Project Sovereign Project | 54107-001, 3rd June 2020, online, assessed October 2022; https://www.adb.org/projects/54107-001/main

This section provides an overview of the possible increase in electrical load under the N-1.5 °C scenario, and the consequent increased demand on the power grid transmission capacities, possible new inter-provincial connections, and/or expanded energy storage facilities.

A. Power sector analysis—Methodology

After the socio-economic (Chapter 3) and geographic analyses (Chapter 4) and the development of the long-term energy pathways for Nepal (Chapter 6), the power sector was analysed with the OECM in a third step.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, will allow a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services, which would be the next step in a power sector analysis.


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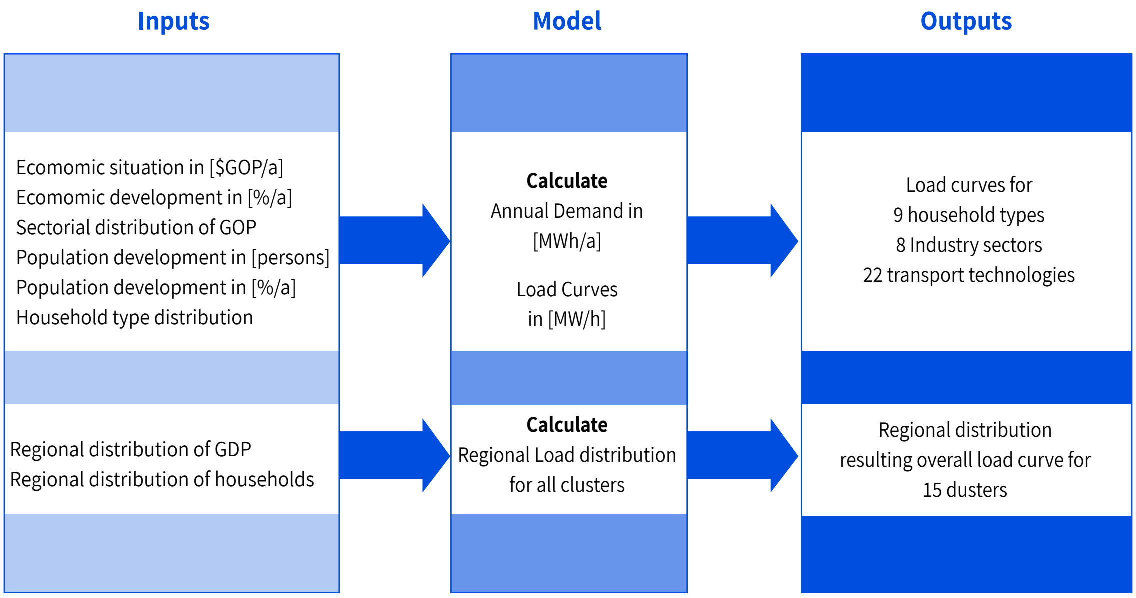

Figure 42: Overview—Energy demand and load curve calculation module

I. Meteorological data

Variable power generation technologies are dependent on the local solar radiation and wind regime. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database *renewable.ninja* (RE-N DB 2018)[74], which allows the hourly power output from wind and solar power plants at specific geographic positions throughout the world to be simulated. Weather data, such as temperature, precipitation, and snowfall, for the year 2019 were also available. To utilize climatization technologies for buildings (air-conditioning, electric heating), the demand curves for households and services were connected to the cluster-specific temperature time series. The demand for lighting was connected to the solar time series to accommodate the variability in the lighting demand across the year, especially in northern and southern global regions, which have significantly longer daylight periods in summer and very short daylight periods in winter.

For every region included in the model, hourly output traces are utilized for onshore wind, utility solar, and roof-top solar PV. Given the number of clusters, the geographic extent of the study, and the uncertainty associated with the prediction of the spatial distribution of future-generation systems, a representative site was selected for each of the five generation types.

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74. RE-N DB (2018) Renewables.ninja, online database of hourly time series of solar and wind data for a specific geographic position, data viewed and downloaded between September and October 2022, https://www.renewables.ninja/
Pfenninger, S, Staffell, I. (2016a), Pfenninger, Stefan and Staffell, Iain (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251–1265. doi: 10.1016/j.energy.2016.08.060

Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected from the database of Stefan Pfenninger (at ETH Zurich) and Iain Staffell (renewable.ninja; see above). The model methodology used by the renewable.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[75], and is based on weather data from global re-analysis models and satellite observations (Rienecker and Suarez 2011[76]; Müller and Pfeifroth, 2015[77]). It is assumed that the utility-scale solar sites will be optimized, so the tilt angle was selected within a couple of degrees of the latitude of the representative site. For the roof-top solar calculations, this was left at the default of 35° because it is likely that the panels will match the tilt of the roof.

The onshore wind outputs were calculated at an 80 m hub height because this reflects the wind datasets used in the mapping. Although onshore winds are likely to be higher than this, 80 m was considered a reasonable approximation and made our model consistent with the mapping-based predictions. A turbine model of Vestas V90 2000 was used.

Limitations: The solar and wind resources can differ within one cluster. Therefore, the potential generation output can vary within a cluster and across the model period (2020–2050).

II. Power demand projection and load curve calculation

The OECM power analysis model calculates the development of the future power demand and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- households;
- industry and business; and
- transport.

Although each sector has its specific consumer groups and applications, the same set of parameters was used to calculate the load curves:

- electrical applications in use;
- demand pattern (24 h);
- meteorological data
    - sunrise and sunset, associated with the use of lighting appliances;
    - temperature and rainfall, associated with climatization requirements;
- efficiency progress (base year 2018 for 2020 until 2050, in 5-year steps;
    - possibility that the electricity intensity data for each set of appliances will change, e.g., change from compact fluorescent lamp (CFL) light bulbs to light-emitting diodes (LEDs) as the main technology for lighting.

