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Research paper

Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: A case study of Nepal

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ABSTRACT

There is a growing number of national, subnational and even company targets for net-zero emissions of CO_2 in support of the Paris Climate Agreement goals of limiting the global average temperature increase within 1.5 °C by 2100. The challenges faced by developing countries in achieving net-zero emissions targets are, however, very prominent due to their common desire for rapid economic growth, improved socio-economic conditions, and greater climate resilience. In addition, this has to overcome many constraints related to the competitiveness, acceptability, and sustainability of proposed and planned low-carbon initiatives. It is thus very important to understand the economic and technical characteristics of net-zero emissions concepts and pathways. The constraints can best be addressed if actual and transparent co-benefits related to these initiatives are identified and reflected during their implementation. Here we employ the Low Emissions Analysis Platform (LEAP) to examine Nepal's recently introduced 'Long-term Strategy for Net-zero Emissions' and to estimate anticipated co-benefits in terms of reducing air pollutants emission and enhancing energy security and energy equity. Under the reference scenario (REF), the annual CO_2 emission is expected to increase from 23 $MtCO_2$ in 2019 to 79 $MtCO_2$ in 2050 with significant increase in air pollutants emissions in the range of 60% (Organic Carbon) to 183% (SO_2), increase in energy import dependency, reaching electricity consumption per capita below one-quarter of the world average. Under the 'With Additional Measures (WAM)' strategy scenario, air pollutants would be reduced in the range of 70% (Organic Carbon) to 85% (Black Carbon) respectively, in 2050 as compared to the REF. Similarly, it results drastic improvement in energy security indicators and energy equity. It is expected that the findings of this study will provide useful input to policymakers, private sector, societal actors and researchers in support of successful implementation of the initiatives for sustainable socio-economic transformation pathways.

1. Introduction

Climate change as a result of global warming due to emissions of greenhouse gases (GHG) is an increasingly urgent major global challenge of our time that impacts the planet and people, now and in the future, in all countries across the world. In the 21st Conference of Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement set specific long-term goals to hold global temperature increase to well below 2 °C, and to pursue efforts to limit it to 1.5 °C, to reach the peak of global GHG emissions and begin their decrease as soon as possible, and to achieve a neutral balance between emissions and removals in the second half of the century (UNFCCC, 2016). As of November 2021, 192 states and EU, representing 98% of global GHG emissions, have ratified or acceded to the Paris Agreement (UNFCCC, 2022b). As of September 2022, 62 parties to the Paris Agreement including 54 countries and European Union (EU) have submitted to the UNFCCC a long-term strategy to attain a net-zero emissions target and more than 100 countries are planning to do so. At present, Bhutan and Suriname are the only two net negative countries in accounting for carbon dioxide emissions and natural uptake within the country borders. China being the

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largest contributor of annual GHG emission has committed to attain net zero carbon emissions by 2060, India has aimed to a net-zero carbon emissions target by 2070, while the EU and most other countries aim to achieve net-zero carbon emissions by 2050. Whereas, small economy countries which are more vulnerable to climate change effects like Maldives, Laos, Malawi etc. have set target to achieve net-zero before or 2050 in their policy document or made declaration (UNFCCC, 2022a). Despite the various mitigation efforts and government commitments, the global GHG emissions are rising, at 49.8 billion metric tons of CO_2-equivalent emissions in 2015 (Ritchie and Roser, 2020), expected to reach 56 billion tons in 2030, which is approximately twice the targeted emissions for 2030, if global warming is to be limited to 1.5 °C, for which emissions would instead need to be reduced by 7.6% annually (UNEP, 2019b).

The role of developing and emerging economies in achieving net-zero emissions targets will be very prominent in the future. As the global economy is beginning to emerge from the impacts of the COVID-19 pandemic, it is expected that it will recover at a slower pace in the event of emerging new COVID-19 variants and geopolitical situations. The immediate priority of developing and emerging nations is faster economic growth to support a socio-economic transformation towards a better standard of living, whereas maintaining climate neutrality and climate resilience is a long-term imperative. They also suffer severely from emissions of air pollutants (AP), with most of the nearly 7 million air pollution-related premature deaths across the world every year being in developing countries (HEI, 2020). As most developing countries are still in the process of addressing the issue of energy equity in terms of access to affordable, reliable, and modern energy for all by 2030 under the UN sustainable development goal, SDG-7 (UNDP, 2021), it is anticipated that demand for modern energy will grow rapidly until access as well as basic per capita energy demand are achieved. Furthermore, energy security on the supply side is also a major concern for developing countries, which mostly depend strongly upon imported fossil fuels. Following the low carbon economic development path is seen as the best option which can address both issues, but its realization depends on many constraints related to the competitiveness, acceptability, and sustainability of the low carbon options under the existing market, trade, financing, and regulatory mechanisms (Goldthau et al., 2020; O'connor, 2010). These constraints can be addressed to a greater extent if all actual co-benefits besides climate benefits, both monetary and non-monetary, are identified and reflected transparently during the assessment and implementation of the low carbon options. During COP26, this was highlighted by mentioning the need for incorporating an environment service charge into commodities trade, and for phasing-out subsidies on fossil fuels, and by more than 100 countries pledging to cut methane emission by 30% and to stop deforestation by 2030. Therefore, it is very important to understand the economic and technical characteristics of the current local and global situation and future low-carbon options.

Nepal is among the 10 most vulnerable countries to climate-change-related disasters and risks (Eckstein et al., 2021) despite its small contributions to global GHG emissions, being 0.06% in 2011, which grew from 0.025% in 1994 (MoPE, 2017; MoSTE, 2014). Nepal's GHG emissions from both energy and non-energy sectors are increasing with growing economic activities, with a 2.5-fold increase from 24 million metric tons in 2000 to 60 million metric tons in 2019, at an annual average growth rate of 4.8% (Government of Nepal, 2021; MoSTE, 2014). As Nepal is preparing for graduating from the category of least developed countries to middle income countries by 2030 (CDP, 2021), it is expected that the pace of economic development will increase in the country, with increasing consumption of fossil fuels if the existing trend of energy consumption continues in the long run as observed in other developed countries (Yamaka et al., 2021).

The country's supply of fossil fuels is mostly based on the import from the neighboring country India, accounting for 22% of merchandise imports from India and 14% of overall imports in 2019/20 (NRB, 2020). Nepal's total export earnings are not enough to pay for the imports of petroleum products (NRB, 2020), raising concerns about the economic vulnerability and energy supply security (Shakya et al., 2022a). In addition, ambient and indoor air pollution from the burning of solid fuels and fossil fuels result in nearly 42,000 premature deaths per year in Nepal (HEI, 2020). Besides, Nepal is still in the process of attaining access to electricity for 100% of its population, along with attaining other economic development goals, including the SDG target 7.1 of providing universal access to affordable, reliable, and modern energy services by 2030. Recent study has shown that energy equity factors like per capita electricity consumption and electricity access plays the major role in the national energy transition mostly in the developing countries (Shakya et al., 2022b).

Nepal is a Party to the UNFCCC since 1992. It has been continuously and actively supporting international efforts on climate change mitigation and adaptation. Nepal submitted its second Nationally Determined Contribution (NDC) in 2020 with quantified mitigation targets along with supporting policies for the reduction of GHG emissions. In 2021, the country has introduced a Long-term Strategy (LTS) for Net-zero Emissions which aspires to achieve sustainable net-zero CO_2 emissions by 2045 (Government of Nepal, 2021). This is in line with the Paris Agreement to address climate change effects and its long-term economic transition goal to reach middle income countries by 2030 pursuing low carbon and sustainable development. The country is in the process of developing and implementing NDC implementation plan following the LTS for Net-zero emissions.

