Attainability of Net Zero Carbon Emission Targets in Nepal under Different Effort-sharing Approaches

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Abstract

Nepal aims to achieve carbon neutrality by mid-century. This study aims to analyze the energy sector transformation needed to achieve the carbon neutrality target. The study employs the AIM/Enduse model as a modelling tool to analyze the energy system. A business-as-usual (BAU) scenario is developed in which energy and technological use follow historical trends. The carbon dioxide (CO_2) emissions in the energy sector in BAU would reach 66.3 $MtCO_2$ in 2050. The study also assesses the carbon budget and carbon dioxide emission allowance with various effort-sharing approaches. Based on the estimated emission allowances, the emission pathway in the energy sector is determined to develop an emission reduction (ER) scenario. The ER scenario also incorporates the Nationally Determined Contributions (NDC) targets of Nepal. In the ER scenario, CO_2 emissions from the energy sector in Nepal peak in 2036, then drop, reaching 6.4 $MtCO_2$ in 2050. The ER scenario would require energy efficiency improvement and electrification of the end-use technologies in all the sectors; and fuel-switching from coal and oil to biomass in addition to electrification in thermal applications in industries. The electricity consumption in the ER scenario would be higher by 70% compared to the BAU scenario in 2050. Hydro, solar and biomass would have crucial roles in the decarbonization of the energy sector. In the ER scenario, the combined power generation capacity of hydropower, solar and wind would reach 72 GW by 2050, which in the BAU scenario would be 37 GW. Policies and incentives that would promote the electrification of end-use technologies and renewable power generation need to be formulated to achieve the mitigations of the ER scenario.

Key words: AIM/Enduse, carbon neutrality, hydropower, Nepal, renewable energy

1. Introduction

Limiting the emissions of anthropogenic greenhouse gases (GHG) emissions to keep the global average temperature below 2ºC and efforts to keep it below 1.5ºC have been major concerns for the climate change community. Studies show that the combined mitigation efforts of countries' currently pledging NDCs would not be sufficient to meet the 2ºC and 1.5ºC targets. The IPCC's special report concludes that net carbon dioxide emissions should reach zero by mid-century to keep the temperature below 1.5°C above the pre-industrial level (IPCC, 2018). Researchers have tried to develop different ways to share GHG emissions using equity principles to keep the emissions below the limit. van den Berg et al. (2020) have presented various effort-sharing approaches to estimating carbon budgets and emission allowances. Nepal submitted its Long-term Strategy for Net-zero Emissions (hereafter referred as 'Nepal-LTS') to the United Nations Framework Convention on Climate Change (UNFCCC) in 2021 (GoN, 2021). The report states that Nepal can achieve carbon neutrality by 2045. Achieving carbon neutrality in Nepal implies decarbonization of the emitting sectors, mainly the energy sector, as well as utilizing carbon sinks, to offset emissions from hard-to-abate sectors. The Nepal-LTS also shows that in the land-use, land-use change and forestry (LULUCF) sector, there would be net CO_2 emissions in the reference scenario. More than 40% of the land area of Nepal is forested. Despite significant forest area coverage, there are net emissions from the LULUCF sector due to high deforestation and timber harvesting (MoFE, 2021a). The LULUCF sector plays a key role in offsetting the emissions to achieve carbon neutrality. The literature finds that mitigation costs in the forestry sector range between $0.5 and $7 per tCO_2 in developing countries, while for industrialized nations the cost is in the range of $1.4 to $22 per tCO_2 (Nabuurs et al., 2007). Nepal has abundant renewable energy resources. The country has the theoretical potential to generate 83 gigawatts (GW) and the economic potential to generate 42 GW from hydropower (WECS, 2010). The solar and wind energy that could be harnessed in Nepal are estimated to be 47.6 GW and 1.6 GW, respectively (Neupane et al., 2022). Nepal aims to utilize the untapped renewable energy resources within its borders to achieve its carbon neutrality target.

There are several studies that have analyzed the GHG implications of various energy and climate policies in Nepal using long-term energy system models (Shakya & Shrestha, 2011; Shakya et al., 2012; Shrestha & Shakya, 2012; Pradhan et al., 2018; Pradhan et al., 2020). To the authors' knowledge, there are no studies that have quantified carbon budget and emission allowance pathways using effort-sharing approaches for Nepal. Therefore, this study estimates the carbon budget and emission allowance pathways with selected effort-sharing approaches using the available methodologies. The study then estimates the carbon sink potential in Nepal during 2020–2050. In addition, CO_2 emissions during 2020–2050 from the industrial processes and product use (IPPU), agriculture and waste sectors are estimated. Based on the emission allowances and CO_2 emissions from the non-energy sectors, the emission allowance in the energy sector is estimated. The study then uses the AIM/Enduse model to develop a business-as-usual (BAU) scenario and emission reduction (ER) scenario. The ER scenario is based on estimated emission allowances in the energy sector derived from the effort-sharing approaches. The ER scenario considers the most challenging emission allowance pathway as the emission limit during 2020–2050. The emission reduction scenario assesses the energy system transformation required in Nepal and emission implications in various energy-using sectors. While most of the earlier studies have focused on GHGs, this paper focuses particularly on carbon dioxide emissions only.