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[75] Pfenninger, S, Staffell, I. (2016b), Staffell, Iain and Pfenninger, Stefan (2016). Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, pp. 1224–1239. doi: 10.1016/j.energy.2016.08.068

[76] Rienecker, M, Suarez MJ, (2011) Rienecker MM, Suarez MJ, Gelaro R, Todling R, et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

[77] Müller, R., Pfeifroth, U (2015), Müller, R., Pfeifroth, U., Träger-Chatterjee, C., Trentmann, J., Cremer, R. (2015). Digging the METEOSAT treasure—3 decades of solar surface radiation. Remote Sensing 7, 8067–8101. doi: 10.3390/rs70608067

III. The [R]E 24/7 dispatch module

The [R]E 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour. The first-generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met. In the case of oversupply, the surplus variable renewable electricity can either be moved to storage, moved to other regions, or—if neither option is available—curtailed. Non-variable renewable sources will reduce output. In the case of undersupply, electricity will be supplied either from available storage capacities, from neighbouring clusters, or from dispatch power plants. The key objective of the modelling is to calculate the load development by region, modifying the residual load (load minus generation), theoretical storage, and interconnection requirements for each cluster and for the whole survey region. The theoretical storage requirement is provided as the “storage requirement to avoid curtailment”. The economic battery capacity is a function of the storage and curtailment costs, as well as the availability of dispatch power plants and their costs. This analysis focuses on the technical storage requirements.

The Figure 43 provides an overview of the dispatch calculation process. The dispatch order can be changed in terms of the order of renewables and the dispatch power plant, as well as in terms of the order of the generation categories: variable, dispatch generation, or storage. The following key parameters are used as input: generation capacity by type, the demand projection and load curve for each cluster, interconnections with other clusters, and meteorological data, from which solar and wind power generation are calculated with hourly resolution. The installed capacities are derived from the long-term projections described in Chapter 6 and the resulting annual generation in megawatt hours is calculated on the basis of meteorological data (in the cases of solar and wind power) or dispatch requirements.