There are limited studies on the co-benefits of low carbon development strategies in Nepal. They analyzed co-benefits related to environmental emissions and/or energy security result from sectoral electrification and energy efficiency (Nakarmi et al., 2014; Shakya and Shrestha, 2011), carbon tax (Pradhan et al., 2020; Shakya et al., 2012), and low carbon development paths (Shrestha and Shakya, 2012). Pradhan et al. (2019) studied the strategies to achieve net-zero GHG emissions for Nepal, but did not analyze co-benefits. Nakarmi et al. (2020) reported health and crop yield benefits with the implementation of measures to reduce short-lived climate-forcing pollutants (SLCP) consisting of black carbon, methane, and $PM_{2.5}$, but they did not analyze co-benefits related to energy security, energy equity and broader air pollutants. The detailed historical emissions of GHGs and air pollutants from technology use in Nepal for 2001 to 2016 were analyzed by Sadavarte et al. (2019), while Shrestha (2018) reported emissions of GHGs and air pollutants from all sectors for one year (2008/09), though again neither explicitly considered the range of co-benefits.

This study attempts to address the research gap related to the earlier studies by analyzing for the first time various co-benefits of Nepal's Long-term Strategy for Net-zero Emissions as follows: (i) it considers, in addition to greenhouse gases (CO_2, CH_4 and N_2O), the emissions of seven air pollutants, namely carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compound (NMVOC), sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$), black carbon (BC), and organic carbon (OC); (ii) it analyzes energy security in terms of accessibility, availability, and affordability by using five distinctive indicators; (iii) it studies the effects on the energy equity in terms of access to sufficient electricity as envisioned in the SDG-7. The findings in this study highlight the co-benefits of the net-zero emissions initiatives in the context of developing countries and provide impetus to diverse actors from policymaking, research, businesses, non-governmental organizations and civil society for successful implementation of the initiatives, and to follow pathways that lead to societal change towards sustainable development.

2. Methods

This study used quantitative method with the use of bottom-up national GHG emission modeling framework to examine present status of environmental emissions and energy indicators and to estimate anticipated co-benefits in terms of reducing air pollutants emission and enhancing energy security and energy equity while implementing recently introduced Long-term Strategy for Net-zero Emissions of Nepal following the Paris Agreement. The main methodological procedures followed in the study consists of following steps:

- development of national GHG emissions inventory estimation model representing all the energy and non-energy activities emitting GHG and air pollutants following 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).
- estimation of the emissions and the indicators for energy for the base year 2019 and future projection till 2050 under base case scenario using econometric model (Shakya and Shrestha, 2011) and projections mentioned in the existing literature for activity demand projections.
- development of policy intervention scenarios for limiting GHG emissions with introduction of activity level targets from energy and non-energy sectors mentioned in the national long-term strategy for net zero emissions.
- comparison and interpretation of the results obtained from the base case and policy intervention case scenarios highlighting effects on the environmental, energy security and energy equity co-benefits.

The detail description on the methodological steps is discussed in the following sections.

2.1. Development of national emissions system

There are various tools and software available that can be used for the analysis of scenarios or to develop a modeling framework for analysis. However, most of them have a specific purpose and have certain limitations, e.g., most of them treat the energy sector and non-energy sector separately. The Low Emissions Analysis Platform (LEAP) modeling tool developed by the Stockholm Environment Institute (Heaps, 2020), in contrast, includes both energy-related and non-energy-related emissions within a single modeling framework. It has the provision of incorporating GHG and other environmental pollutant emission factors as per the IPCC guideline for national GHG inventories. Furthermore, LEAP can analyze the interactions and their implications among the energy and non-energy sectors, the economy, and the environment. This study has used the LEAP modeling tool for developing different scenarios representing LTS for net-zero emissions in Nepal by 2050.

The Nepal-LEAP model developed for this study is primarily divided into energy and non-energy sectors which are dependent on macroeconomic and demographic indicators. Along with these, resource, technological, and emission factor databases are also fed into the system, firstly to create a base model and then the future scenario development activities. The energy and the non-energy sectors are subdivided into sub-sectors, each having further categorization according to sectoral activities. The detailed structures of the disaggregated sub-sector activities for energy and non-energy sectors are given in Appendix A.1 and A.2, respectively. This modeling framework has also been used for analyzing GHG emissions in support of the formulation of Nepal's LTS for net-zero emissions (CES/UNDP, 2021; Government of Nepal, 2021). Fig. 1 shows a flowchart for the activities conducted for the modeling analysis in this study.

2.2. Economy and demography

In the study, the energy-consuming activities are linked with economic and demographic parameters (Pradhan et al., 2019; Shakya and Shrestha, 2011; Shrestha and Shakya, 2012). The agricultural, commercial, and industrial activities are taken to be dependent on the respective GVA (gross value added) in each sector. Meanwhile, in the residential sector, the total energy demand is dependent primarily on the population. The transport sector is dependent on both economic and demographic parameters for freight and passenger transportation, respectively. GDP growth rates have been taken from the targets set for the national economy in government documents (MoF, 2016, 2020; NPC, 2014, 2017, 2020). For the reference case, the annual GDP growth rate of 7% between 2022 and 2050 as stipulated in the 15th development plan has been considered.

South Asia is expected to face its worst economic crisis for several years due to impacts of the COVID-19 pandemic, and Nepal's real GDP in 2020 decreased by ca. 2.1% and increased by 1.8% in 2021 compared to the previous year (World Bank, 2020) while an 8.5% growth was envisaged in the Nepal Government's budget for 2019/20. The Nepal Government budget for 2021/22 includes a projected GDP growth rate of 7%, assuming a quick recovery of economic activities in the post-COVID-19 pandemic period (MoF, 2020). Thus, a growth rate has been considered to increase from 1.8% to 7% during 2021 to 2022 considering economy bounce back as it did in 2016/17 after the April 2015 earthquake. The demographic development is assumed to include a population growth rate of 1.35% and an urbanization rate of 2.8% (CBS, 2012, 2014, 2020).

2.3. Structure of emissions from energy consuming sectors

The study has taken a bottom-up approach for estimating energy-consuming activities and associated emissions. A first-level categorization of sectors has been adopted as per the national energy synopsis report and thus divided into five economic sectors (agriculture, commercial, industrial, residential, and transport). There are 325 demand technologies considered in the energy sector. Each sector is further subdivided as per subcategory and end-use in subsequent sectors (Fig. A.1). Under the agriculture sector, the end-use service demand comprises water pumping for irrigation and farm machinery such as tractors and threshers. The commercial sector is sub-categorized into three types based on the Nepal Standard Industrial Classification (NSIC), consisting of tourism and trade, financial and real estate, and other services. The industrial sector has been classified into nine categories by type of products and economic output as per NSIC. In the case of the residential sector, it is subdivided into rural and urban categories as the energy consumption patterns in those areas are quite different based on the energy resource availability, affordability, infrastructure development, and other socio-economic drivers. The transport sector is initially classified into three groups: intercity (passenger, long-distance transport), intracity (passenger, short-distance transport within the local area), and freight (transportation of goods and materials). It is further classified as per the vehicle types into the respective groups. The total population of vehicles in each province is taken from the total number of registered vehicles in the province as per the list published by the Department of Transport Management. The emission factors used in the analysis are taken from