This paper is organized as follows: Section 2 presents the methodology used in this study. Section 3 presents the results, which include estimation of carbon budget and emission allowances, and energy and CO_2 emission implications in a BAU scenario and an ER scenario. Section 3 also discusses the primary energy consumption and final energy consumption in the two scenarios in addition to CO_2 emissions from the energy sector. Section 4 summarizes the findings of the study and concludes the report.

2. Methodology

2.1 Estimating Carbon Budget and CO_2 Emission Allowances

"Carbon budget" indicates a finite number that quantifies the allowable CO_2 emissions during a given time to keep the global temperature within a certain limit. The carbon budget in this study is calculated following van den Berg et al. (2020). The effort-sharing approaches examined are: "grandfathering" (GF), "immediate per capita convergence" (IEPC), "per capita convergence" (PCC), "equal cumulative per capita emissions" (ECPC), "ability to pay" (AP) and "greenhouse development rights" (GDR). The equity principle used in these effort-sharing approaches can be categorized into sovereignty, equality, responsibility, capability and need or any combination of two of these principles. These equity principles use current emissions, population shares, per capita emissions, gross domestic product (GDP) per capita, historical cumulative emissions and combinations of two of these indicators for calculating carbon budget and emission allowances. More details on underlying assumptions used in the effort-sharing approaches such as equity principles, basic tenets and methodology can be found in van den Berg et al. (2020). This study uses effort-sharing approaches to estimate the CO_2 emission allowance instead of greenhouse gases. The start year is assumed to be 2018. For the GF approach, the emissions allowances are assumed to be in proportion to the emissions of 2018.

2.2 Structure of the AIM/Enduse Model

The AIM/Enduse model is a bottom-up cost optimization model where the total energy system cost to meet the required energy service demand is minimized by selecting a combination of technologies subjected to given constraints such as energy limits, technological availability, emission limits and others. The structure of the AIM/Enduse Model is shown in Fig. 1. The energy technology module of the model refers to devices that convert energy into the desired energy services. For example, a cookstove is an energy technology that converts energy (biomass, LPG, electricity) into heat to meet the heat demand associated with cooking as an energy service category. Similarly, in the transport sector, cars convert gasoline (energy) to meet the demand for passenger transport as another kind of energy service. In the case of the power sector, energy includes hydro, oil, coal, solar, etc., and energy technologies include hydropower plants, oil power plants, coal power plants, solar PV and others. The energy service in the power sector is electricity. Electricity is also an energy source for other sectors. Energy service demands are given exogenously except for electricity generation in the case of the power sector. Energy service demands are estimated based on population, economic activities, etc. For instance, households' cooking service demand will depend on the future population, passenger service demand will depend on income, road networks, etc. Technological details such as initial cost, operating and maintenance (O&M) costs, lifetime, etc. are provided as inputs to the model. Similarly, energy prices, emission factors of each energy type, energy availability, etc. are given as inputs to the model. Based on the input data provided, the AIM/Enduse model determines the combination of energy technologies required to meet the projected future service demands under a given set of constraints at minimum system cost.

2.3 Nepal's AIM/Enduse Model

Nepal's AIM/Enduse model is the energy system model of Nepal developed using the AIM/Enduse modelling framework. It comprises six economic sectors: the agriculture, commercial, power, industry, transport and residential sectors. The AIM/Enduse model has also been used previously for energy and carbon policy analysis in Nepal (Pradhan et al., 2018; Pradhan et al., 2019; Pradhan et al., 2020). Earlier studies analyzed the effects of carbon prices and cooking electrification on energy and GHG emissions. The residential sector has been disaggregated into three physiographic regions (Mountains, Hills and Terai) and Kathmandu Valley. These regions are further classified into urban and rural areas. This categorization was done with an aim to represent the differences in useful energy in cooking and heating, and also to ensure the suitability of technological options. For example, biogas options are most suitable in the Terai region due to the favorable climatic conditions. In the model, biogas has been modeled directly as the primary energy source. Energy sources such as animal dung and biodegradable wastes are not accounted for in primary energy if they are used for biogas production, to avoid double counting. In this study, only carbon dioxide (CO_2) emissions are analyzed. The CO_2 emission factors of different energy sources are based on the Third National Communication of Nepal (MoFE, 2021b).

The main drivers of energy service demands are GDP and population. Similar methods have been used in other studies in Nepal (Shrestha & Rajbhandari, 2010; Shakya & Shrestha, 2011; Shakya et al., 2012). The base year's energy prices in the model are based on import prices for coal and oil. Prices of fuelwood are based on the Energy Sector Synopsis Report of Nepal (WECS, 2010). In the power sector, investment cost, service life and operating and maintenance (O&M) costs of each power plant are input exogenously to the model. It is assumed that the minimum share of storage hydropower plants will be 15% of the electricity generation mix by 2025 and will increase to 30% by 2050. The model's technology data were obtained from different national sources (MinErgy, 2012; NEEP/GIZ, 2012; Shrestha et al., 2018; Shrestha et al., 2021) as well as international sources (Kainuma et al., 2003; IEA, 2014; IEA, 2017; IEA, 2020; IEA, 2021).