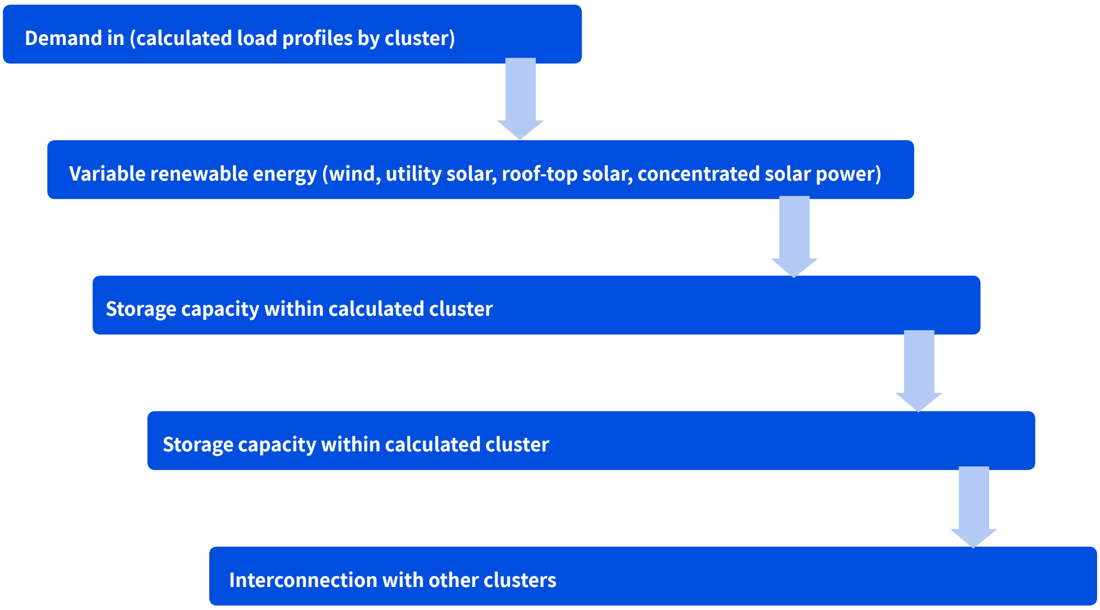

Figure 43: Dispatch order within one cluster

Overview: input and output—[R]E 24/7 energy dispatch model

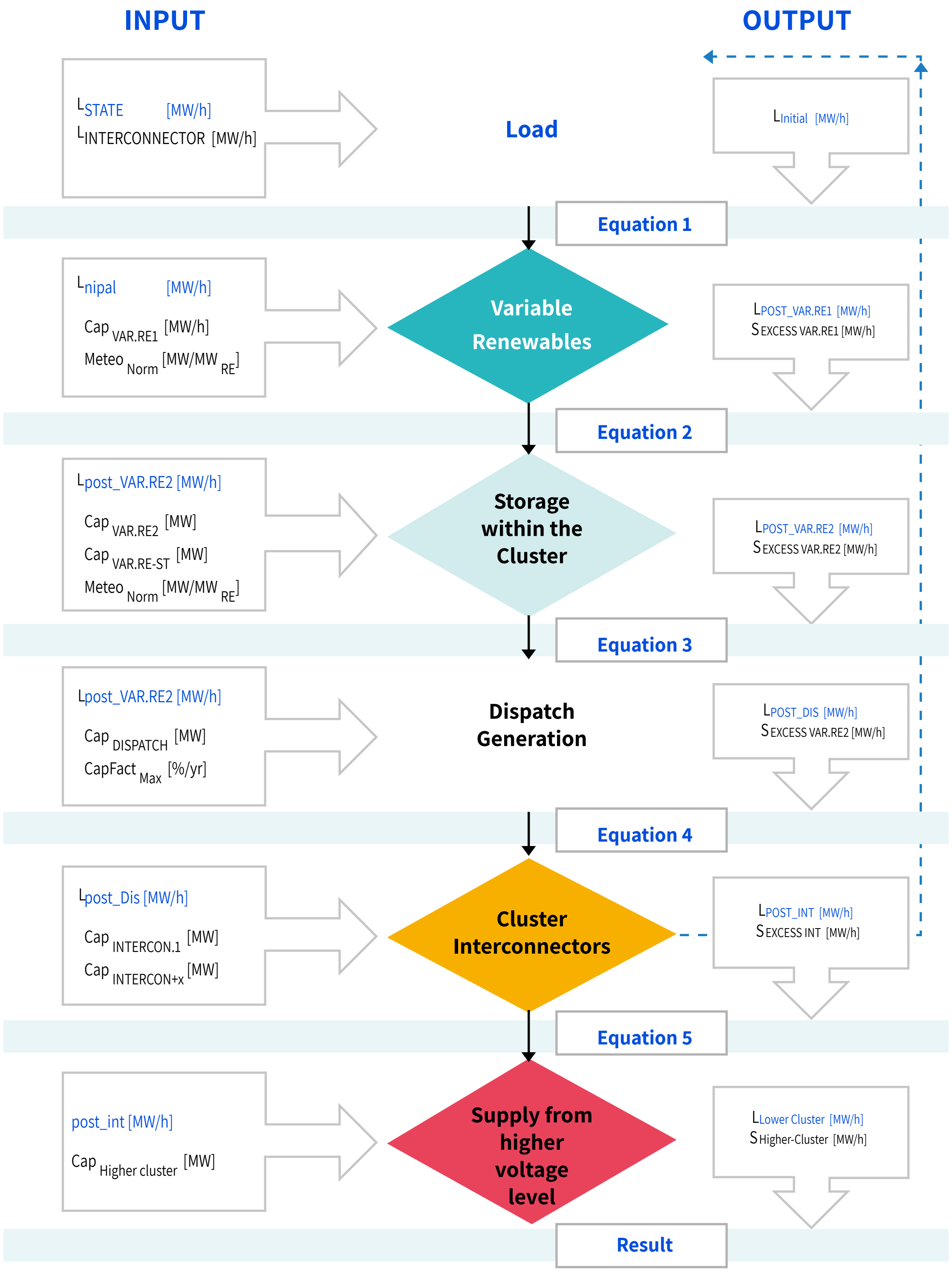

Figure 44: Overview—Input, output, and dispatch order

Figure 44 gives an overview of the input and output parameters and the dispatch order. Although the model allows changes in the dispatch order, a 100% renewable energy analysis always follows the same dispatch logic. The model identifies excess renewable production, which is defined as the potential wind or solar PV generation that exceeds the actual hourly demand in MW during a specific hour. To avoid curtailment, the surplus renewable electricity must be stored with some form of electrical storage technology or exported to a different cluster. Within the model, excess renewable production accumulates through the dispatch order. If storage is present, it will charge the storage within the limits of the input capacity. If no storage is included, this potential excess renewable production is reported as 'potential curtailment' (pre-storage). It is assumed that a certain number of behind-the-meter consumer batteries will be installed, independently of the system requirements.

Limitations

The calculated loads are not optimized with regard to local storage, the self-consumption of decentralized producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may be well below the calculated values.

B. Development of power plant capacities

Nepal has substantial untapped renewable energy potential, as described in Chapter 4. However, the overall consensus in the Nepalese energy debate is to expand the power sector while remaining carbon-free, insofar as Nepal's electricity generation capacity (apart from a few diesel generators) is already 97% decarbonized. Large hydropower plants provide the bulk of the grid-connected electricity generation, whereas solar PV generators are primarily used off-grid. However, solar PV generators will expand rapidly and provide increasing electricity, both grid-connected and off-grid in micro-grids, especially in remote areas of the country, where the national power grid cannot reach villages because of the geography of Nepal. In this analysis, we contribute to the debate on the role that decentralized renewable electricity generation—mainly solar PV, but also mini-hydro and biomass fuel generators—can play in the future.

In terms of Nepal's renewable electricity potential, the vast majority of future generation will be solar PV. Wind resources are very limited and the land-locked country has no access to any offshore renewable energy resources. Hydropower plants have already been the backbone of the Nepalese power sector for decades, whereas sustainable biomass resources are limited. The potential for geothermal heating systems (heat pumps) for low-temperature heating is significant.

Therefore, the capacity for solar PV installations will increase substantially under the N-1.5 °C pathway. The average market until 2025 will range around 120 MW per year between 2022 and 2035 and increase to around 1,100 MW per year between 2036 and 2045. Nepal's hydropower plant capacity will grow by a factor of 5, from 2,082 MW in 2022 to 10,000 MW in 2050. Under the N-1.5 °C pathway, the contribution of wind will remain small, increasing from currently under 10 MW to 400 MW in 2050.

Despite the rapid growth in the solar PV capacity, the power generation mix will remain largely unchanged, with over 90% hydropower generation until 2035. By 2040, solar PV will already provide 20% of Nepal's electricity generation, increasing to over 40% in 2050.