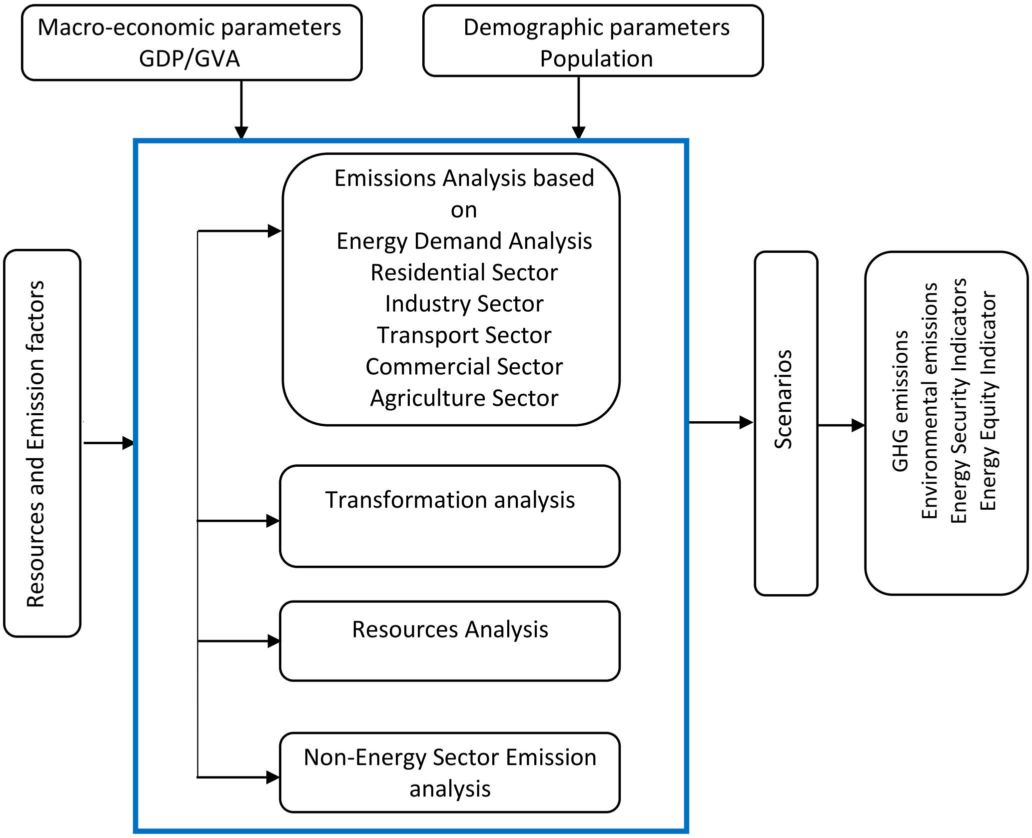

Fig. 1. Low Emissions Analysis Platform (LEAP) Structure and Quantitative Analysis Flow chart (Based on Heaps, 2020) used for analysis of Nepal's strategies for net-zero GHG emissions and associated co-benefits.

various reports and studies, selecting the country and technology-specific data as much as possible (Bhattacharya et al., 2002; Bond et al., 2013, 2004; EEA, 2019; IPCC, 1996, 2006; Sadavarte et al., 2019; Shrestha et al., 2013; Venkataraman et al., 2010). The stocks and prices of domestic energy resources for biomass (fuelwood, agriculture residues, and animal waste), hydropower, solar, and others are considered from various national documents (AEPC, 2008; NEA, 2021; NOC, 2021; WECS, 2010, 2019, 2021). The estimated rates of fuel price increase during 2020–2050 are based on earlier studies and reports (Greenpeace International, 2015; IEA, 2021; Teske et al., 2011). Further detail is given in the supplementary materials.

2.4. Structure of emissions from non-energy sectors

For the non-energy sector, industrial processes and product use (IPPU), waste, and agriculture, forestry and other land use (AFOLU) have been considered with structural distributions as shown in Fig. A.2. Fugitive emissions (IPCC category 1B) have not been considered in this study as such emissions are considered negligible in the country (CES/UNDP, 2021; Government of Nepal, 2021). To estimate the emissions in the non-energy sector, the study refers to the (IPCC, 2006) Guidelines (IPCC, 2006) using the Tier1 method due to the data limitation (CES/UNDP, 2021).

2.5. Descriptions of scenarios

Three main scenarios are considered in this study:

- A reference scenario (REF) assuming continuation of current trends (without the implementation of recently-decided policy measures);
- A scenario with existing measures (WEM) mentioned in the plans and policies adopted up to 2020;
- A scenario with additional measures (WAM) beyond those listed under WEM and which are feasible for the country.

These are described in the following subsections.

2.5.1. Reference (REF) scenario

The reference scenario assumes that current trends of various parameters will continue in the future as well if existing policies remain in place as they are. The major assumptions of this scenario for the projections in the future, with 2019 as the base year, are as follows. Other descriptions of the reference scenario used here are described in a report by CES/UNDP (2021):

- Annual average population growth rate during 2022–2050: 1.35%.
- Annual average GDP growth rate during 2022–2050: 7% with the composition of GDP VA following the trend observed in the past.
- Technology-mix of the end-use activities in the energy and non-energy sector in future years: similar to the recent calibrated year or base year.
- No new policy interventions during 2019 to 2050.
- Livestock and crop production projections: as in Kumar et al. (2019) until 2035 and then following the average growth rate during 2030–2035 mentioned in Enahoro et al. (2019).
- Fertilizer consumption: a linear growth during 2020–2050 with 121 kg per hectare in 2019 and 175 kg/ha by 2050 (MOALD, 2020).
- Changes in the land-use area including forest area during 2020 to 2050: as mentioned in MoFE (2021).
  Other descriptions of the reference scenario used here are mentioned in CES/UNDP (2021).

2.5.2. With existing measures (WEM) scenario

In this scenario, the same methodology has been used as in the reference scenario, but with a focus on the intervention measures specified in the plans and policies implemented and adopted up to 2020. It assumes the GDP growth rate to be the same as in the reference scenario. The mitigation measures consist of the implementation of low carbon technologies considered in the extended Nationally Determined Contribution (eNDC) 2020, the roadmap for achieving the SDGs by 2030 prepared by the National Planning Commission (NPC), and the government's other existing plans and policies (CES/UNDP, 2021). The details about mitigation measures and targets (CES/UNDP, 2021; Government of Nepal, 2021) considered in various energy and non-energy sectors in the WEM scenario are presented in Table 1 and Tables S11-14 respectively. They are briefly mentioned here. Mitigation measures in the energy sector include: electrification in major end-uses in all economic sectors such as efficiency improvement and alternative clean fuel intervention in the application of industrial process heat; substituting traditional brick kilns with 100% zigzag firing technique and biomass fuel mix in the brick industry; fuel switching to modern fuels (electricity, LPG) and renewable energy technologies (e.g., solar, biogas); and a modal shift to mass electric mobility in the transport sector. In the agriculture sector, they include biogas digesters 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 implementation of methane recovery, anaerobic digesters, and waste incinerator; however, the WEM scenario assumes that their implementation level is low. In the land use, land-use change and forestry (LULUCF) sector, mitigation measures include reduction in forest degradation and deforestation along with increased plantation and sustainable management of forests. There are no interventions in the industrial processes and products use (IPPU) sector in the WEM scenario.