3. Results and Discussion

3.1 Carbon Budget and Emission Allowances

Figure 2 presents the carbon budget for Nepal during 2018–2100 estimated using various effort-sharing approaches. The results show that the ECPC, AP and GDR approaches allow a higher carbon budget to Nepal due to its low emissions in the past and relatively lower GDP in the future. The GF approach allocates the lowest carbon budget during the period due to Nepal's low share of CO_2 emissions in 2018. The IEPC approach allocates carbon budgets based on population, whereas the PCC approach considers population and present emissions, therefore neither approach allocates a large carbon budget to Nepal.

The CO_2 emission allowances during 2020–2050 using various approaches are presented in Fig. 3. The results show that the GF, IEPC and PCC approaches allow higher emissions initially but require zero emissions to be approached by 2050. In the case of the AP and GDR, the emission allowances would increase during 2020–2050. The GDR approach allows higher emissions than the AP during 2020–2050. The AP approach allows emissions

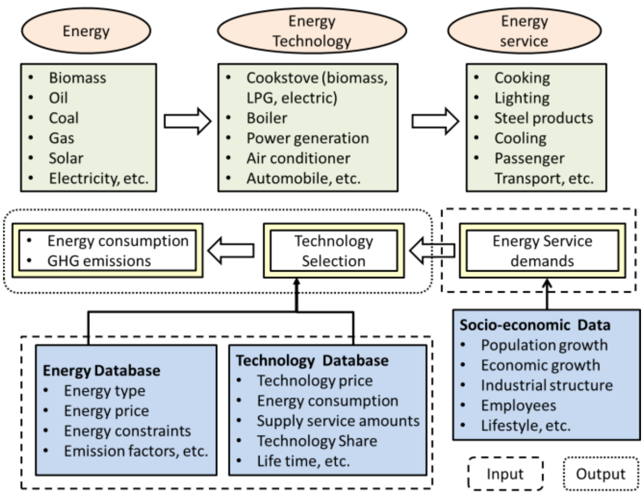

Fig. 1 Structure of the AIM/Enduse model.

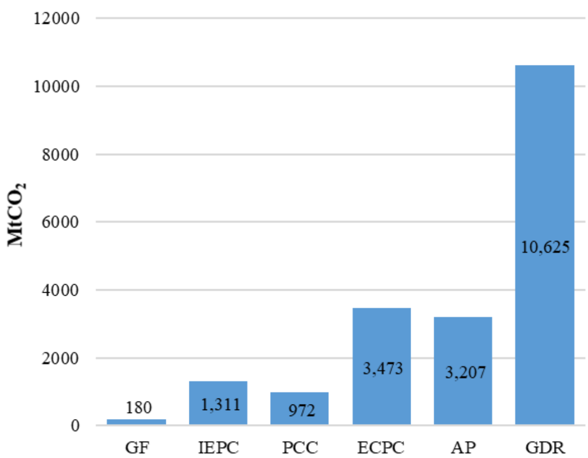

Fig. 2 Carbon budget for Nepal during 2018–2100.

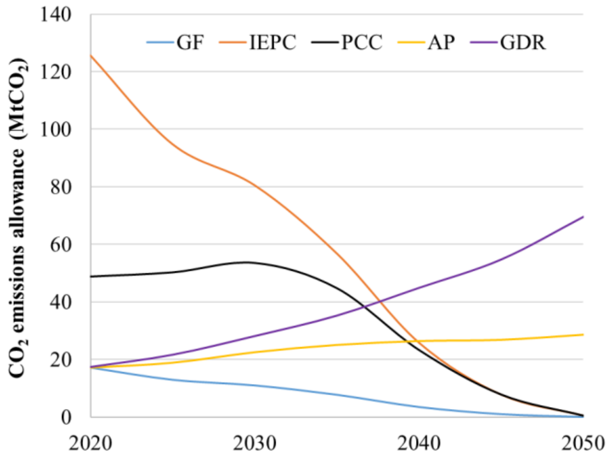

Fig. 3 CO_2 emission allowance for Nepal during 2020–2050.

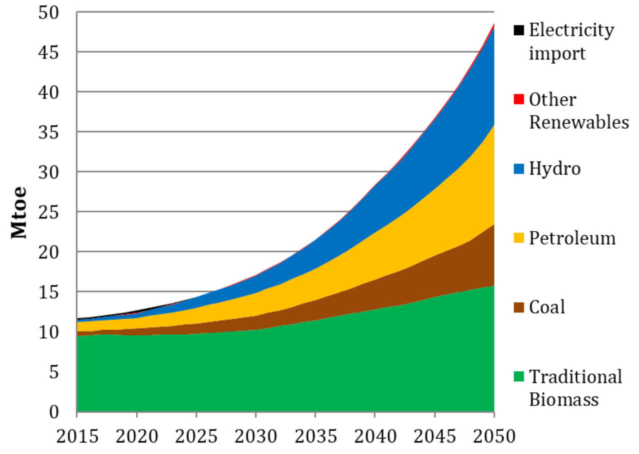

Fig. 4 TPES in the BAU scenario during 2015–2050.

based on GDP per capita during the period whereas the GDR considers both capability and responsibility. The emission allowance in the GDR approach is based on the Responsibility-Capacity Index (RCI), which incorporates GDP per capita and income distribution measures.

