Carbon Neutral Bhutan: sustaining carbon neutral status under growth pressures.

Dorji Yangka (dorjlhen@gmail.com)
Curtin University https://orcid.org/0000-0002-0969-3793
Vanessa Rauland
ClimateClever
Peter Newman
Curtin University

Research

Keywords: Bhutan, energy policy, carbon neutral, growth, LEAP model, nexus, emissions

Posted Date: December 8th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-38348/v2

Abstract

Background: Bhutan has pledged to remain carbon neutral (CN) in perpetuity. Whether they can sustain this is questionable due to the country's increasing economic growth (GDP) and commitment to gross national happiness (GNH) outcomes, both of which can lead to a rise in greenhouse gas (GHG) emissions. The nexus between GHG, GNH and GDP is the essence of the Paris Agreement and Sustainable Development Goals global project.

Results: Through scenario modelling using the Long-range Energy Alternative Planning (LEAP) model, the study finds that the carbon neutral declaration will derail between 2037 and 2050 without mitigation measures. By putting in place mitigation measures especially in the industry and transport sectors, CN can be retained even under high growth pressure, which may cost just 2% of GDP. CN can be easily retained under low economic growth, but this could undermine GNH. High growth will require immediate interventions to enable electrification of industry and transport.

Conclusions: The options to remain CN will require Bhutan to adopt more efficient technologies and electrify industry and transport under both low and high growth scenarios. The additional cost to the Bhutanese economy is feasible through low and high growth opportunities. The options are similar to those confronting emerging nations struggling with issues of climate commitments under economic growth pressures. All will need to adapt their specific economic contexts to achieve the simultaneous objectives of the Sustainable Development Goals whilst addressing the net zero Paris agenda. Bhutan shows it is possible.

Background

Bhutan is famous for its Gross National Happiness indicator [1-4]. It is less well known for its status as one of the few Carbon Neutral countries in the world. It achieved this status in 2011 [5] and reaffirmed it in 2015 for the Paris Agreement [6]. This has the potential to be a strong model for any emerging nation to follow as the pressure to go beyond simply reducing emissions and reach CN status is set to grow [7-9]. But at the same time nations and cities looking to achieve CN status must show how this can be set in strong economic policy. As well as the CN and GNH commitments, Bhutan has a policy to become a middle-income country by 2023 which means substantial increases in GDP. At the heart of these intertwined issues lies energy, 'the golden thread that connects economic growth, social equity and environmental sustainability' [10]. This paper looks at how Bhutan will need to transform its energy system if it is to continue its CN status in the light of competing demands for economic growth and GNH. The challenge is how to manage environmental goals when faced with competing economic and social goals, a challenge that has been set since the Brundtland Commission [11] and now the Sustainable Development Goals [12].

This nexus is the challenge for every nation but especially emerging nations under growth pressures. It calls for economic analysis that can integrate the three interconnected goals for GNH, GDP and GHG in

Figure 1. The figure shows what Bhutan is attempting to do and is a unique way for a developing country to have reduced these complex issues down to three key indicators. No other country has developed a Gross National Happiness set of indicators. It is why Bhutan is worth seeing as a case study of a globally significant approach.

The following sections provide a brief synthesis on the relationship between economic growth, carbon emissions, energy use and social wellbeing. It then highlights Bhutan's energy system, the context of earlier studies conducted on energy modelling and emissions reduction, then gives the results from seven economic scenarios created to examine the nexus growth pressures and their policy recommendations. A separate Methods section shows the scenario storylines and how the modelling was done as well as the scope and limitations of the study.

Carbon emissions, energy use and socio-economic wellbeing

While the relationship between carbon emissions, energy use and economic growth appear simple, they are in fact complex, intertwined and evolving. This is demonstrated by the volumes of research uncovering issues of coupling and decoupling phenomena among these variables [14] and others that explore energy and economic system decarbonisation for a net zero transition [15], which is the new term for carbon neutrality. The complexity intensifies when the social dimension is included due to many indirect ways that energy is consumed; for Bhutan, the social is primarily considered through its GNH index (see Box 1). It is not hard to see that in the GNH Index there are indicators that traditionally would have led to increased energy consumption such as 'economic development', 'living standard' and even 'health' and 'education', though decoupling all of these is now part of the UN agenda to achieve the SDG's and the Paris Agreement at the same time.

Box 1. Components of GNH Index

a) Four pillars of GNH:
 1) Good governance, 2) environmental conservation,
 3) economic development and 4) cultural preservation
b) Nine domains of GNH:
 1) good governance, 2) psychological wellbeing, 3) time use,
 4) living standard, 5) health, 6) education, 7) ecological diversity,
 8) community vitality and 9) cultural diversity.

See CBS [16] for details on the 33 indicators and how the GNH index is calculated.

There are different approaches and methods to analyse and understand the nexus between all these GNH and GDP variables that can help us to understand their implications for carbon neutrality in Bhutan. Some approaches use qualitative methods, others use econometric techniques, and some others use spatial-based land-use planning and integrated energy-economy models, which are either top-down, bottom-up or hybrid. These will be briefly explained before showing how they were used in this paper.