2.5.3. With additional measures (WAM) scenario

This scenario builds on the GHG mitigation measures considered in the WEM scenario and also includes the accelerated rate of penetration of measures and the impacts of additional mitigation actions that are feasible for the country. It assumes the GDP growth rate is the same as that of the reference scenario. The details about measures and targets (CES/UNDP, 2021; Government of Nepal, 2021) considered in WAM scenario are presented in Tables SI11-14. They include implementation of all the proven technologies to the currently-acknowledged maximum technical feasibility to achieve net-zero CO_2 emissions before or by 2050. In the energy sector, the measures include electrification in major end-uses in all the economic sectors. The interventions in the industrial sector involve: electrification in motive power, boilers, and process heat; switching to alternative fuel mixes and hydrogen technology in the cement industry; and adoption of electric tunnel kilns in the brick industry. Likewise, the mitigation measures to reduce CO_2 emissions in the transport sector involve the introduction of fuel cells for passenger and freight vehicles, the use of electric vehicles, a synthetic fuel mix in aviation, and a modal shift to mass electric transportation. In the non-energy agriculture sector, over 20 mitigation measures have been considered, and the mitigation technologies are based on the most recent findings as of 2021, while the implementation potential is assumed to be the maximum technically feasible. Similarly, in the waste sectors, the mitigation measures are implemented at full technical feasibility by 2050. In the IPPU sector, carbon capture utilization and storage is considered as the primary mitigation measure to reduce CO_2 emission in the cement industry. The mitigation measures in LULUCF are similar to the WEM scenario, but the level of implementation is more stringent. It is assumed that agri-residue burning on fields would be completely stopped by 2050.

2.6. Indicators of co-benefit measures

2.6.1. Ambient air pollutants emission

This study considers the seven major air pollutants emission which are responsible for the negative effects on the public health, crops yield, forest and other socio-economic and environmental effects (Karlsson et al., 2020; Nakarmi et al., 2020; Sonwani et al., 2022). The air pollutants considered in this study are carbon monoxide, nitrogen oxides, non-methane volatile organic compound, sulphur dioxide, particulate matter, black carbon, and organic carbon.

2.6.2. Energy security indicators

Energy security deals with long-term security of supply of energy resources in terms of availability, accessibility and affordability and can be represented by using different indicators (Kruyt et al., 2009). This study used five different indicators of energy security, i.e., net energy import ratio (NEIR), the share of renewable energy (SRE), Shannon–Weiner Index (SWI).[1] the ratio of import fuel cost to GDP (FGDP), and energy intensity of GDP (EGDP) (Kruyt et al., 2009). NEIR measures the dependence on imported fuels for the supply of energy commodities, with higher values signifying a higher level of import dependency (accessibility). Similarly, SRE indicates the self-sufficiency in the energy supply from national resources, with a higher value indicating desirable conditions (availability). SWI measures the level of diversification of energy resources, with a higher value indicating a more diversified energy resource mix. Here four types of energy resources are assumed for calculation purposes (fossil fuels, biomass, hydropower, and others). The maximum possible value of SWI is 1.39 (if an equal amount of energy is supplied by each energy resource) and the minimum possible value is zero (if supplied by only one type of energy resource). FGDP indicates affordability of the energy consumption with a higher value indicating economic vulnerability due to its scale of expenditure of the foreign currency as compared to the national GDP. Finally, EGDP is a measure of the energy efficiency of the national economy, with a higher value indicating more dependence on the limited non-renewable energy resources.

2.6.3. Energy equity indicators

In this study, the electricity consumption per capita is taken as the proxy of the energy equity or energy poverty indicator (Shakya et al., 2022b). There is a large disparity in the per capita electricity consumption between developed and developing countries. Per capita electricity consumption is expected to rise during the economic transition of a developing country following the trends observed in the developed countries in the past (Shakya et al., 2022b).

3. Results and discussion

3.1. Analysis of reference scenario

3.1.1. GHG and AP emissions in the reference scenario

The annual total CO_2 emissions from the energy and non-energy sectors in 2019 were 23 Megatons Carbon Dioxide ($MtCO_2$), which is expected to rise to 34 $MtCO_2$ in 2030 and 79 $MtCO_2$ in 2050 under the reference scenario. In 2019, non-energy-related emissions accounted for 46% of net total CO_2 emissions after deducting carbon sequestration from the forest and it would gradually decline to 32% by 2050. The annual CO_2 emission from LULUCF is estimated to roughly double, from 8 $MtCO_2$ in 2019 to 17 $MtCO_2$ by 2050.

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[1] Shannon-Wiener Index $SWI = \sum_i s_i \ln s_i$ where, s_i = the share of fuel 'i'.

Table 1
Low carbon technology penetration targets of energy sector for WEM and WAM scenarios.
Source: CES/UNDP (2021) and Government of Nepal (2021).

Scenario/Target Year sectors	WEM -2050	WAM-2050
Residential	Urban: 20% LPG, 70% electric cooking 75% electrification in space heating, water heating Rural: 10% ICS, 40% LPG, 40% electric Cooking 50% electric space heating, 25% electric water heating	Urban/Rural: 100% electric cooking 100% LED lighting
Industrial sector	*Food and beverage:* 100% electrification in process heat and motive power, 50% electric Boiler *Textile and leather products:* 100% electrification in process heat and motive power, 100% electric boiler *Industrial chemical rubber and plastics:* 50% electrification in process heat, 100% in motive power, 50% electric Boiler *Mechanical engineering, metallurgy:* 50% electrification in process heat, 100% in motive power *Electrical engineering products:* 100% electrification in process heat and motive power, *Wood products and paper:* 50% electrification in process heat, 100% in motive power, 50% electric boiler *Bricks and clay products:* 100% electrification in motive power Substitute traditional Brick Kilns with 100% Zigzag Kiln and 25% biomass fuel mix by 2027 *Cement and non-metallic products:* 75% alternative clean fuel and 25% coal in process heat, 100% in motive power Limestone usage to improve energy efficiency by 20% 100% LED lighting 2% efficiency improvement rate	100% electrification in *Food and beverage,* *Textile and leather products.* *Industrial chemical rubber and plastics,* *Mechanical engineering, Metallurgy,* *Electrical engineering products and wood products and paper* *In bricks and clay products:* 100% electrification in motive Power 100% electric tunnel kiln by 2050 *Cement and non-metallic products:* 70% alternative clean fuel, 10% electric, 5% hydrogen, 15% coal in process heat, 100% electric in motive power
Transport sector	*Intercity*: 30% electric train, 20% electric car 40% diesel bus (bus/minibus) 10% airplane *Intracity*: 33% electric bus 20% electric car 5% electric motorcycle 35% public bus (bus and minibus) 2% monorail *Freight:* 30% electric train	Intercity: 20% electric bus 20% electric car 30% electric train 20% fuel cells electric bus, 10% airplane (synthetic fuels) Intracity: 20% electric car 48% electric bus 10% electric motorcycle 2% monorail 10% fuel cells electric car 10% fuel cells electric bus Freight: 40% electric train 30% electric vehicles 30% fuel cells vehicles
Commercial sector	100% electrification	100% electrification
Agriculture sector	*Water pumping:* 40% electric, 40% Solar PV pumping *Farm machinery:* 25% electricity	*Water pumping:* 60% electricity, 40% Solar PV pumping *Farm machinery:* 100% electrification

The annual total GHG emissions (CO_2, CH_4, and N_2O) from the energy end-use sector and non-energy sector in 2019 were 60 $MtCO_2e$, which would reach 79 $MtCO_2e$ in 2030 and 142 $MtCO_2e$ in 2050 in the reference scenario, which also clearly shows a significant contribution (61.5%) of non-CO_2 GHGs. The share of non-energy-related emissions was 71% of the net GHG emission in 2019. In 2050, the share of energy-related emissions would be 43%. The emissions from agriculture accounted for 46% in 2019 which would decrease to 34% in 2050. The shares of waste and IPPU would remain less than 8% and 5%, respectively, of total GHG emissions through 2019–2050. There would be net emissions rather than sequestration from the LULUCF sector during 2019–2050 in the reference scenario. In addition, with no additional cleaner solutions (policies and plans) there would be a significant increase (at least 60%) in emissions of various air pollutants (AP) during 2019–2050, e.g., OC by 60% and SO_2 by 183% (Table 2), contributing to indoor and ambient air pollution which is already severe in the country.