3.2 Energy and Emissions in BAU

The study developed a BAU scenario which served as a reference or baseline for comparison. The BAU scenario assumes that the technological and energy use pattern follows the historical trends as considered in other studies in the case of Nepal (Pradhan et al., 2018; Pradhan et al., 2020).

3.2.1 Primary Energy Supply

Figure 4 presents the total primary energy supply (TPES) during 2015–2050 in the BAU scenario. The TPES would grow from 12 Mtoe in 2015 to 17 Mtoe in 2030 and nearly 49 Mtoe in 2050. Biomass consumption during 2015 and 2050 would grow by 67%. Petroleum products in the TPES would surge from 1.2 Mtoe in 2015 to 12 Mtoe in 2050 and the use of coal would rise from 0.6 Mtoe in 2015 to 8 Mtoe in 2050. Hydro in the TPES would grow at 11% on average during 2015–2050. In 2050, the hydro in the TPES would be 12 Mtoe. Biomass would remain the dominant energy source in the TPES during 2015–2050, but its share would fall from 81% in 2015 to 32% in 2050. Hydro's share would grow from 3% in 2015 to 26% in 2050. Coal and petroleum products would also have significant shares of 16% and 26% in 2050, respectively. Their shares in 2015 were 5% and 10% respectively. Imported electricity accounted for 1.3% of the TPES in 2015, but by 2050 Nepal would generate enough electricity to meet its own domestic demand. The share of other renewables would be 1.0% in 2050, and was very insignificant in 2015.

3.2.2 Final Energy Consumption

In the BAU scenario, final energy consumption (FEC) would reach 17 Mtoe in 2030; it would be 48 Mtoe in 2050, which is four times higher than the FEC of 2015 (Fig. 5). Biomass would remain the dominant fuel, although its share in the final energy mix would drop from 82% in 2015 to 59% in 2030 and further to 32% in 2050. The shares of other fuels in the FEC in 2050 would increase. There would be a significant increase in the shares of petroleum, coal and electricity. The share of electricity would increase from 3% in 2015 to 12% by 2030 and 24% by 2050. Similarly, in 2050, the shares of coal and petroleum products would be 16% and 26%, respectively, as compared to 5% and 10%, respectively, in 2015. Biogas and other renewables (solar, wind) would represent a tiny portion (1%) of the final energy mix in 2050.

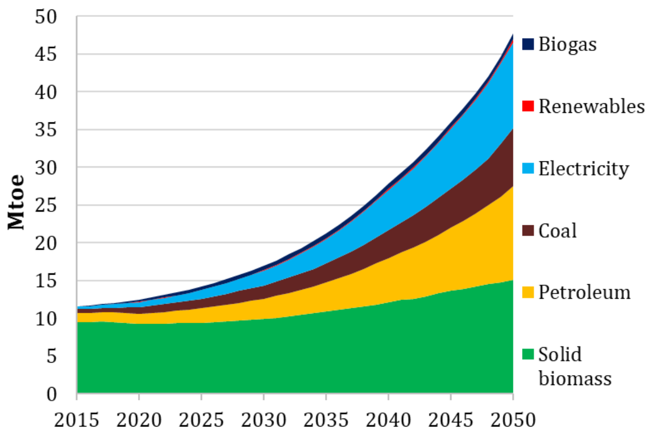

Fig. 5 FEC by fuel type in BAU during 2015–2050.

3.2.3 CO_2 Emissions

The CO_2 emissions during 2015–2050 in the BAU scenario are shown in Fig. 6. Total CO_2 emissions would increase from 6 $MtCO_2$ in 2015 to 15 $MtCO_2$ in 2030 and 66 $MtCO_2$ in 2050. Biomass is considered carbon neutral (i.e., its consumption and production are assumed to take place in a sustainable manner), therefore, CO_2 emitted from biomass burning is not accounted for.

The trend of residential CO_2 emissions would remain broadly flat during 2015–2050; as such its share would

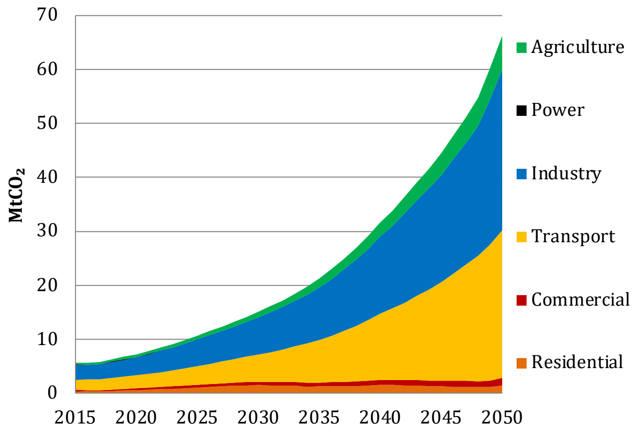

Fig. 6 CO_2 emissions during 2015–2050 in BAU.