Qualitative approaches, such as through a social ecological lens, assist with understanding the high level need to transform political and cultural dimensions among others beyond techno-economic fixes, for example on the need for drastic emission reduction towards carbon neutrality [17]. A social ecological lens was also used to inform spatial-based emission modelling for urban development [18, 19] that can bring out high emission spots. Econometric techniques show that the GDP-emission relationship is non-linear and varies across countries and their socio-economic structures as well as by the functional form used in the analysis [20]. Econometric analysis of the GDP-emission nexus mostly illuminates the presence or absence of the Environmental Kuznets Curve (EKC). This shows an inverted U-shaped curve indicating that economic growth can lead to reductions in energy after a certain development level is reached. Energy-economy models enable quantitative and holistic assessment of climate policy [21] and they can be applied to design a low carbon society [22]. Energy-economy models have been deployed to assess different techno-economic options to reach an emission reduction target [23, 24]. This study also uses an energy-economy model called LEAP – Long-range Energy Alternative Planning, designed especially for emerging countries, to investigate the future of carbon neutral Bhutan (see the Methods section).

Net Zero Transition and Carbon Neutral Challenge

The Paris Agreement requires a net zero transition by 2050 for a 1.5°C world. However, the sum of the nationally determined contributions (NDCs) are nowhere close to achieving this and every nation must now ratchet up their commitments as part of the Agreement. Modelling such as in this paper is required to ascertain how each country can move towards carbon neutrality. Modelling such as in this paper is required to ascertain how each country can move towards carbon neutrality. Moreover the pathways to a net zero transition are multiple, contested and disruptive [25] and how the underlying drivers interact and evolve are context-specific and place-based. Thus place-based studies such as that for Bhutan undertaken in this research can demonstrate how to resolve such complexity, and thereby contribute to expanding the knowledge base required globally to address this critical problem. Net zero transition for a country like Bhutan means carbon neutrality that does not impede the growth in its other goals towards happiness and being a middle-income country – these are the growth pressures that are part of every nation's approach to the future.

The broadly accepted intention of CN is to balance the carbon going into the atmosphere with the inputs and outputs of any economic activities and requires the measurement, reduction, and finally offsetting of emissions [26, 27]. Birchall [28] considers CN as an extension of long- term climate policy and GHG mitigation strategies that should be applied at the national level. While there is an International Standard 14067:2018 for the carbon footprint of products, there is no universal definition or framework for CN at the national level and many of the countries that have pledged carbon neutrality have not clearly defined it, although in some cases broader strategies for achieving it have been outlined [29, 30].

Several countries have pledged to become CN [30], though Bhutan is one of the very few that have actually achieved this status. Carbon neutrality has many definitions but the one Bhutan has used is based on neutralizing greenhouse emissions with forest-based carbon sequestration [13] – taking a territorial approach. The definition used here is the simplest for developing policy scenarios. While some may argue that it should include the export of renewable hydropower (to India), this would imply that the import of embedded carbon in many consumer items was well understood, which it is not and is in fact very complex. This paper will therefore be examining scenarios that fit within the carbon neutralizing sink capacity provided by Bhutan's current and growing forests.

Whether Bhutan can remain CN in perpetuity is uncertain. The Climate Action Tracker [31] expressed concern over the rising GHG emissions in Bhutan. Yangka [32] also cast doubt on the long-term carbon neutrality of Bhutan based on the extrapolation of carbon emission levels from 2005 to 2050. Thus, the challenge for Bhutan is how it can remain CN under social and economic growth pressures [13].

Energy System of Bhutan

Bhutan is endowed with 24,000 MW of hydropower potential and 71% forest cover. It lacks fossil fuel reserves except for a limited sub-bituminous coal [33]. This pattern of natural resource endowment provides a natural advantage for Bhutan in upholding its CN declaration in a carbon constrained world. However, Bhutan also has very energy intensive and highly polluting industry sectors such as the cement, iron and steel, calcium carbide and ferrosilicon industries. Despite its small economy, Bhutan was also listed, along with eleven other countries around the world, as a key economy for silicon production [34]. Bhutan also has a very rigid transportation system, in which commuters do not have the choice of different modes of transportation, since there are no railways and waterways and limited air transport, relying predominantly therefore on the surface road transport system based on trucks, cars and motorbikes. This is dependent on 100% imported diesel and gasoline from India. In 2014, the base year of this study, both the transport and the industry sectors contributed 30% each to the total GHG emissions, which is expected to increase substantially over the planning period of this study.

Total energy demand in Bhutan increased from 402 ktoe in 2005 [35] to 650 ktoe in 2014 [33] leading to an increase in the per capita energy consumption from 0.63 toe to 0.87 toe. Between these two periods, energy consumption in the transport and industry sectors witnessed a growth of 200% [33]. In 2014, fossil fuels (petroleum and coal) formed the largest share at 37%, followed by biomass at 36% and hydropower at 28%. At the sector level, industry and transport together formed 56% of the total energy consumption.

Energy-Economy Modelling for Bhutan's Carbon Neutral Assessment

There are many studies on emissions reduction using an energy-economy modelling framework, but they are primarily to examine how to reach a desired emission reduction target without necessarily leading to carbon neutrality. Most carbon neutral studies are at city or other sub-national level [17, 36] and a few are at global level [15] with only limited studies at national level [21]. The fundamental difference between a generic emission reduction and a carbon neutral study is that the latter includes carbon offsetting, which for Bhutan is the forest-based carbon sequestration. But for Bhutan there are only limited studies covering long term integrated energy-economy modelling and policy analyses let alone studies on carbon neutral issues (see Yangka and Newman [37]). Shrestha, et al. [38] highlighted a number of options to reduce GHG emissions, while Yangka and Diesendorf [39] quantified the benefits of expanding electric cooking in terms of reduction in the emissions of CO_2 and other local air pollutants.