3.1.2. *Energy security*

How would the energy security of the country be affected over time in the reference scenario? To answer this question, for

Table 2
National GHG emissions (in Megatons per year) and AP emissions (in 10^3 tons per year) during 2019 to 2050 in Nepal under the reference scenario.

Emission	2019	2030	2050	Ratio 2050/2019
CO_2	23.064	34.723	78.637	3.4
CH_4	1.242	1.514	2.137	1.7
N_2O	0.0085	0.0101	0.0143	1.7
Total GHG emissions[a], $MtCO_2e$	60.076	79.783	142.245	2.4
CO	3153	3545	5427	1.7
NO_X	146	186	404	2.8
SO_2	31.5	39.1	89.3	2.8
NMVOC	653	738	1140	1.7
$PM_{2.5}$	285	313	470	1.6
BC	36.5	43.3	78.6	2.2
OC	126	138	202	1.6

[a] Total GHG here includes CO_2, CH_4, and N_2O with CO_2 equivalent of CH_4 and N_2O estimated based on 100-year global warming potential (GWP) of 28 and 265 respectively as used in the IPCC Fifth Assessment Report (AR5). MtCO2e stands for Megatons Carbon Dioxide equivalent with mentioned GWP.

Table 3
Energy security indicators in the REF scenario during 2019–2050 (unit: in % except SWI and EGDP).

Indicator	2019	2030	2040	2050
Net energy import ratio (NERI)	29.8%	34.9%	41.8%	47.3%
Share of renewable energy (SRE)	70.2%	65.1%	58.2%	52.7%
Shannon–Weiner Index (SWI)	0.86	0.97	1.01	1.03
Imported fuel cost to GDP ratio (FGDP)	18.4%	25.6%	22.6%	20.4%
Energy intensity of GDP (EGDP) (GJ/1000 USD)	46.7	30.4	21.1	15.8

selected years Table 3 presents five different indicators of energy security as defined in Section 2.6.2.

The increasing trend of SWI shows the growing diversification in the deployment of primary energy resources during the study period, which is mostly due to a decrease in the share of traditional biomass and an increase in the shares of fossil fuels, hydropower, and other renewables. The increasing trend of NIER and decreasing trend of SRE shows the increasing dependency on imported fuels and decreasing contribution of renewable energy in the total primary energy supply. At the same time increasing SWI indicates the improving energy supply mix with better distribution of the share of energy resources. This indicates that the country's dependence on imported energy (mainly fossil fuels) would increase significantly during 2019–2050 despite an increased level of diversification in the use of energy resources. The value of FGDP increases till 2030 but slightly decreases after 2030 to reach 20.4% by 2050 indicating a higher economic vulnerability. In the case of EGDP, there will be a gradual decrease in the value indicating improvement in energy efficiency in Nepal over 2019–2050 mostly due to fuel switching during urbanization and economic growth from traditional biomass with lower conversion efficiency to commercial energy (fossil fuels and electricity) with higher conversion efficiency. The share of traditional biomass in the total primary energy supply would change from 63.6% in 2019 to 42.1% in 2050.

3.1.3. Energy equity

In this study, the electricity consumption per capita is taken as the proxy of the energy equity or energy poverty indicator. It will increase by 159% from 276 kWh in 2019 to 715 kWh per capita in 2050 under the REF scenario (Fig. 2). This means even in 2050 the electricity consumption per capita in Nepal will reach only 21% of the global average of 3358 kWh per capita in 2019. This indicates that under the REF scenario, the issue of energy equity will still prevail in 2050, thus affecting the well-being of the majority of population of the country.

3.2. Implications of net-zero emissions strategy

3.2.1. Reduction in GHG emissions

The WEM scenario would generally show a significant reduction in CO_2 and other emissions. Annual CO_2 emissions would only be 3.9 $MtCO_2$ in 2030, a decrease of 89% compared to the emissions in the REF scenario, though they would then increase to 29.4 $MtCO_2$ in 2050, a 63% decrease compared to the REF scenario (Table 4). This seemingly odd result is due to the saturation of the sequestration potential of forests in the LULUCF sector in the WEM scenario (CES/UNDP, 2021; MoFE, 2021). In the WAM scenario, there would be a net sequestration during 2022–2033, and then again from 2045 onwards. In 2050, there would be a net CO_2 sequestration of about 6 $MtCO_2$ per year (Government of Nepal, 2021; MoFE, 2021). Regarding methane, the country would be able to reduce its emission by 17% in 2030 under the WAM scenario, which would reach 40% by 2050, thus supporting the CH_4 emission reduction target as envisioned during the recent COP26 of the UNFCCC. In terms of total CO_2e greenhouse gases, under the WEM scenario there would be a 44% reduction in the emissions in 2030 and likewise a 44% reduction in 2050, while under the WAM scenario the reduction would be 61% in 2030 and 78% in 2050, all compared to the REF scenario.

3.2.2. Reduction in air pollutant emissions

The implementation of the measures to reduce carbon emissions also would result in significant reductions in the emissions of air pollutants, as shown in Table 4 and Fig. 3.

Under the WEM scenario, there would be a substantial reduction in AP emissions in 2050 compared to the REF scenario, ranging from 41% for NO_x emissions to 80% for NMVOC emissions. The co-benefit value further increases under the WAM scenario, with a reduction of about 70% or more for the emissions of all air pollutants, e.g., 69.9% for OC and 85.6% for BC. Reduction in AP emissions are mostly due to the fuel switching from emission intensive fossil fuels to electricity from renewable energy like hydropower in the energy sector and reduction in the uncontrolled burning of agri-residue and waste in non-energy sector. This reduction in AP emissions would result in clear health benefits in terms of avoided sickness and deaths, as well as reduced crop yield loss due to the effects of air pollutants (Kuylenstierna et al., 2020; Nakarmi et al., 2020; UNEP, 2019a). It is worth it mentioning two key species here, namely CH_4 and BC, which are short-lived climate-forcing pollutants (SLCPs). CH_4 is a potent GHG and a precursor to the formation of ground-level ozone (another GHG which is also an air pollutant, toxic to humans and plants), while BC is an air pollutant and another strong global warming agent (UNEP, 2019a,b). The reduction of BC emissions by 86% and CH_4 emissions by 17% by 2050 is expected to yield immediate climate benefits as well. In addition, various other benefits are also expected, since improved air quality reduces the negative effects on the environment and ecosystems, as well as on glaciers and snowfields on the mountains, and in turn on aviation, tourism and infrastructure (UNEP, 2019a,b). These results highlight that Nepal's existing decarbonization strategies and potential additional plans would be valuable for cutting emssions of non-CO_2 GHGs and climate-forcing air pollutants in the short term, along with deeply cutting CO_2 emission in the long run. Similar results of air pollutants reduction due to low carbon initiatives were reported in other studies for Nepal (Shakya and Shrestha, 2011; Shrestha and Shakya, 2012), China (Zhang et al., 2021), and India (Mittal et al., 2015).