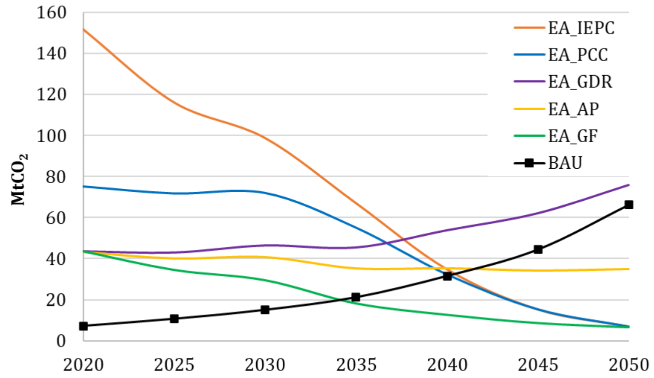

Fig. 7 CO_2 emissions in BAU and emission allowances in the energy sector.

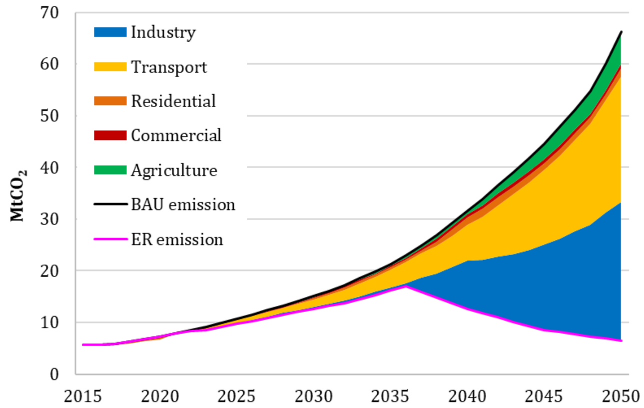

Fig. 8 CO_2 emission reduction by sector in the ER scenario.

decrease from 6% in 2015 to 2% in 2050. The industry and transport sectors were the first and second largest emitters of CO_2 in 2015 accounting for 16% and 11% of the emissions, respectively. The commercial and agriculture sectors contributed around 6% of GHG emissions in 2015. In 2050, the industrial sector would be the highest CO_2 emitter (45%) while the transport sector (41%) would stand second. The agriculture and commercial sectors would account for 10% and 2%, respectively, of the total CO_2 emissions in 2050. The share of the power sector in CO_2 emissions would remain negligible during 2015–2050.

3.3 Energy and Emissions in the ER Scenario

The emission reduction (ER) scenario is based on the emission allowances estimated as discussed in Section 3.1. The emission reduction scenario first estimates the carbon sequestration potential in Nepal during 2020–2050 from the LULUCF sector. Based on the estimation of CO_2 emissions from the IPPU, agriculture and waste sectors, as well as sequestration from the LULUCF sector, the emission allowances in the energy sector are estimated such that the sum of the emissions and sequestration is equal to the emissions allowance estimated from the effort-sharing approaches. The emission sequestration from the LULUCF sector is based on the estimation in the 'with additional measures' (WAM) scenario of the Nepal-LTS submitted to the UNFCCC. The emission allowances in the energy sector are used as the emission limit in the ER scenario.

Figure 7 compares CO_2 emissions in the energy sector in the BAU scenario and the emissions allowances in the energy sector as estimated by using effort-sharing approaches. Emission allowances estimated from different effort-sharing approaches are represented by abbreviations. The emission allowances in AP and GDR, i.e., EA_AP and EA_GDR do not comply with the carbon neutrality target of Nepal; therefore, these emission pathways will not be considered in the analysis. The results show that Nepal's energy sector emissions in BAU would not exceed the emission allowances up to 2034 in EA_GF and 2040 in EA_IEPC and EA_PCC. The emission pathway in EA_GF is the most challenging pathway in the case of Nepal; therefore, this study considers the emission limit in 2035 to 2050 from EA_GF for the ER scenario. In the ER scenario, the emission reductions in 2040 and 2050 from the BAU levels would be 60% and 90% in 2040 and 2050, respectively. In the ER scenario, the NDC targets of Nepal are also considered.

3.3.1 CO_2 Emissions

Figure 8 presents the CO_2 emission reduction in the energy sector by sub-sector in the ER scenario compared to the BAU scenario. The total CO_2 emissions in the BAU and ER scenarios are also presented in the figure. Following the emission limit as discussed earlier, the total CO_2 emissions would peak in 2036 reaching 17 $MtCO_2$ and then decline to 12.6 $MtCO_2$ in 2040 and 6.5 $MtCO_2$ in 2050. The transport sector would offer the largest emission reduction up to 2038, whereas after 2038 the emission reduction would be the highest from the industry sector. In 2040, the emission reductions from the BAU level in the industry and transport sectors would be 9.4 and 6.8 $MtCO_2$, respectively. The emission reduction in 2040 from the residential, agriculture and commercial sectors would be 1.5, 0.73 and 0.68 $MtCO_2$, respectively. In 2050, the emission reduction from the industry and