The National Low Carbon Strategy for Bhutan [5] is the only report discussing CN in Bhutan. The Strategy [5] was developed using a Microsoft Excel based model with a low GDP growth rate of 5.7%, which does not include a cost module. The analyses assumed saturation of travel demand and industrial output by 2020. Such assumptions invariably lead to lower emission levels, thereby overlooking the need to foresee the challenges of CN development and the subsequent policy implications as the country grows (see also the ‘Scope and Limitations’ section). Only one study provides information on the probable costs of Bhutan’s CN pathway into the future [37] but does not have the full scenarios outlined here. The method in this study is based on the Long-range Energy Alternatives Planning (LEAP) model, enabling the nexus between carbon neutral, happiness and economic development goals to be analysed under various growth pressures. Methods of analysis and the different scenarios are outlined in a separate Methods section below with further details provided in the Appendix.

Results And Discussion

Results and Discussion of Bhutan’s CN Futures

The Bhutan-LEAP model runs of the seven scenarios are shown in Table 1in two groups: Group A is a baseline of essentially present growth with high and low growth variations, including the present Nationally Determined Contributions (NDC), and the other, Group B, is how the CN status is retained under the growth pressures and what this will take in terms of technology and policy.

Table 1 Group A and Group B scenarios

Group A (baseline) scenarios	*Group B (Carbon neutral) scenarios*
1) Business As usual (BAU)	5) Carbon Neutral BAU (CNBAU)
2) High economic growth (HGDP)	6) Carbon Neutral HGDP (CNHGDP)
3) Low economic growth (LGDP)*	
4) Nationally Determined Contribution (NDCplan)	7) Carbon Neutral NDC (CNNDCplan)

Note: Group B forms the corresponding carbon neutral counterpart of the group A scenario.
* carbon dioxide equivalent (CO_2e) emissions remain well below the carbon neutral budget of Bhutan (see section on Emission Trajectory).

Emissions Trajectory: Implications on Carbon Neutral Pledge

The emissions trajectory is the most important model results that shed light on the future carbon neutral status. The trajectories for the total GHG emissions under each scenario in Group A and B are shown in Table 2.

Table 2 CO_2e emissions (MT-million tonnes) under each scenario

Group A scenarios	*2014*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
BAU	2.40	2.67	3.16	3.76	4.54	5.54	6.78	8.28
HGDP	2.40	2.74	3.44	4.43	5.82	7.70	10.28	13.97
NDCPlan	2.40	2.60	3.00	3.46	4.16	5.01	6.06	7.25
LGDP	2.40	2.61	2.92	3.21	3.49	3.73	3.95	4.19
Group B scenarios								
CNBAU	2.40	2.52	2.82	2.89	3.42	4.06	4.76	5.58
CNHGDP	2.40	2.51	2.87	2.92	3.53	4.23	5.04	6.00
CN_NDCPlan	2.40	2.52	2.83	2.89	3.49	4.23	5.14	6.21

The Group A scenarios are not very encouraging. The CN sink capacity of 6.3 MT's of CO_2e is exceeded in most of the Group A scenarios especially BAU, but also even in the NDC plan scenario. The emissions level exceeds the sink capacity by 2037 under the HGDP scenario, by 2044 under the BAU scenario and by 2047 under the NDC plan scenario. These results suggest the need for intervention to limit the carbon emissions within the CN sink capacity. Reducing carbon emissions inadvertently contributes to strengthening the environmental dimension of the GNH since socio-environmental sustainability forms the core premise for GNH and measuring and minimising carbon emissions is a must for climate policy and the SDGs. Without mitigation measures, the emissions level remains below the sink capacity only under the low economic growth outlook. Bhutan does not envision such a lean horizon, as like most emerging nations the Bhutanese dream of improving their living standard in the 21st century when humanity moves out of poverty towards a more sustainable and comfortable livelihood as suggested by the Sustainable Development Goals . Thus, these set of scenarios (Group A) do not work and other scenarios are needed to demonstrate how to resolve the conflicts between these three core goals of increasing wealth, improving happiness and maintaining carbon neutrality.

The Group B Scenarios show what mitigation measures can do to keep Bhutan within its forest sink capacity and thus sustain its carbon neutral status going into the future and thus will be analysed in more depth. The results show that there are measures that can keep the emissions within the carbon sink capacity but at varying mitigation costs as explained further in the next section. The results are summarised with their CN counterpart in Figures 2 a), b) and c)[1].

a. BAU and its carbon neutral counterpart
b. NDC Plan and its carbon neutral counterpart
c. HGDP and its carbon neutral counterpart

The total CO_2e emissions steadily rose in all the scenarios, however, as can be seen, the rise is lower in the corresponding CN scenarios (orange colour in figures) due to fuel switching and energy efficiency measures. Figure 3 shows the role of reducing carbon intensity in three key scenarios; although the total emissions increase, the carbon intensity of the Bhutanese economy steadily improves from 2.67

$kgCO_2e$/US$ in the base year to 0.41$kgCO_2e$/US$ by the end of the planning horizon in the CNHGDP scenario. This demonstrates the potential of the Bhutanese economy to decouple its growth from environmental pressure whilst meeting its CN goal [14]. The question then becomes whether this is feasible.