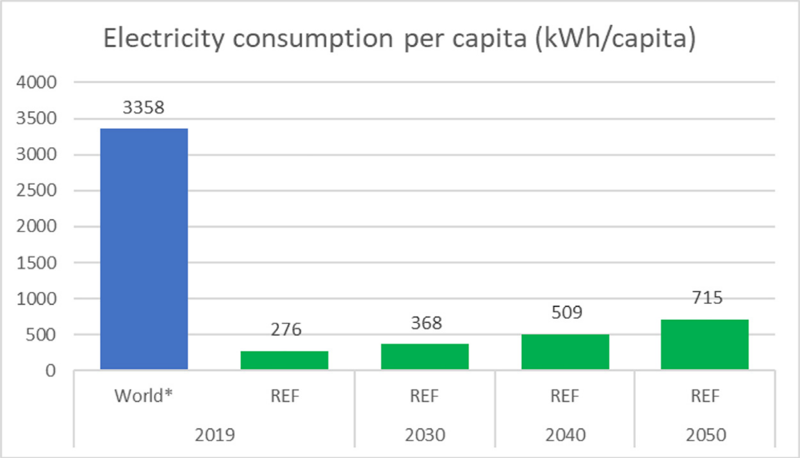

Fig. 2. Electricity consumption per capita (kWh per capita) in Nepal under the REF Scenario. Note: data obtained from https://ourworldindata.org/grapher/per-capita-electricity-consumption?time=2019.

Table 4
Change in GHG (in Megatons, Mt, per year) and AP emissions (in 10^3 tons per year) from energy and non-energy sectors in the WEM and WAM scenarios (in thousand Metric tons, mMt) National GHG emissions and AP emissions during 2019 to 2050 in Nepal under the reference scenario.

Emission	2019	2030			2050		
	REF	REF	WEM	WAM	REF	WEM	WAM
CO_2	23.064	34.723	3.943	−5.793	78.637	29.433	−5.730
CH_4	1.242	1.514	1.372	1.256	2.137	1.754	1.283
N_2O	0.0085	0.0101	0.0076	0.0068	0.0143	0.0070	0.0032
Total GHG emission[a], CO_2e	60.076	79.783	44.356	31.193	142.245	80.382	31.032
CO	3153	3545	1842	1932	5427	1881	1352
NO_X	145.9	185.7	139.0	136.1	403.9	237.4	73.9
SO_2	31.5	39.1	24.4	23.6	89.3	43.2	16.3
NMVOC	652.9	738.1	286.4	302.4	1139.5	226.5	167.2
$PM_{2.5}$	284.6	312.7	153.8	166.6	469.6	152.0	122.0
BC	36.5	43.3	20.5	21.4	78.6	25.0	11.3
OC	126.3	137.7	73.4	78.7	201.5	69.1	60.6

[a]Total GHG here includes CO_2, CH_4, and N_2O, where CO_2 equivalent of CH_4 and N_2O is based on 100-year global warming potential (GWP) of 28 and 265 respectively as used in the IPCC Fifth Assessment Report (AR5).

3.2.3. *Energy security enhancement*

The strategic measures aimed at net-zero CO_2 emissions would result in substantial improvement in energy security indicators. As compared to the REF scenario, both WEM and WAM scenarios show a drastic reduction (Fig. 4) in the NEIR, due to reduced import dependency, and an increase in SRE, indicating improvement in the accessibility and availability of sustainable energy resources. This is due to the fuel switching from the imported fossil fuels to electricity from renewable energy in the energy sector. The required power generation capacity by 2050 will increases from 10.1 GW under the Reference scenario to 35.9 GW under WEM and 51.8 GW under WAM which is mostly supplied by hydropower. For the energy mix (SWI), the WEM scenario shows improvement in all years as compared to the REF scenario, whereas the WAM scenario shows a reduced energy mix after 2045, mostly due to the significant reduction in the consumption of fossil fuels as a result of decarbonization measures. In terms of affordability and economic vulnerability, both WEM and WAM scenarios show improvements in energy security as is evident in the reduced values of FGDP due to avoidance of imported fossil fuels. Likewise, the efficiency of energy use increases as shown by the continued reduction in the value of the EGDP indicator attributed to the higher efficiency of electric devices compared to the fossil fuel-based devices. Similar results of improvement in energy security due to low carbon measures were reported in other studies for Nepal (Shakya and Shrestha, 2011; Shrestha and Shakya, 2012), India (Pathak and Shukla, 2016) and Europe (Schwanitz et al., 2015).

3.2.4. *Energy equity improvement*

Our analysis shows that net-zero emissions initiatives would also help to address energy equity issues, because there would be a significant increase in electricity consumption per capita in 2050 (Fig. 5). Under the WEM scenario, in 2050 it will reach 2499 kWh per capita and under the WAM scenario it would be 3396 kWh reaching the average world value. There would be a ca. 12-fold increase in electricity consumption per capita between 2019 and 2050 (WAM vs. REF) under low carbon initiatives thus helping to address energy equity issues of the country. Similar results of improvement in energy equity, indirectly through increase in the electricity consumption compared to the base case, due to low carbon measures were reported in other studies for Nepal (Shakya et al., 2012; Pradhan et al., 2019).

4. Conclusions

In order to keep the increase in global average temperature well below 2 °C by end of the century, as called for by the Paris Agreement, global carbon dioxide emissions would have to drop to net zero by around mid-century. Many countries across the globe are putting forward decarbonization strategies, setting net-