However, there will be a rapid increase in the electricity demand with the high electrification rates in the transport and heating sectors. After 2035, the majority of the Nepalese solar market will provide electricity for households and electric mobility. By 2040, solar PV will generate 11 TWh—Nepal's projected electricity demand in 2023. By 2050, hydropower and solar PV will provide over 98% of the country's electricity demand, which is projected to increase 10-fold relative to 2021.

Table 46: Nepal—Average annual changes in installed power plant capacity (main technologies) [in MW/a]

Power Generation: average annual changes in installed capacity						
	2021–2025	**2026–2030**	**2031–2035**	**2036–2040**	**2041–2045**	**2046–2050**
Hydro	0.3	1.1	0.7	0.0	0.0	0.0
Wind (onshore)	0.000	0.023	0.009	0.003	0.004	0.055
PV (roof-top)	0.102	0.155	0.113	1.013	1.275	1.949
PV (utility-scale)	0.034	0.052	0.038	0.338	0.425	0.650

C. Utilization of power generation capacities

Table 47 and Table 48 show the installed capacities for roof-top and utility -scale solar PV under the N-1.5˚C scenario in 2030 and 2050, respectively. The distributions are based on the regional solar potentials and the regional electricity demands, with the aim of generating electricity where the demand is located. Whereas roof-top solar PV power generation is modular and can be installed close to the consumer or even integrated into buildings, utility-scale solar PV is usually further away from settlements and close to medium- or high-voltage power lines. Furthermore, solar power plants (utility-scale PV) have double-digit megawatt capacities, on average. The best solar resources are in the south of the country along the border with India[78].

Table 47: Nepal N-1.5˚C pathway—Installed photovoltaic capacities by region (2030)

N-1.5 °C pathway 2030	Province 1	Madhesh	Bagmati	Gandaki	Lumbini	Karnali	Sudurpaschim
	[MW]	**[MW]**	**[MW]**	**[MW]**	**[MW]**	**[MW]**	**[MW]**
Photovoltaic (roof-top)	199	194	239	97	201	67	100
Photovoltaic (utility-scale)	50	49	60	24	50	17	25

Table 48: Nepal N-1.5 °C pathway—Installed photovoltaic capacities by region (2050)

N-1.5 °C pathway 2050	Province 1	Madesh	Bagmati	Gandaki	Lumbini	Karnali	Sudurpaschim
	[MW]	**[MW]**	**[MW]**	**[MW]**	**[MW]**	**[MW]**	**[MW]**
Photovoltaic (roof-top)	3,563	3,478	4,281	1,745	3,606	1,193	1,792
Photovoltaic (utility-scale)	891	869	1,070	436	901	298	448

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[78] The assessment has excluded conservation areas in solar PV resource potential map in Fig. 23 which has the high resource potential zone. While considering the overall areas, the highest PV potential would be in the north-west region.

The N-1.5 °C scenario aims for an even distribution of variable power plant capacities across all regions by distributing roof-top and utility-scale solar PV power-generation facilities accordingly. In this analysis, it is assumed that 80% of the solar PV installations are roof-top and 20% are utility-scale power plants. The distribution is based on the population in each of the sub-regions. Compared with the vast solar potential, wind generation will be very limited and will not compensate for differences in seasonal generation. However, to diversify the generation mix to reduce the seasonal storage requirements, the wind resources of Nepal should be used to the highest possible degree.

By 2030, variable power generation will increase to just under 10% in all regions, whereas the proportion of dispatchable renewables—hydropower—will remain above 90% in all regions.

However, by 2050, variable solar PV generation will increase to around half of the regional electricity supply in all provinces of Nepal.

Table 49: Nepal—Power system shares by technology group

Power Generation Structure in Percentage of Annual Supply [GWh/a]		N-1.5 °C		
		Variable Renewable	Dispatch Renewable	Dispatch Fossil
Province 1	2020	0%	100%	0%
	2030	7%	93%	0%
	2050	45%	55%	0%
Madesh	2020	0%	100%	0%
	2030	6%	94%	0%
	2050	40%	60%	0%
Bagmati	2020	0%	100%	0%
	2030	9%	91%	0%
	2050	54%	46%	0%
Gandaki	2020	0%	100%	0%
	2030	8%	92%	0%
	2050	47%	53%	0%
Lumbini	2020	0%	100%	0%
	2030	8%	92%	0%
	2050	50%	50%	0%
Karnali	2020	0%	100%	0%
	2030	8%	92%	0%
	2050	48%	52%	0%
Sudurpaschim	2020	0%	100%	0%
	2030	7%	93%	0%
	2050	53%	47%	0%

The significant regional differences in the power system shares—the ratio between dispatchable and non-dispatchable variable power generation—will require a combination of increased interchange, storage facilities, and demand-side management incentives.

Table 50: System-relevant generation types

Generation Type	Fuel	Technology
Limited Dispatchable	Fossil, uranium	Coal, brown coal/lignite, (including co-generation)
	Renewable	Hydropower, bio-energy, and synthetic fuels, geothermal, concentrated solar power (including co-generation)
Dispatchable	Fossil	Gas, oil, diesel (including co-generation)
		Storage systems: batteries, pumped hydropower plants, hydrogen- and synthetic-fuelled power and co-generation plants
Variable	Renewable	Bio-energy, hydro, hydrogen- and synthetic-fuelled power, and co-generation plants
	Renewable	Solar photovoltaic, onshore wind

Table 50 shows the system-relevant technical characteristics of the various generation types. Future power systems must be structured according to the generation characteristics of each technology in order to maximize their synergy. Power utilities can encourage sector coupling—between industry, transport, and heating—in order to utilize various demand-side management possibilities and to maximize the cross-benefits. The integration of large shares of variable power generation will require a more flexible market framework. Those power plants requiring high capacity factors because of their technical limitations regarding flexibility ("base-load power plants") might not be desirable to future power system operators. Therefore, capacity factors will become more a technical characteristic than an economic necessity. Flexibility is a commodity that increases in value over time.