The Cost of Emission Reduction in the Bhutan Economy

The LEAP model calculates total system cost from a societal perspective, where various scenarios can be compared based on their Net Present Value (NPV). The total system cost comprises demand costs, transformation costs and net resource costs.

Within the limits of the mitigation measures specified and selected (see Table 1 under Methods section), the cost to Bhutan of mitigating carbon emissions so as to hold the emissions level below the sink capacity will be US$2.07/tonne CO_2e in the CNBAU scenario and US$37.93/tonne CO_2e in the CNHGDP scenario as there is a lot more carbon to be removed and this is more difficult technologically (more of the expensive F8050 – 80% emission reduction by 2050). Under the CN_NDC Plan scenario (which assumes that certain measures will be taken in advance of the CN measures as per Table 2, Methods section), Bhutan has the potential to save US$ 8.07/tonne CO_2e. This low cost is due to the no-regret/cost savings mitigation measures (IS + MF30) highlighting the benefits of early action.

The high cost associated with the CNHGDP scenario highlights the issues around high growth. To maintain its carbon neutral status following the NDC Plan scenario, Bhutan could be saving US$ 7.2m/yr over the planning period (i.e. to 2050) and in the low growth BAU scenario, Bhutan would only bear an annual average cost of US$ 2.2m/yr. However, under the high growth scenario which would appear necessary for the middle level economy and higher GNH objectives, Bhutan would need to spend US$95m/yr. On the other hand, this is just 2% of GDP due to the extra opportunities created by such growth. High economic growth creates the need for more rapid change in carbon neutrality measures as well as the means to do them. This growth is not in opposition to the happiness agenda as the policy commitments to fairness, sufficiency and well-being measured by the GNH criteria [37] also result in increases in GDP. In other words, rising GDP is an imperative for a low-income emerging country to expand and improve its critical infrastructures such as water supply, transport, health and education - a collective requirement to deliver decent living standards [41]. Empirical studies in Bhutan [42] show that education and income have positive effects on choosing cleaner energy, which in turn can facilitate other good life provisions (see section on Energy and Electricity Demand).

This suggests a need to explore climate financing options to help to cover the additional costs under the low growth and high growth scenarios, in the early phases and adjusting as growth changes. Under both scenarios Bhutan would need to ensure the opportunities created from economic growth can include the technological switches required to maintain carbon neutrality. This will need to include both public and private commitments to these changes. The biggest challenge is switching from fossil-based technologies to electric technologies so that they can be hydropower-based. In particular, the electric transport system entails large cost attributable to relatively high capital cost of electric trucks and an electric passenger transport system, however these systems are all reducing rapidly in cost. For example, an electric public transport system can be introduced that removes many cars from the road system [43] with technologies like the Trackless Tram (involving cross-over autonomous rail technologies) which is around one tenth of the cost of urban rail as no track work is required [44]. Such options can reduce the oil burden on the Bhutanese GDP, while increasing GNH whilst reducing GHG. Such disruptive technologies are not included in the modelling.

Energy and Electricity Demand in Bhutan

Considering that energy is interconnected to economic wellbeing, social equity and environmental sustainability [10], understanding the future trajectory of energy consumption is important. Access to modern and clean energy (SDG7) has a greater number of synergies than trade-offs with other SDGs that are vital for fostering human wellbeing [45]. Considering the SDGs and GNH have many common grounds, modelling the CN measure ‘MF30’ for the building sector: residential and commercial (see Table 1 under Group B scenario in the Methods section) alongside other energy efficiency and fuel switching options in other economic sectors is likely to enhance GNH. Furthermore, Bhutan will need its hydropower-based electricity system to expand deeper into various energy end-uses, as is being expounded by many expert studies on how to remove fossil fuels from the economy by becoming more electric [7, 46, 47]. In Bhutan this means greater use of electricity in the transport and industry sectors. The LEAP model shows this where carbon neutral scenarios lead to larger increases in electricity demand compared to non-carbon neutral counterparts as shown in Table 3. For example, under the HGDP and CNHGDP scenarios per capita annual average electricity consumption increases at 7.0% and 7.8%.

Table 3 Electricity demand under different scenarios (Billion kWh)

Scenarios	2014	2020	2025	2030	2035	2040	2045	2050
BAU	1.89	2.37	3.36	4.70	6.53	8.91	11.96	15.79
CNBAU	1.89	2.37	3.36	4.65	6.54	9.06	12.32	16.48
HGDP	1.89	2.50	3.92	6.10	9.25	13.60	19.75	28.71
CNHGDP	1.89	2.86	4.80	7.74	11.73	17.41	25.63	37.88
NDCPlan	1.89	2.39	3.36	4.62	6.34	8.61	11.55	15.29
CN_NDCPlan	1.89	2.61	3.87	5.52	7.40	9.86	13.00	16.96
LGDP	1.89	2.25	2.88	3.57	4.31	5.03	5.77	6.62

Implications for GNH from the Scenarios

The above discussion around carbon emission reduction, economic growth, and access to modern and clean energy with concurrent increase in energy demand provides a basis for an initial attempt to assess their plausible implications on the domains of GNH. This is shown in Table 4.