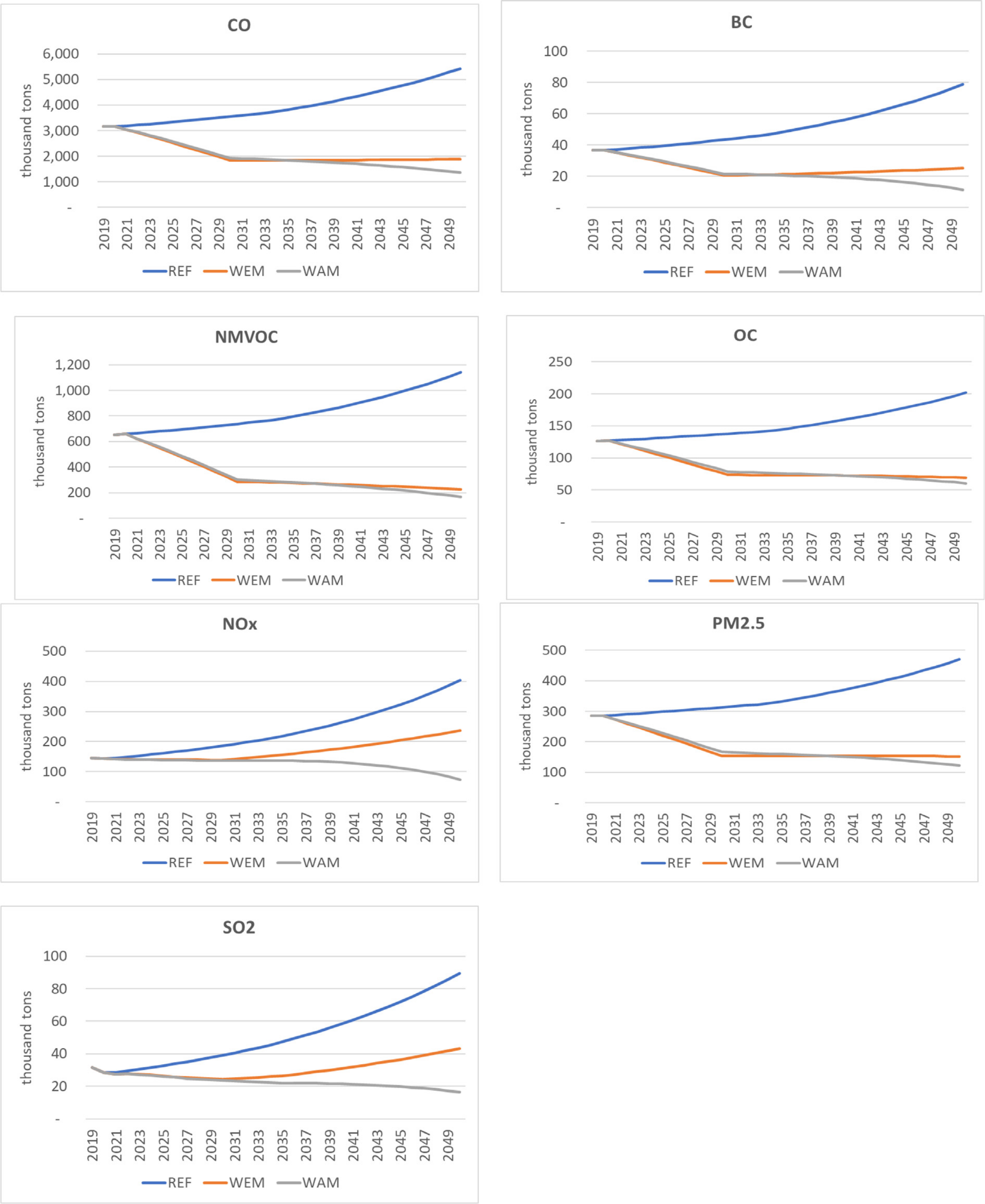

Fig. 3. Emissions of air pollutants under the REF, WEM and WAM scenarios during 2019–2050 in Nepal.

zero targets around 2050 as their commitments to this global effort. The role of developing countries in achieving net-zero emissions targets will be very prominent. However, they face the challenge of balancing short-term economic growth, desired for attaining a socio-economic transformation towards higher standards of living, with maintaining climate neutrality and climate resilience in the long run. This study has focused on Nepal in this context and used the Low Emissions Analysis Platform (LEAP) platform to analyze the multiple co-benefits, besides reducing carbon dioxide emissions, that would result from the implementation of Nepal's recently-introduced 'Long-term Strategy for Net-zero Emissions'.

Two major policy intervention scenarios were considered, consisting of With Existing Measures (WEM) and With Additional Measures (WAM). Both of these lead to a substantial reduction in emissions of air pollutants, along with improvements in energy security and energy equity compared to the reference (REF) scenario. For instance, emissions of seven different air pollutants would be reduced by at least 40% (41.2% for NOx and 80.1% for

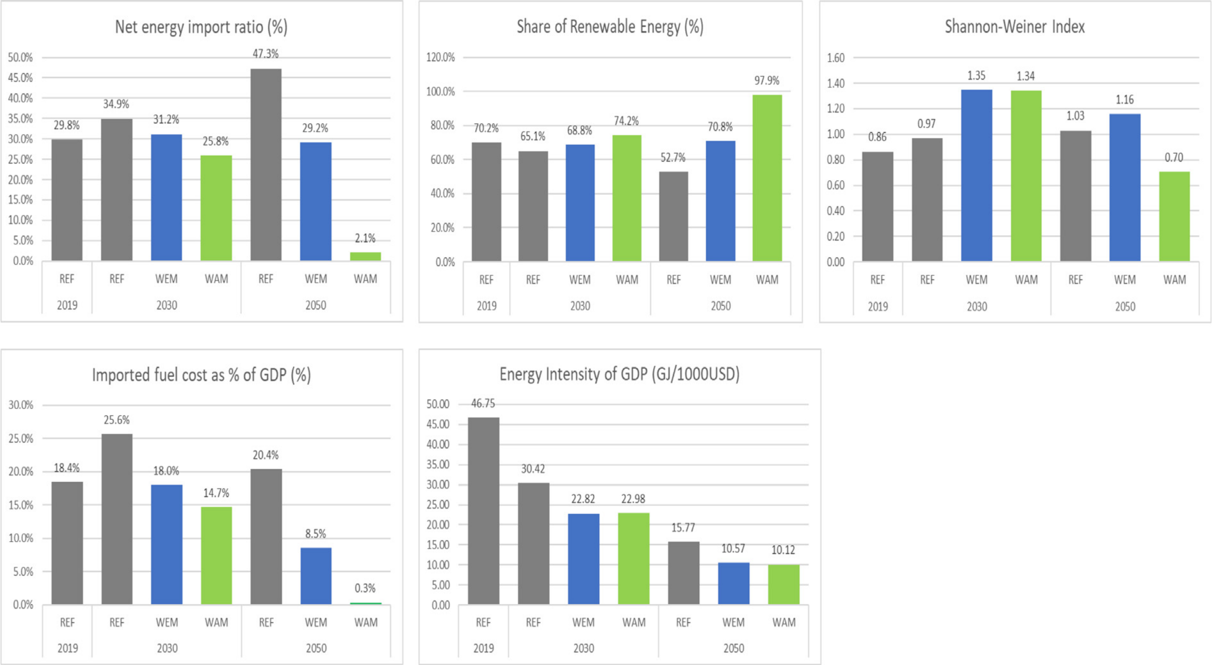

Fig. 4. Change in energy security indicators in WEM, and WAM scenarios relative to the reference (REF) scenario in Nepal during 2019–2050.

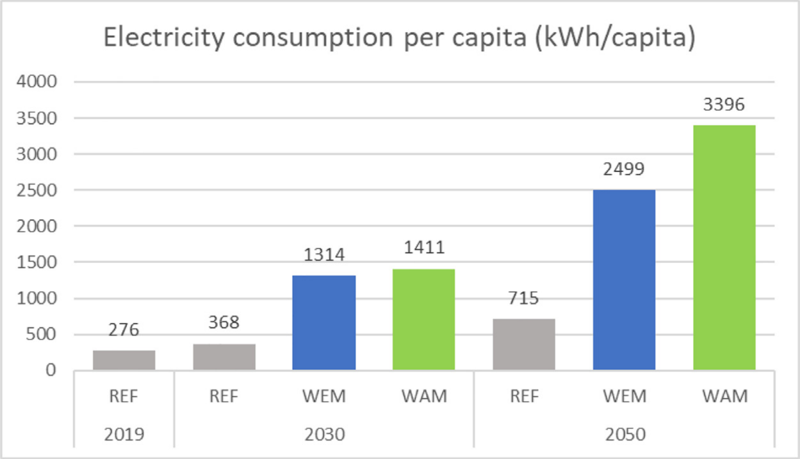

Fig. 5. Change in electricity consumption per capita (an energy security indicator) in Nepal in the year 2019, 2030 and 2050 under the REF, WEM, and WAM scenarios.