D. Development of load, generation, and residual load

Table 51 shows the calculated annual demand, maximum and minimum loads, and the calculated average load by region for 2021. The results are based on the N-1.5 °C pathway projections. To validate the data, we compared our results with the real-time data published by the Nepal Electricity Authority (NEA 2022)[79] .

The statistical data for each province for 2021 were not available at the time of writing, so the values are estimates and may vary by ±10% for each data point. However, the published online data of the Nepal Electricity Authority (NEA) for Nepal's power sector is within the same order of magnitude. The calculation of the maximum, minimum, and average loads for the base year (2020/21) are important in order to calibrate the OECM and to compare the values with future projections.

Table 51: Nepal—Calculated load, generation, and residual load in 2020/21

Real Load (rounded)—measured by grid operators in 2018	Electricity Generation [TWh/a]	Maximum Load (Domestic) [MW]	Maximum Generation [MW]	Minimum Load [MW]	Average Load [MW]
Province 1	1.4	210	300	135	163
Madesh	1.6	228	327	149	178
Bagmati	1.7	251	349	164	197
Gandaki	0.7	102	142	67	80
Lumbini	1.4	211	330	138	166
Karnali	0.5	70	109	46	55
Sudurpaschim	0.8	116	195	70	89
Nepal total	**8.1**	**1,188**	**1,753**	**769**	**927**

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[79] NEA (2022), Nepal Electricity Authority Energy Details—online database, viewed during September and October 2022, https://www.nea.org.np/

Table 52 shows that according to calculation, the average load will decrease by a factor of approximately 3–4 in each province over the next decade. By 2050, the overall electricity load of Nepal will increase by a factor 8.6 relative to that of 2020, with variations between 6 and 10 by region.

The increase in load is attributable to the increase in the overall electricity demand with the electrification of cooking, heating, and cooling, which constitutes an increase of the living standards of all Nepalese households as they acquire more residential appliances. Furthermore, the growth of the commercial and industrial sectors of Nepal and the electrification of transport will lead to a sharp increase in the electricity demand and therefore the overall power load. This increased load will require an expansion of Nepal's power distribution and transmission grid, both within Nepal and as interconnections with neighbouring countries—especially India.

The calculated load for each province depends on various factors, including the local industrial and commercial activities. A detailed analysis of the planned expansion of economic activity for each province was beyond the scope of this research and the results are therefore estimates. The residual load is the difference between the power generation and the demand—a negative residual load indicates an oversupply, whereas a positive value implies an undersupply.

The development of power generation is assumed to grow proportionally to the growth in demand in each province. A more detailed assessment of the exact locations of power generation is required to optimize the required expansion of transmission grids. To reduce the residual load to avoid an over- and/or undersupply for each province, either increased grid capacity or more storage systems will be required.

Table 52: Nepal—Projection of load, generation, and residual load until 2050

Nepal Development of Load and Generation		**N-1.5 °C**			
		Maximum Load	**Maximum Generation**	**Maximum Residual Load**	**Peak Load Increase**
		[MW]	[MW]	[MW]	[%]
Province 1	2020	210	300	0	100%
	2030	828	1,322	−494	394%
	2050	2,092	3,724	−1,632	995%
Madesh	2020	228	327	0	100%
	2030	961	1,551	−590	422%
	2050	2,444	3,756	−1,312	1073%
Bagmati	2020	251	349	0	100%
	2030	964	1,676	−712	384%
	2050	2,281	4,857	−2,576	910%
Gandaki	2020	102	142	0	100%
	2030	393	659	-−266	384%
	2050	930	1,799	−870	910%
Lumbini	2020	211	330	0	100%
	2030	788	1,442	−654	373%
	2050	1,774	3,979	−2,204	840%
Karnali	2020	70	109	0	100%
	2030	261	467	−206	373%
	2050	587	1,306	−719	840%
Sudurpaschim	2020	116	195	0	100%
	2030	377	822	−60	63%
	2050	726	2,226	−1,500	626%
Nepal	2020	1,188	1,753	0	100%
	2030	4,572	7,939	−3,367	385%
	2050	10,834	21,647	−10,813	912%

Increased electric mobility will require additional capacity in the power grid to accommodate the higher charging loads for vehicles. Our analysis shows that with the smart distribution and management of electric vehicle charging stations, additional transmission lines will be required. The high share of solar PV will lead to high generation peaks during summer months and low generation capacities during winter. To manage the generation peaks of solar PV generators, utility-scale installations will require on-site storage capacity, whereas roof-top PV will require increased 'behind-the-meter' storage facilities (see Section F).

E. Development of inter-regional exchange of capacity

The inter-regional exchange of capacity is a function of the load development and generation capacity in all seven provinces. The OECM distributes generation capacity according to the regional load and the conditions for power generation. The locations of existing hydropower plants are fixed and the installation of new capacities will depend upon geographic conditions and the nature conservation requirements. Nepal's significant potential for additional hydropower stations provides flexibility in choosing the right location for additional hydropower plants. To prevent unnecessary expansion of the electricity grid, the projected increase in the regional electricity demand and additional electricity export plans should inform the expansion of the local power generation capacity.