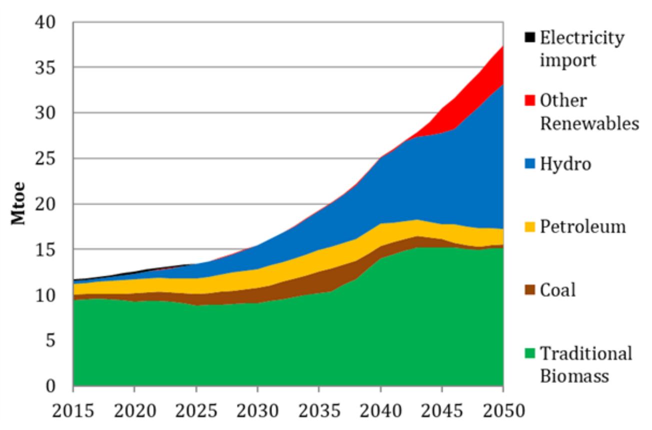

Fig. 9 PES in the ER scenario during 2015–2050.

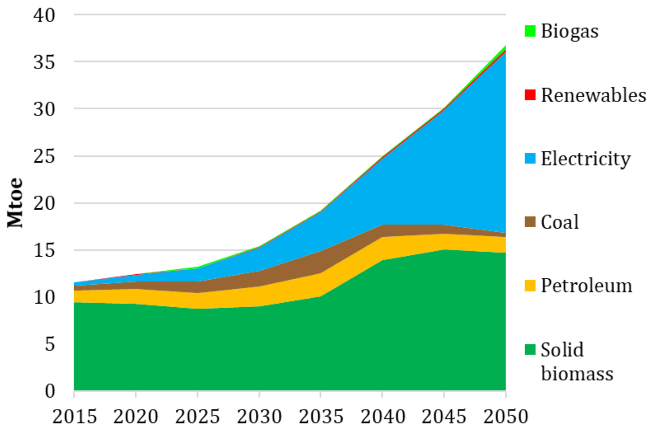

Fig. 10 FEC by fuel type in the ER scenario during 2015–2050.

transport sectors would be 26.9 and 24.2 $MtCO_2$ respectively. Similarly, the emission reduction from the agriculture, residential and commercial sectors in 2050 would be 6.3, 1.5 and 1.0 $MtCO_2$, respectively. The cumulative CO_2 reduction during 2015–2050 in the industry, transport, agriculture, residential and commercial sectors would be 206.1, 202.3, 38.6, 20.2 and 13.0 $MtCO_2$, respectively. The power sector would be completely dependent on hydropower; therefore, there would be no emission reduction from the power sector.

3.3.2 Primary Energy Supply

The primary energy supply (PES) in the ER scenario is presented in Fig. 9. The PES would reach 15.5 Mtoe in 2030 and 37.4 Mtoe in 2050. The PES in the ER scenario would be lower than the BAU level by 23.1%. This is due to the high level of electrification combined with energy efficiency improvement in the end-use technologies in the ER scenario. Biomass would remain the dominant fuel during the period, except in 2050, when hydro would account for the highest share of the primary energy supply, 42.6%. The share of biomass would drop from 73.7% in 2020 to 58.7% in 2030 and 40.5% in 2050. The share of hydro would increase from less than 5% in 2030 to 16.6% in 2030, 28.6% in 2040 and 42.6% in 2050. The share of other renewables (mainly solar) would be 11.3% in 2050; its share in 2040 would be only 0.5%. The use of coal would gradually increase during 2015–2035, but after 2036 the consumption of coal would decline. The use of coal for thermal applications would be replaced by electricity and biomass after 2035. Petroleum consumption would peak in 2040, and then decline during 2040–2050. During 2040–2050, there would be a massive increase in solar power. This is due to additional solar PV capacity required to electrify the end-use technologies. The hydropower capacity in 2050 would reach 47 GW. Similarly, the solar PV and wind capacities in 2050 would reach 23.5 GW and 1.5 GW, respectively. The total power generation capacity in BAU in 2050 would be only 37 GW, whereas the total power generation capacity in the ER scenario would be 72 GW.

3.3.3 Final Energy Consumption

Final energy consumption during 2015–2050 in the ER scenario is given in Fig. 10. Biomass will play a key role in the final energy mix during that period. The consumption of biomass would remain flat during 2015–2030, but the consumption would increase after 2030. Biomass will have an important role in substituting for coal and oil in thermal applications in industry. The consumption of coal and petroleum products would decline after 2035. Electricity would have a crucial role in the decarbonization of the end-use sectors mainly in the transport and industry sectors. Electric vehicles would displace internal combustion (IC) engine vehicles in both passenger and freight transport. Hydrogen-based technologies would not be cost competitive compared to EV technologies in the transport sector. In the residential and commercial sectors, electricity would replace LPG in cooking and heating. The agriculture sector would rely mainly on electricity and partially on solar energy for pumping. Electric tractors would replace diesel tractors in the agriculture sector. In the industry sector, electric boilers and heat pump technologies would be used in process heating.