Table 4. Plausible impact of emissions reduction, energy access and economic growth on GNH.

Nine domains of GNH	Reduced carbon emission	Increased access to modern and clean energy	Increased economic growth for middle- income aspiration
Psychological wellbeing	✓	✓	✓
Time use	NK	✓	✓
Community vitality	NK	✓	✓
Cultural diversity	NK	NK	NK
Ecological diversity	✓	✓	x
Living standard	NK	✓	✓
Health	✓	✓	✓
Education	NK	✓	✓
Good governance	✓	✓	✓

✓ indicate positive impact; x – negative relation; NK – not known;

On assessing the likely impacts, the indicators associated with each of the nine domains were considered. A tick mark attached to a GNH domain under energy, emission or GDP does not necessarily show unequivocal and unilateral positive impacts on all the indicators under that domain. For example, the time use domain has work and leisure as the two indicators, but the tick mark for the time use domain is attributed to 'work' but not to 'leisure'. Economic growth entails production and consumption, which inadvertently leads to ecological damage and ecological diversity is beyond emissions reduction and clean energy.

Table 4 highlights the need for more extensive future research (e.g. through surveys, interviews or focussed group meetings) to analyse any potential deeper implications of the plausible impacts shown here. A carbon neutral economic growth fuelled by hydropower and other clean energy sources alongside energy efficient technologies can lead to an overall enhancement of GNH as shown by a number of plausible positive impacts on the nine domains of GNH.

[1] We did not assign confidence intervals due to an uncertainty in how to do so in such model-based projection. It may be possible to place confidence interval in the stylised terms of low, medium and high but not in quantified terms that are readily applied in econometric techniques. This may be a limitation of this study, but it is also a strength of the model that any nation can afford to do such work since LEAP is provided free of cost for use for developing countries.

Conclusions

This study adds to the literature on CN development at the national level, using long term energy-economy modelling for the case of Bhutan. The study has shed light on some key concerns for Bhutan if it intends to sustain its CN status under growth pressures. This paper has shown that despite having clean hydroelectricity, if Bhutan follows the 2014 BAU energy-economy pathway, the GHG emissions arising from it will exceed the sink capacity by as early as 2037 under high economic growth due to its industry and transport GHG. Low growth will mean the CN goal is easier to maintain but it will not achieve other goals. The model however does show that all three goals of increased wealth and happiness can be achieved and at the same time maintaining carbon neutrality, through greater electrification of industry and transport. This shows that the integration of CN with economic growth and the SDG's can be achieved by other developing nations, a message of great hope as we approach the future.

Nevertheless, such general conclusions require more detailed and nuanced policy directions in any one location. In this case the LEAP model suggests Bhutan can leapfrog existing carbon intensive technologies by adopting efficient technologies and fuel switching options to curb its rising carbon emissions especially in the industry and transport sectors. But the model runs for the various scenarios show that energy system changes in Bhutan are possible to maintain its CN status though there are additional costs that may make this difficult, except under the CN_NDC Plan scenario where Bhutan will achieve both financial savings as well as sufficient emissions reduction to maintain CN. However, this is not the high growth scenario that is more likely due to Bhutan's aspiration and policy of becoming a middle-income nation by 2023 and its policy of maintaining its fairness, sufficiency and well-being as measured by GNH. Under these high growth pressures Bhutan will need to rapidly electrify their industry and transport as part of its economic growth strategy. The costs are not prohibitive, just 2% of GDP, and the results achieve GNH and GDP commitments. Disruptive innovations in transport and industry may make this even easier as reduced cost solutions for electric transport and industry electrification suggested for Bhutan are likely to be part of the agenda of economic growth in all emerging nations under growth pressures [9]. Such approaches have been called regenerative development as a way of showing that reducing impacts is not enough when a net zero outcome is required [48].

This study therefore recommends detailed planning by any emerging nation as it approaches the future under such growth pressures whilst needing to adapt their economies to the net zero Paris agenda. The modelling of Bhutan's future suggests it will need to develop a CN strategy that can avoid the structural path dependence and lock-in of carbon intensive infrastructure by enabling new CN technologies for simultaneous growth in GDP and GNH with reductions in GHG. Such changes should not be too difficult though concerted efforts may be required such as to identify potential barriers to deploy these options and seek access to finance [49]. Such development issues are central to the future planning of any emerging nation and this study shows that it is possible to maintain CN status under both low and high growth pressures. The Bhutan study undertaken here is a demonstration of how developing and developed nations, can avoid the lock-in of structural path dependence on carbon intensive activities whilst growing economically and socially. But the particular context of each place will need to be addressed so that growth pressures can be adapted to achieve these simultaneous goals.

Methods

This study used the Long-range Energy Alternatives Planning (LEAP) model to conduct an integrated energy system analysis of Bhutan through scenario modelling. LEAP is an energy system model developed by the Stockholm Environment Institute (SEI), which is flexible, user-friendly and free for emerging economies [50]. The objective function of LEAP is cost minimisation from a societal perspective. LEAP can support combinations of top-down and bottom-up approaches to energy system modelling [51], and it is capable of modelling issues beyond technological choices and thus is useful for capacity building applications [52] and to assess Sustainable Development Goal issues [51, 53]. The LEAP model is increasingly being used for low emission development (LED) studies, notably in emerging economies [51, 52, 54-60]. In building the LEAP Bhutan model, its optimisation capability was used for electricity generation expansion alongside its simulation features. The simulation model gives more flexibility to the user to incorporate practical issues.