Solar and wind power generation, as well as decentralized bio-energy power and/or micro-hydropower plants, is modular and can be distributed according to the load in the first place. However, as the share of variable renewable electricity increases, and the space available for utility-scale solar and the (very limited) onshore wind generation facilities will decrease. Power may then have to be generated further from its point of consumption.

Careful planning of the distribution of electricity generation capacities (both solar PV and hydropower plants) to match the local demand will be very important. Furthermore, charging devices for electric vehicles should be operated within a load management scheme.

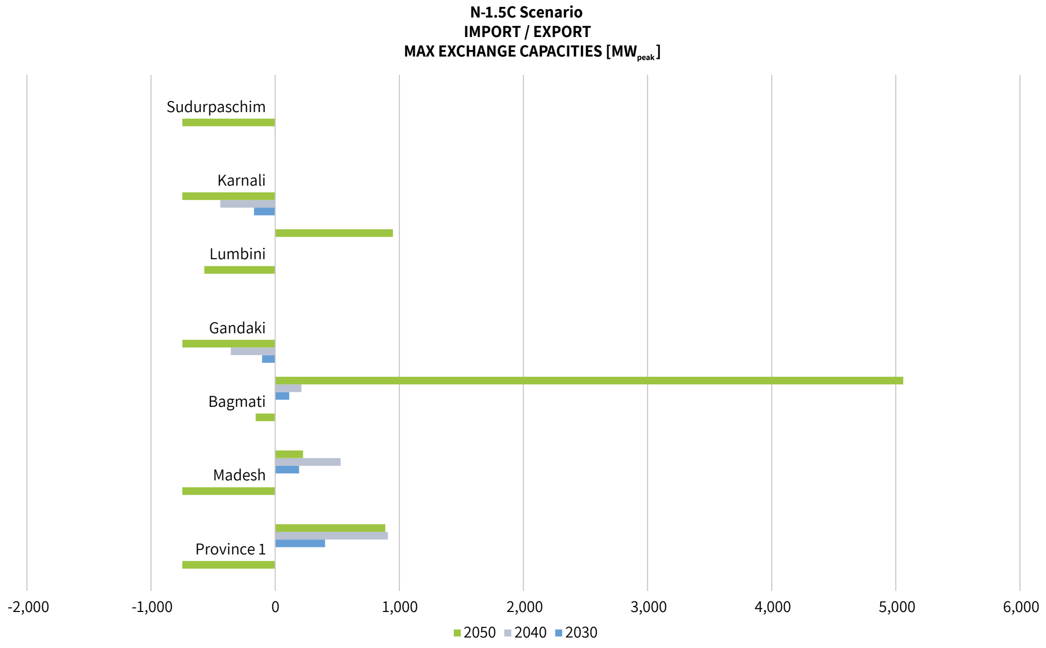

Figure 45: Nepal—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to load increase, under the N-1.5 °C scenario

The N-1.5 °C scenario prioritizes the security of supply with local generation, while utilizing electricity import and export to surrounding countries for the management of generation. Utility-scale solar PV installations, as well as small- and medium-sized decentralized power generation, will interact with local demand-side management and storage facilities (see Section F)—from dedicated energy communities—on low- and medium-voltage levels, which will reduce upgrades of the distribution grid. It was beyond the scope of this project to quantify this effect, which requires additional research.

Figure 45 shows the calculated exchange capacities between the seven defined sub-regions of Nepal in 2030, 2040, and 2050 for all three scenarios. The values on the left of 0 show the maximum loads imported into the sub-regions and those on the right show the maximum loads exported.

Example: Under the N-1.5 °C scenario, the Gandaki region will require a maximum of around 5,000 MW of exported energy (hydroelectricity) to be transported to neighbouring provinces and/or India by 2050. The increased interconnection requirements of all other provinces will remain under 200 MW in the calculated projections.

A detailed local assessment is required of whether a new power grid interconnection can be built, or if regional micro-grids with increased storage capacity are a better solution. Stand-alone micro-grids are the preferred option because the construction of transmission grids will be impractical, especially in Nepal's remote regions, such as the Himalayan region in the north.

Limitations

The calculated loads are not optimized with regard to local storage, self-consumption by decentralized producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may differ from the actual values. Furthermore, the calculated export/import loads to neighbouring countries are simplified and combined into a single value. Peak load and peak generation events do not occur at the same time, so their values cannot be simply summed. Moreover, peak loads can vary across all regions and appear at different times. Therefore, to sum all the regional peak loads will only provide an indication of the peak load for the whole country. The maximum residual load[80] shows the maximum undersupply in a region and indicates the maximum load that will be imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. Optimizing the interconnections for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be supplied by one or more of the following options:

- imports from other regions through interconnections;
- battery storage facilities on-site at solar PV installations and for electric vehicles;
- available back-up capacities, such as gas peaking plants;
- load and demand-side management.

In practice, security of supply will be achieved with a combination of several measures and will require the in-depth analysis of regional technical possibilities.

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80. Residual load is the load remaining after the local generation within the analysed region is exhausted. There could be a shortage of load supply due to the operation and maintenance of a coal power plant or reduced output from wind and/or solar power plants.

F. Storage requirements

The quantity of storage required will be largely dependent upon the storage costs, grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands (Wendong 2016)[81]. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt-hour than the storage costs. Cebulla et al. (2018))[82] reported that "in general terms, photovoltaic-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap". In an analysis of 400 scenarios for Europe and the USA, they also found that once the share of variable renewables exceeds 40% of the total generation, the increase in electrical energy storage power capacity is about 1–2 GW for each percentage of variable renewable power generation in wind-dominated scenarios and 4–9 GW in solar-PV-dominated scenarios.