4. Conclusions and final remarks

This study used effort-sharing approaches from the existing literature to determine the carbon budget and emission allowances for Nepal during 2020–2050. The estimates show that "ability to pay" (AP) and "greenhouse development rights" (GDR) would allow Nepal to emit 28.7 $MtCO_2$ and 69.6 $MtCO_2$, respectively in 2050. The emission allowances of these two approaches are not in line with Nepal's carbon neutrality target. In the other three approaches, i.e., "grandfathering" (GF), "immediate per capita convergence" (IEPC), and "per capita convergence" (PCC), carbon dioxide emissions would converge to approximately zero by 2050. Based on the emission allowance, CO_2 emissions that would be allowed from the energy sector were calculated using the CO_2 emission estimates from the IPPU, agriculture, LULUCF and waste sectors. This was used as a basis for an emission pathway in the energy sector for achieving carbon neutrality and referred to as the emission reduction (ER) scenario. The AIM/Enduse model was used to assess the energy and emissions implications in the BAU and ER scenarios.

The CO_2 emissions in the BAU scenario would reach 15.1 $MtCO_2$ in 2030 and 66.3 $MtCO_2$ in 2050. In the ER scenario, the emissions in the energy sector would peak in 2036, reaching 17 $MtCO_2$ and then drop continuously up to 2050, reaching 6.5 $MtCO_2$. The CO_2 emissions from the energy and other sectors (IPPU, agriculture) would be offset by carbon sequestration from the forestry sector. Nepal-LTS reports that the CO_2 sequestration potential in Nepal in 2050 from the LULUCF sector would be 9.2 $MtCO_2$. To achieve carbon neutrality by 2050, renewable-based power generation would need to be deployed on a massive scale. In BAU, the power generation capacity would be 37 GW. In the ER scenario, the capacity requirement would reach 72 GW. In addition, biomass would also play a crucial role in meeting industrial thermal energy demand. Electric vehicles would have a major role in the decarbonization of the transport sector. In the industry sector, electric boilers and industrial heat pumps would be required to replace fossil-fuel based boilers in process heating. The use of LPG cookstoves for cooking and heating would be replaced by electric cookstoves and heaters in the residential and commercial sectors. However, decarbonization of the energy sector would be a challenging task. Nepal already has plans and policies for promoting electric vehicles and electric cooking. However, achieving carbon neutrality means electrification of end-use technologies to the optimum level. Reduction in the costs of solar PV technologies and batteries would favor the electrification target, but proper policies would need to be implemented to promote electricity-based technologies and phase out fossil-fuel based technologies. Electrification of cooking technologies and transport vehicles is already underway, yet the electrification of other end-uses in industry as well as agriculture, residential, and commercial sectors would require appropriate policies as well as financial incentives. In addition, the power grid and distribution network would need to be upgraded to provide a reliable and stable power supply. Furthermore, measures other than financial support should be taken into consideration such as green finance or climate finance options.

Biomass is carbon neutral if it can be harvested in a sustainable way. Achieving carbon neutrality also implies higher use of biomass energy. Therefore, policies that promote sustainable harvesting of biomass will be crucial. The forestry sector is not only a source of carbon neutral energy, but also a carbon sink. The forestry sector plays an important role in offsetting the carbon dioxide emissions from hard-to-abate sectors, i.e., sectors in which the clean energy transition is not straightforward due to lack of alternative technologies or high implementation costs. The cost of carbon removal in the forestry sector lies in the range of \$0.5 to \$7 per tCO_2 for developing countries, so the forestry sector should also be prioritized for carbon dioxide mitigation. Carbon removal through afforestation, forest restoration and forest management must be implemented at an optimum level.

This study has focused on achieving carbon neutrality by 2050 and analyzed only carbon dioxide emissions in the energy sector. The study finds that carbon neutrality is achievable with decarbonization of the energy sector and carbon sequestration from the LULUCF sector. However, IPCC states that "limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane." The agriculture sector is the major source of methane emissions in Nepal. In terms of GHG emissions, Nepal has higher GHG emissions from its agriculture sector than from its energy sector. GHG mitigation in the agriculture sector will be challenging as there are limited technological and mitigation measures in the agriculture sector. Also, non-CO_2 emissions from biomass energy use exceed the total carbon dioxide emissions from fossil-fuel burning in Nepal (MoSTE, 2014). The use of biomass can be considered carbon neutral in CO_2 terms, but non-CO_2 emissions from biomass must not be ignored. Therefore, efforts to reduce non-CO_2 GHG emissions should also be prioritized in future research.

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References

Government of Nepal (GON) (2021) Nepal's Long-term Strategy for Net-zero Emissions. Retrieved from https://unfccc.int/sites/default/files/resource/NepalLTLEDS.pdf (accessed 9 April 2022)

IEA (International Energy Agency) (2014) Technology Roadmap: Solar Photovoltaic Energy. OECD/IEA, Paris.