Scope and limitations

In this study, discussions and analysis are limited to those topics which are deemed pertinent to understanding the overall energy mix, the associated cost and GHG emissions purely from a CN perspective. For this reason, the trend and implications of local air pollutants, are not analysed as the focus is primarily on GHG emissions represented by carbon dioxide equivalent (CO_2e) consisting of carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_2O). The study also does not incorporate embodied carbon emissions, or costs associated with infrastructure, houses and buildings including retrofits, which can reduce energy demand. The easiest step for emission reduction from a modelling exercise would be demand reduction through reduction in energy services such as cooking, lighting or passenger-km travelled. But such heavy dependence on absolute end-use demand reduction may not be an appropriate policy tool for a poor emerging country wanting to grow its economy. Notwithstanding this, options for reducing final energy demand (without necessarily reducing end-use demand – a matter of people's lifestyle) are explored in the LEAP-Bhutan model through energy efficiency, technological shift and fuel switching. Learning rates[1] are assumed only for disruptive, rapidly expanding technologies such as wind, solar photovoltaic and electric transport systems (see Appendix).

It should also be acknowledged that LEAP do not provide the feedback loop of price adjustment arising from a specific mitigation measure [52]. Furthermore, this study also does not analyse the implications of changes to forest cover and its sink capacity is taken as reported by the National Environment Commission [61]. The Constitution of Bhutan has mandated that the State must ensure a minimum of 60% forest cover for all time and until now, forest cover in Bhutan is being maintained at 71% [62].

This study uses the baseline data sets openly accessible in Yangka and Newman [37], which were collected from various sources for the same research project. However, the scope, scenario formulations, and the issues analysed and discussed were distinct from the earlier work. For example, this paper formulated seven distinct scenarios against four in the earlier work. In any case, the scope of modelling an energy-economy system is extensive where scenario formulation comprises different combinations of macroeconomic variables alongside techno-economic variables under an overarching storyline (see the sections below).

Structure of LEAP-Bhutan model and general assumptions

The LEAP-Bhutan model comprised of four main branches: Key Assumptions, Demand, Transformation and Resources, which are further subdivided as per the research requirement and data availability as shown in the Appendix (A1). Key Assumptions consist of the macro-economic parameters which are deployed as drivers of future energy consumption and they are linked at the activity levels under each of the demand sectors. The Demand branch consists of four major demand sectors: Residential, Commercial/Services, Industry and Transport. These are further disaggregated into sub-sectors and end-use type purely based on data availability. Energy consumption in the agriculture sector in Bhutan is negligible compared to other sectors, hence it is accounted under 'others' in the commercial sector. The transformation branch is comprised of energy conversions such as electricity generation, coal mining among others. The Resources branch includes primary energy sources and secondary energy sources whether imported or indigenous.

The planning period extends from 2014 to 2050. The emission factors and the global warming potential (GWP) were taken from the technology and emission database (TED) of LEAP. For details on the general assumptions adopted in this study see Appendix (A2). Further information on the data sets and their sources are provided in Appendix (A3)

Distinct features of LEAP-Bhutan model

LEAP-Bhutan model is relatively simple in that there are no fossil fuel extraction and conversion processes such as oil refineries except for coal mining, biogas production, briquette making and the hydropower system. On the demand side, there is no rail system or water ways for transport and limited domestic air ways. Petroleum products are consumed in all the demand sectors; they are imported from India as Bhutan has no oil reserves or oil refineries.

It was noted that there are distinct energy usage patterns in the urban and rural residential areas of Bhutan, which may call for a unique policy intervention, however such disaggregated data are not available in the Energy Data Directory [33]. Further, in the Energy Data Directory, the Industry sector was categorised based on electrical voltage levels such as high, medium, low voltage irrespective of the production system. In this study, the Industry sector was categorised based on industrial output, which was deemed more appropriate for assessing technological options for CN development. Also, in the Industry sector, this study considers charcoal, woodchips and bamboo chips that are being used as reducing agents and as raw materials in the production process, which were not provided in the Energy Data Directory. These goods are mostly imported from India and the required data are synthesised from Department of Industry [63] and Revenue and Customs [64]. All these features lead to distinct parameterization of LEAP-Bhutan model.

Energy Resource and supply

The LEAP model requires the reserve levels for exhaustible resources and yield levels for renewable resources. Such data were calculated from the Bhutan Energy Data Directories [33, 35]. Techno-economic parameters for existing and candidate power plants were obtained from various data sources (see Appendix (A2) and (A3)). The generation profile of the hydropower plants were constrained by the availability curve based on the actual monthly electricity generation obtained from the Druk Green Power Corporation [66]. See Appendix (A2) for details. Increasing exports of renewable energy would theoretically increase the sink capacity for Bhutan's emissions though this is not considered in this analysis due to the need to also include imports of embedded carbon in a range of products. However, as a general climate policy, exporting renewables to India would be of value to both the global carbon agenda and the local economic growth agenda, while increasing imports from the Indian grid is harmful to both.