When variable power generation shares exceed 30%, storage requirements increase. The share of variable generation will exceed 30% between 2025 and 2030 under both Energy [R]evolution scenarios in all regions. Therefore, a smart grid integration strategy that includes demand-side management and the installation of additional decentralized and centralized storage capacities must be established.

Over the past decade, the cost of batteries, especially lithium batteries, has declined significantly. Similarly, solar PV costs have also declined significantly. Storage is economic when the cost per kilowatt-hour is equal to or lower than the cost of generation. Therefore, if storage costs are high, curtailment could be economic. However, there are several reasons for curtailment, including transmission constraints, system balancing, and economic reasons (NREL 2014)[83]. The California Independent System Operator (CISO)[84] defines economic curtailment during times of oversupply as a market-based decision. "During times of oversupply, the bulk energy market first competitively selects the lowest cost power resources. Renewable resources can 'bid' into the market in a way to reduce production when prices begin to fall. This is a normal and healthy market outcome. Then, self-scheduled cuts are triggered and prioritized using operational and tariff considerations. Economic curtailments and self-scheduled cuts are considered 'market-based'".

I. Storage requirements

Nepal currently operates a large fleet of run-of-river hydropower plants with no pump storage capacity. However, according to the Global Pumped Hydro Atlas (ANU 2022)[85], Nepal has 2,800 good storage sites. The utilization of this potential by implementing additional water reservoir storage capacities and pumped

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[81] Wendong (2016), Wei, Wendong et al. Regional study on investment for transmission infrastructure in China based on the State Grid data,10.1007/s11707-016-0581-4, Frontiers of Earth Science, June 2016.

[82] Cebulla et al. (2018), How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, Journal of Cleaner Production, February 2018, https://www.researchgate.net/publication/322911171_How_much_electrical_energy_storage_do_we_need_A_synthesis_for_the_US_Europe_and_Germany/link/5a782bb50f7e9b41dbd26c20/download

[83] Wind and Solar Energy Curtailment: Experience and Practices in the United States; Lori Bird, Jaquelin Cochran, and Xi Wang, National Renewable Energy Laboratory (NREL), March 2014, https://www.nrel.gov/docs/fy14osti/60983.pdf

[84] Impacts of renewable energy on grid operations, factsheet, https://www.caiso.com/Documents/CurtailmentFastFacts.pdf

[85] ANU (2022), Australian National University, 100% Renewable Energy Group, Global Pumped Hydro Energy Storage Atlas, https://re100.eng.anu.edu.au/global/

hydro storage (PHS) facilities will put Nepal in a comfortable position to integrate large amounts of variable solar PV power generation.

For example, there are three types of hydropower plants in Switzerland:

- Run-of-river power plants, which use the available volumes of passing river water and have limited possibilities to regulate the output; winter is usually the time with the lowest production volumes.
- Storage power plants, which are 'run-of-river' power stations with a water storage reservoir on the intake side. Power generation can be increased and reduced within the water reservoir capacity to complement the variable demand and/or solar generation.
- Pumped hydro storage (PHS) power plants, which have a water storage reservoir on both sides (in-take and out-flow) and can pump water after electricity generation back into the in-take reservoir. PHS plants can operate as a short-, medium-, or long-term electricity storage technology. Historically, PHS systems have been used to balance inflexible nuclear power plants, which must operate in base-load mode, and to hedge against price fluctuations on power markets.

In this analysis, we assume that 'peak-shaving' is used to avoid peak generation events. The term 'peak-shaving' refers to the reduction in the solar or hydro generation capacity in times of high production. Peak-shaving involves pro-actively managing solar generation by reducing the output, e.g., from utility-scale PV, to eliminate short-term spikes. These spikes only appear for a limited time—from minutes to hours—and significantly increase the actual grid or storage capacity because the capacity must cope with the highest peak.

With peak-shaving, this peak can be reduced with only a minor effect on the overall annual generation because peak events are relatively infrequent. The assumed "economic curtailment rate" for the N-1.5 °C pathway will increase to 5% relative to the annual generation (in GWh/a) for solar PV for the years until 2030, and to 10% between 2031 and 2050. However, economic curtailment rates are dependent upon the available grid capacities and can vary significantly, even within Nepal. Curtailment will be economic when the power generated by a PV power plant exceeds the demand for only a few hours a day and this event occurs rarely across the year. Therefore, the expansion of storage capacities will not be economically justifiable.

To build up the additional required storage capacity, we assume that a percentage of the solar PV capacity will be installed with battery storage. The suggested solar battery system must be able to store the entire peak capacity for 4 full load hours. The N-1.5 °C scenario requires that all utility-scale solar PV and 75% of all roof-top PV systems built after 2030 must be equipped with a battery or other storage technology systems.

The estimates provided for storage requirements also presuppose that variable renewables—solar PV—will be first in the dispatch order, ahead all other types of power generation. Priority dispatch is the economic basis for investment in utility-scale solar PV and wind projects. The curtailment rates or storage rates will be significantly higher when priority dispatch is given to, for example, hydro power plants in 'base-load' generation mode.

This case has not been calculated because it would involve a lack of investment in solar in the first place. With decreasing storage costs, as projected by Bloomberg (2019)[86], interconnections may become less

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[86] Bloomberg (2019), A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldi-Scot, Bloomberg NEF, March 5 2019, https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

economically favourable than batteries. The storage estimates provided are technology neutral and do not favour any specific battery technology.