IEA (2017) Energy Technology Perspectives 2017. Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2017 (accessed 9 April 2022)

IEA (2020) Energy Technology Perspectives 2020. Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2020 (accessed 9 April 2022)

IEA (2021) Net Zero by 2050: A Roadmap for the Global Energy Sector. Retrieved from https://www.iea.org/reports/net-zero-by-2050 (accessed 9 April 2022)

Intergovernmental Panel on Climate Change (IPCC) (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. *In*; V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, R. P. C. Péan, S. Connors, J.B.R. Matthews, X. Z. Y. Chen, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfild (eds.) IPCC, Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157940

Kainuma, M., Matsuoka, Y. and Morita, T. (2003) Climate Policy Assessment: Asia Pacific Integrated Modeling. Springer, Japan.

MinErgy (2012) A Roadmap for Efficient Brick Production in Nepal. Retrieved from http://www.repic.ch/files/6113/7544/1756/SB_AGHH_Minergy_Road_Map.pdf (accessed 9 April 2022)

Ministry of Forests and Environment (MoFF) (2021a) Expanding Forestry Sector for Long-Term Strategy (LTS) in Nepal, eds. Kathmandu.

Ministry of Forests and Environment (MoFF) (2021b) Nepal's Third National Communication (TNC) to the United Nations Framework Convention on Climate Change (UNFCCC). Retrieved from https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/986542371_Nepal-NC3-1-Nepal_TNC_Final.pdf (accessed 9 April 2022)

Ministry of Science Technology and Environment (MoSTE) (2014) Nepal Second National Communication to United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/resource/docs/natc/nplnc2.pdf (accessed 9 April 2022)

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., et al. (2007) Forestry. *In*: Metz, B., Davidson, O., Bosch, P., Dave, R. and Meyer, L., eds. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Nepal Energy Efficiency Programme/GIZ (NEEP/GIZ) (2012) Baseline Study of Selected Sector Industries to Assess the Potentials for More Efficient Use of Energy. Retrieved from http://energyefficiency.gov.np/downloadthis/baseline_study_of_selected_sector_industries.pdf (accessed 9 April 2022)

Neupane, D., Kafle, S., Karki, K.R., Kim, D.H. and Pradhan, P. (2022) Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis. *Renewable Energy*, 181: 278–291. https://doi.org/10.1016/j.renene.2021.09.027

Pradhan, B.B., Limmeechokchai, B. and Shrestha, R.M. (2019) Implications of biogas and electric cooking technologies in residential sector in Nepal: A long term perspective using AIM/Enduse model. *Renewable Energy*, 143: 377–389. https://doi.org/10.1016/j.renene.2019.05.026

Pradhan, B.B., Shrestha, R.M. and Limmeechokchai, B. (2020) Achieving the Paris Agreement's 2 degree target in Nepal: the potential role of a carbon tax. *Climate Policy*, 20(3): 387–404. https://doi.org/10.1080/14693062.2020.1740149

Pradhan, B.B., Shrestha, R.M., Pandey, A. and Limmeechokchai, B. (2018) Strategies to Achieve Net Zero Emissions in Nepal. *Carbon Management*, 9(5): 533–548. https://doi.org/10.1080/17583004.2018.1536168

Shakya, S.R., Kumar, S. and Shrestha, R.M. (2012) Co-benefits of a carbon tax in Nepal. *Mitigation and Adaptation Strategies for Global Change*, 17(1): 77–101. https://doi.org/10.1007/s11027-011-9310-1

Shakya, S.R. and Shrestha, R.M. (2011) Transport sector electrification in a hydropower resource rich developing country: Energy security, environmental and climate change co-benefits. *Energy for Sustainable Development*, 15(2): 147–159. http://dx.doi.org/10.1016/j.esd.2011.04.003

Shrestha, R.M. and Rajbhandari, S. (2010) Energy and environmental implications of carbon emission reduction targets: Case of Kathmandu Valley, Nepal. *Energy Policy*, 38(9): 4818–4827. http://dx.doi.org/10.1016/j.enpol.2009.11.088

Shrestha, R.M. and Shakya, S.R. (2012) Benefits of low carbon development in a developing country: Case of Nepal. *Energy Economics*, 34, Supplement 3: S503–S512. http://dx.doi.org/10.1016/j.eneco.2012.03.014

Shrestha, R.M., Acharya, J., Rajbhandari, S. and Pradhan, B.B. (2018) Sustainable Energy Access Planning: A Case Study. Asian Development Bank (ADB), Manila. Retrieved from https://www.adb.org/sites/default/files/publication/448631/sustainable-energy-access-planning-case-study.pdf (accessed 9 April 2022)

Shrestha, R.M., Limbu, T.R., Pradhan, B.B., Paudel, A. and Karki, P. (2021) Energy Efficiency in South Asia: Opportunities for Energy Sector Transformation. Asian Development Bank, Philippines.

van den Berg, N.J., van Soest, H.L., Hof, A.F., den Elzen, M.G.J., van Vuuren, D.P. et al. (2020) Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change*, 162(4): 1805–1822. https://doi.org/10.1007/s10584-019-02368-y

WECS (2010) Energy Sector Synopsis Report 2010. WECS, Ministry of Energy, Kathmandu.

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