Projection of energy demand

Population, Household, GDP, per capita GDP and Sectoral Value Added were used as the drivers of energy consumption that ultimately effects CO_2e emissions, the 'Impact' in this study under the ImPACT formulation popularly called the Kaya Identity [67-69] for greenhouse gas emissions and 'T' being represented by various 'technologies' in the LEAP model. These drivers were also used for modelling the low carbon scenario for India [70] and carbon neutral transport system in Iceland [71]. See Appendix (A4) for details. Considering the lack of studies specific to Bhutan to establish an elasticity value between the macroeconomic parameters and the sectoral energy demand, this study assumes an elasticity value of one between the chosen driver and the sectoral energy demand. Yophy, et al. [72] had used GDP elasticity of energy demand as one for the Taiwan LEAP model. It was recognised that elasticity values change over time and are brought about by structural changes and energy efficiency gains, which are separately modelled through fuel substitution and efficiency improvements in the LEAP-Bhutan model over the planning period.

Projection of energy prices

Price of domestic biomass energy was assumed to increase at 3% per annum [39] and for bamboo chips and wood charcoal, which are mostly imported from India for use in the Industry sector were assumed to rise at 4.1% per annum [73]. The prices for petroleum products (see Appendix (A4), table A.13) were projected to follow the international oil price and thus indexed to the price changes calculated from US-DoE [69]. It is reasonable to project the price of petroleum products in Bhutan along with the international oil price projection, since the oil import dependency of India is expected to increase from 74% in 2013 to 91% by 2040 as per the world energy outlook special report [74]. In that report prices of oil, coal and natural gas in India were projected by linking to international prices.

Scenarios storyline and carbon neutral measures

Considering Bhutan's rising carbon emissions [6, 32, 61] and the need to keep these emissions within the carbon neutral budget of Bhutan, plausible energy-economy pathways were explored. Raskin, et al. [46] note the benefits of scenario analyses stating that 'Scenarios enlarge the canvass for reflection to include a holistic perspective over space, issues and time' (pg. 3). Thus, numerous scenarios can be imagined and formulated to explore the future. This study deviates from the usual scenario analyses of comparing alternative scenarios to a baseline in that two groups of scenarios were formulated – Group A and Group B - to provide a clear understanding of the underlying assumptions that drive each scenario and also to expand the scenario space (see following sections). Group A has four different baseline scenarios of growth against the use of a single baseline in the existing energy-economy planning literature, but they are all plausible baselines. Group B has the corresponding CN scenarios; the aim here is to investigate what it will take for Bhutan to sustain its CN pledge if it pursues those plausible growth pathways defined in Group A.

The scenarios under group A emerge from a macroeconomic outlook and entail a distinct energy system pattern – in terms of type and amount of energy consumed, type of primary resources extracted, and type of demand technology used by the demand sectors. Group A comprise the Business-as-usual (BAU) scenario, the high economic growth (HGDP) scenario, the low economic growth (LGDP) scenario and the Nationally Determined Contributions (NDC) Plan scenario. The NDCPlan scenario attempts to depict some of the key aspects of the NDC committed to by Bhutan, which had outlined nine broad strategies [6] but without specific targets. This present study assigned some reasonable quantitative targets for modeling purposes based on past trends and other national level documents, with an intention to reduce carbon emissions.

Group B consists of the CN counterparts for each of the scenarios in Group A though with a distinct sector in focus (e.g. the 'advanced technology' scenario focusses just on the transport and industry sectors and the 'modern fuel' scenario focusses just on the residential and commercial sectors). Group B is intended to decouple the growing Bhutanese economy and its energy demand from GHG emissions, thereby holding the emission levels within the sink capacity. Decoupling is explained in Newman [14]. To formulate Group B scenarios, distinct and exclusive CN measures are specified as shown in Table 1. Group B scenarios are therefore more challenging to the economy than Group A but are not seen as highly radical or beyond possibilities.

The various scenarios will be examined to see how they keep within the sink capacity of 6.3 MT (million tons) of CO_2e – this is the total forest sink capacity that can neutralize any carbon emissions produced in Bhutan – apparently taking a territorial approach. Combinations of mitigation measures will also be done to form Group B scenarios.

Group A scenarios

Group A scenarios consists of the BAU, HGDP, LGDP and the NDCPlan scenarios. The BAU scenario represents the 2014 energy-economy trajectory and assumes a GDP growth rate similar to that witnessed in the past two decades (refer table 2). Major policy interventions are not anticipated except for the general trends such as the declining usage of fuelwood in the residential and service sectors due to achievement of nation-wide electrification and some push in the public transport sector. The HGDP scenario represents the high economic growth rate of 10% per annum until 2025 and thereafter sustaining at 7.8%. In recent years Bhutan has achieved such high growth as a result of the commissioning of mega-hydropower projects. The LGDP scenario represents low economic growth of 5.6% which further declines to 2.5% by 2050. Bhutan has also witnessed such low economic growth in 2012.

Group B scenarios and mitigation measures

For each of the scenarios under Group A, a corresponding CN scenario was formulated based on the selection of mitigation measures outlined below.

This study specified four aggregated measures based on data availability, suitability to Bhutan's context and the emerging global vision shown in Table 1 with detail descriptions provided in Appendix (A5.3).