Table 53 shows the storage required to avoid curtailment, or in other words, the entire surplus generation at any given time, by region, under the N-1.5 °C scenario without peak-shaving. With the high share of hydropower, which is dispatchable, storage capacities to avoid curtailment for grid-connected solar PV will not be required until 2030 in the case of priority dispatch for solar PV, which will mean that the output of hydropower must be reduced to avoid production peaks. After 2030, the penetration of solar PV will increase significantly, and additional storage capacity will be required.

The storage demand for micro-grids and off-grid systems must be calculated individually and is not part of this assessment. However, micro-grids always require either a storage system with a capacity large enough (in terms of both the electricity supply in kilowatt-hours and the required load in kilowatts) to bridge the gap in times of low or no generation possibilities.

Table 53: Nepal—storage requirements to avoid curtailment

Storage Requirements to Avoid Curtailment		**N-1.5 °C Pathway**	
		Required Storage to Avoid Curtailment (overproduction)	**Required Storage Capacity to Avoid Curtailment**
		[GWh/a	**[GW/a]**
Province 1	2020	0	0.00
	2030	0	0.00
	2050	1,454	1.80
Madesh	2020	0	0.00
	2030	0	0.00
	2050	938	1.50
Bagmati	2020	0	0.00
	2030	0	0.00
	2050	4,014	2.78
Gandaki	2020	0	0.00
	2030	0	0.00
	2050	936	0.95
Lumbini	2020	0	0.00
	2030	0	0.00
	2050	2,483	2.37
Karnali	2020	0	0.00
	2030	0	0.00
	2050	647	0.68
Sudurpaschim	2020	0	0.00
	2030	0	0.00
	2050	1,317	1.16
Nepal	2020	0	0
	2030	0	0
	2050	11,789	11

II. Cost development—battery storage technologies

Battery technologies have developed significantly over the past decade, and the global annual market increased from 700 MW in 2015 to close to 16,000 MW in 2021 (IEA-BAT 2020)[87] . The market is split roughly equally between grid-scale storage and 'behind-the-meter' storage for solar PV projects. The rapidly growing demand for electric vehicles has significantly accelerated the development of battery technologies, and manufacturing capacities have grown by double digits, with costs decreasing accordingly. The battery costs per kilowatt-hour storage capacity decreased from US$668 in 2013 to US$137 in 2020—a reduction of 79% over the past 7 years. Bloomberg New Energy Finance estimates that battery costs will decline further to around US$58 by 2030.

III. Further research required

A calculation of the required investment costs in storage technologies that will be needed after 2030 and by 2050 would entail such high uncertainty that such estimates seem meaningless. Furthermore, a more-detailed storage technology assessment for the N-1.5 °C scenario based on the specific situation of Nepal—with its unique potential for hydro pump storage—is required. The Nepalese potential for pumped hydro storage systems has been assessed in multiple research projects already (Sah et al. 2014[88]).

The authors recommend that published research be reviewed to determine the extent to which hydro pump storage–which is among the most efficient grid-connected electricity storage systems that include an option for seasonal electricity storage–can be implemented preferentially in Nepal. However, battery storage systems are probably the preferred option for micro-grids and stand-alone power generation in remote areas.

G. Summary: Power sector analysis for Nepal

The N-1.5 °C scenario prioritizes the use of decentralized regional roof-top solar PV and utility-scale solar PV power generation to complement the plant expansion of Nepal's hydropower generation capacity. This will rapidly increase the electricity available for the country's economic development while keeping electricity generation carbon neutral. The power demand of Nepal will increase significantly over the coming decades with its significant economic growth rate and the implementation of electric mobility and electric heating to reduce its dependence on fuel imports.

By 2030, variable solar PV power generation will reach around 8%, whereas the proportion of dispatchable renewables—mainly hydropower—will remain over 90% in all regions. The current actual interconnection capacities—including those under construction—between all regions seem sufficient until 2030 if battery storage capacities, in parallel with the expansion of solar PV, are implemented. The modelling results indicate that the planned transmission grid upgrades within Nepal will be sufficient in the short term.

However, Nepal operates a large fleet of run-of-river hydropower plants with no water reservoir storage capacities or PHS, and should evaluate the extent to which their untapped potential can be utilized.

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[87] IEA-BAT (2020) IEA Energy Storage – website viewed October 2022, https://www.iea.org/reports/grid-scale-storage

[88] Sah et al. (2014), Sah, N. K., Uprety, M., Bhandari, S., Kharel, P., Suman, S., & Maskey, R. K. (2014). Prospects of Storage and Pumped-Storage Hydropower for Enhancing Integrated Nepal Power Systems. Hydro Nepal: Journal of Water, Energy and Environment, 15, 37–41. https://doi.org/10.3126/hn.v15i0.11290

The projected sharp increase in solar PV systems will require both short-term and long-term (seasonal) storage after 2030. The N-1.5 °C scenario will lead to an installed capacity of 2 GW by 2035—similar to the current hydropower capacity—and close to 25 GW solar PV by 2050—2.5 times the projected hydro power capacity for 2022.

With peak-shaving, solar production spikes can be reduced, with only a minor effect on the overall annual generation because the peak events will be relatively infrequent. The assumed “economic curtailment rate” for all three scenarios will be up to 5%—with regard to the annual generation (in GWh/a) of solar PV and onshore wind—for the years until 2030 and 10% between 2031 and 2050. To build up the additional storage capacity required, we assume that a proportion of the solar PV capacity will be installed with battery storage. The suggested solar battery system should be able to store the entire peak capacity for 4 full load hours.

The N-1.5 °C scenario requires that all utility-scale solar PV and 75% of all roof-top PV systems built after 2030 be equipped with battery or other storage technology systems.

To conclude, a large solar PV power generation share of around 70% by 2050 is feasible for Nepal under the documented assumptions.

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