NMVOC) in 2050 under the WEM scenario, increasing to about 70% or more (OC by 69.9% and BC by 85.6%) under the WAM scenario. Reduction of these air pollutants, including short-lived climate-forcing pollutants (SLCP) such as BC and methane, is expected to produce additional benefits from avoided adverse health outcomes and crops yield losses, along with reduced impacts on glacier melting and climate. Furthermore, there would be a drastic improvement in energy security indicators, with a reduction in the net energy import ratio, increase in the share of renewable energy, and decreases in the imported fuel cost to GDP ratio and the energy intensity of GDP. In the case of the energy mix, both WEM and WAM show improvement till 2044, but from 2045 onwards WAM shows a slight decrease due to a significant reduction in the use of fossil fuels affecting diversity of energy supply. In addition, net-zero emission initiatives help increase electricity consumption per capita, thus supporting improving the energy equity issue.

Our analysis helped understand how net-zero greenhouse gas emissions strategies and pathways, in this case in Nepal, can leverage multiple co-benefits such as those mentioned above, if they are identified, valued and incorporated during implementation of decarbonization options. In doing so, they can also help address many conditional constraints related to the competitiveness, acceptability, and sustainability of the low carbon options. It is expected that the insights from this study will provide valuable guidance for decision makers during evaluation of existing and future policy options regarding making investment decisions, prioritizing research and development needs, putting societal change in the country following a sustainable development pathway. Further studies can be done in quantification of the health benefits, effects on the agricultural yield etc. due to reduction in the environmental emissions under net zero path way.

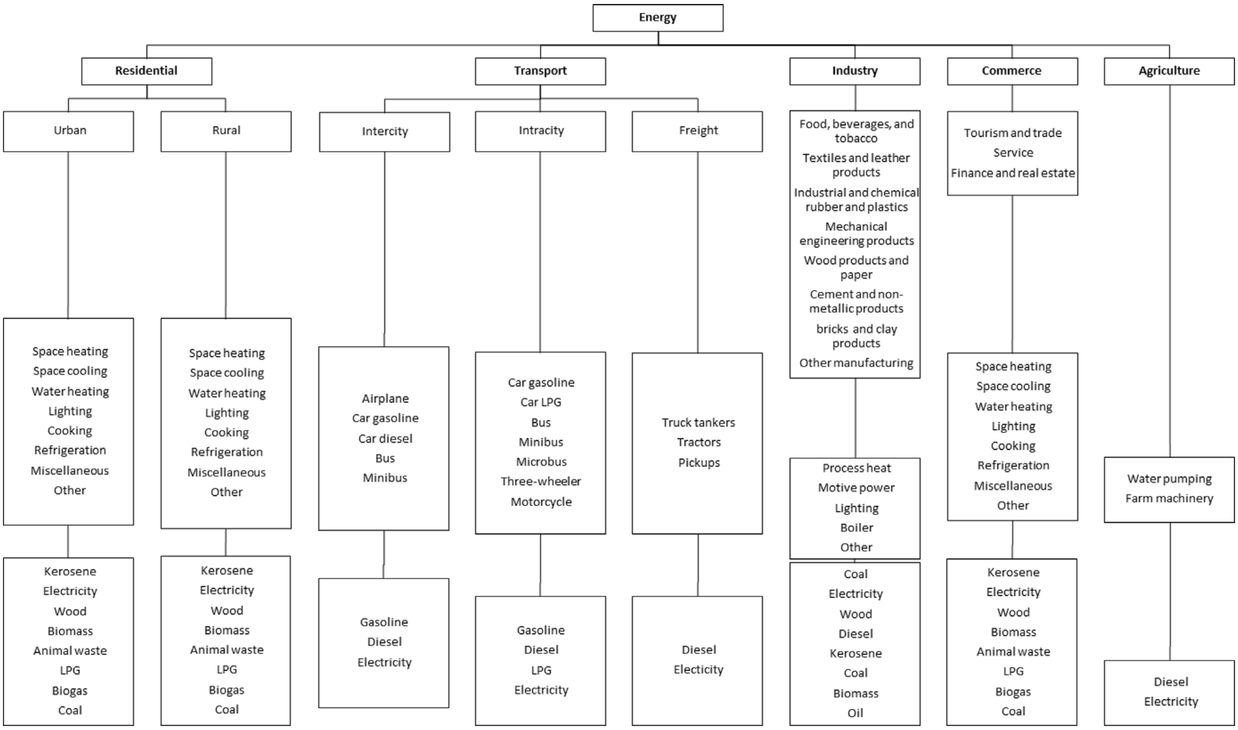

Fig. A.1. Energy sector structure.

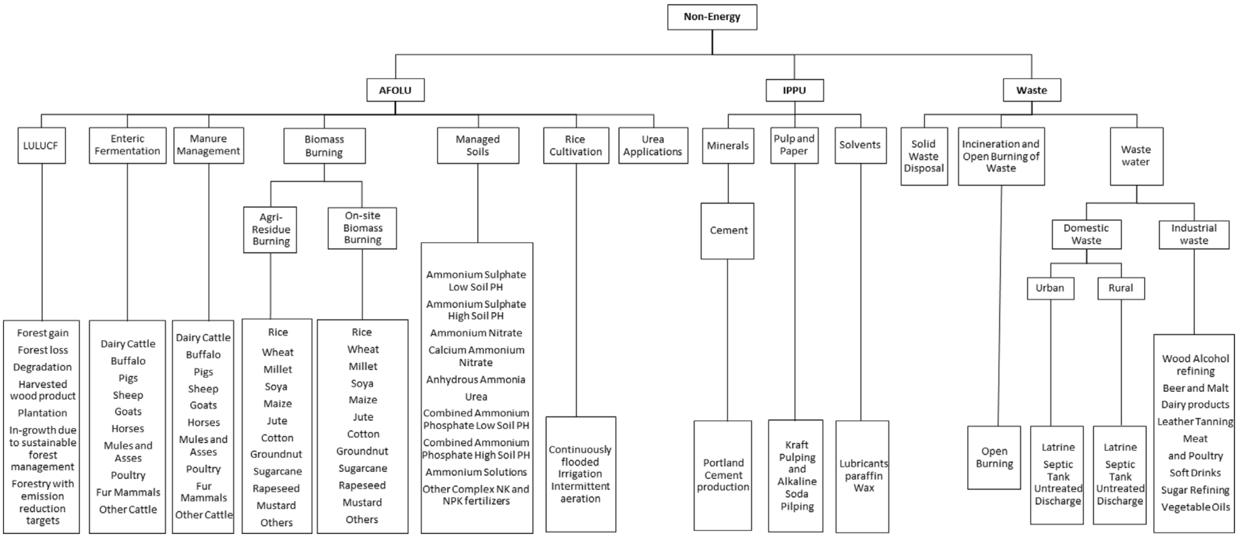

Fig. A.2. Non-energy sector structure.

CRediT authorship contribution statement

Shree Raj Shakya: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Amrit Man Nakarmi:** Methodology, Writing – review & editing. **Anita Prajapati:** Data curation, Formal analysis. **Bijay Bahadur Pradhan:** Data curation, Formal analysis. **Utsav Shree Rajbhandari:** Data curation, Formal analysis. **Maheswar Rupakheti:** Visualization, Writing – review & editing. **Mark G. Lawrence:** Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

See Figs. A.1 and A.2.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2023.01.055.

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