Table 1 Carbon Neutral measures

CN Measure Groups	*Sector Measures*			
	Residential	*Commercial*	*Transport*	*Industry*
IS (Industrial Symbiosis)	Not Applicable	Not Applicable	Not Applicable	Blended cement [76] and waste heat recovery in other three major industry sub-sectors [77]
ATECH (Advanced TECHnology)	Not Applicable	Not Applicable	Electric vehicles penetration follow the trajectory specified under the 2DS of the IEA [47]; LRT is introduced in passenger transportation catering to 30% of the travel demand from 2030;	Oxy-combustion technology in cement industry from 2045 [78]; Maerz PFR kiln system in the CaCd industry [79];
MF30 (Modern Fuel by 2030)	Traditional bioenergy and kerosene usage in the residential and commercial sectors are reduced to zero (replaced by biogas and electricity) by 2030 following SDG 7 (universal access to modern and clean energy for all)		Not Applicable	Not Applicable
F8050 (80% Fossil fuel reduction by 2050)	Fossil fuel energy demand is reduced by 80% by 2050 as per the target set by IPCC [80], largely driven by hydroelectricity displacing fossil fuels. This consists of different combinations of demand technologies (in terms of share or the year of entry) in each category of end-use demand in a manner that reduces fossil fuel consumption by 80% by 2050. It is not a summation of the other three measures: MF30, ATECH and IS.			

Selection of the mitigation measures

The mitigation measures outlined in Table 1 above were then deployed one by one onto the BAU scenario to obtain the cost of mitigating a tonne of GHG through the cost-benefit summary report in the LEAP model. It was observed that none of the measures except for the F8050 were effective enough on their own to keep the GHG emissions within the sink capacity, despite some of the measures being no-regret options (i.e. options with no cost or negative cost, meaning they save money). Given these limits, the mitigation measures were combined to form groups of cost-effective CN measures to hold the emission level within the sink capacity at the lowest cost of mitigation during the planning period. The process of moving from one combination to the next is based on the cost of mitigation shown in Figure 1. The cheaper options (e.g. 1st and 2nd lowest) were combined first to see if the emissions level remains within the sink capacity, if not, then the 1st is combined with the 3rd lowest and so on. If the combination of any two measures failed to keep the emission levels within the sink capacity, then the combination of three measures were applied onto the scenario under investigation. This leads to the formation of Group B scenarios.

Group B – Carbon Neutral Scenarios

The CNBAU represents the Carbon Neutral BAU scenario, which includes the two mitigation measures 'IS + ATECH' that form the least cost option in holding the emissions level within the sink capacity. Similarly, CN_NDCPlan represents the Carbon Neutral NDCPlan scenario with 'IS + MF30' as the combined measures. The CNHGDP represents the Carbon Neutral high economic growth (high GDP) scenario with 'IS + MF30 + F8050' as the combined measures. Under the LGDP scenario, the emissions level remains well below the sink capacity, thus application of the mitigation measures does not arise. Low growth may not be an effective policy, however, as economic and social goals are largely pushing the country towards a high growth future based on the need to create opportunities and growth provides these. Growth is therefore driving the politics inevitably in this direction as in most emerging countries looking to break out of poverty. Its implications for energy need to be addressed.

Table 2 The Scenarios – sector conditions and their growth trends

Sectors Conditions				
	Residential Sector	*Commercial sector*	*Transport sector*	*Industry sector*
BAU conditions	Fuelwood usage is all end-uses expected to decline to 23% by 2050 following the declining rural population; Saturation of households with heating facilities to increase from 50% in 2014 to 70% by 2050;	Fuelwood usage declines by 50%;	Bus share increases from 45% to 65% by 2050; Passenger transport by air increases from 20 to 25% by 2050; Light diesel truck share increases from 17% to 30% by 2050;	
NDC Plan conditions (from the broad strategy outlined in the NDC)	Fuelwood usage decreases to 10% by 2050; Biogas reaches full potential of 20,000 plants by 2030, which meets 28% of cooking energy demand;	Fuelwood usage decreases to 10% by 2050	Electric vehicles share in the market assumed to follow half of the intake rate specified under 2DS of the IEA [47].	Improved refractories in cement industry and efficiency improvement in Iron & Steel and Ferro Alloy industries [76]; Vocarse kiln system in CaCd Industry [79];
Group A Scenarios				
BAU	BAU conditions with GDP growth rate of 7.8% and sustaining at 5.6% until 2050			
HGDP	High GDP growth rate of 10% in 2020 and 2025, thereafter declining to 7.8% by 2050, inherited from BAU			
LGDP	Low GDP growth rate of 5.6% in 2020 and declining to 2.5% by 2050, inherited from BAU			
NDC Plan	NDC conditions with BAU growth rate			
Group B Scenarios				
CNBAU	BAU with CN measures consisting of ATECH and IS			
CNHGDP	HGDP scenario with CN measures consisting of F8050, IS and MF30			
CN_NDC Plan	NDC Plan scenario with CN measures consisting of IS and MF30			

[1] Learning rates refer to a percentile value which implies reduction in the cost of technologies when its production amount doubles

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

All data generated or analysed during this study are included in this published article (attached as supplementary information files).

Competing interests

The Editor-in-Chief of the journal, Peter Newman, is an author of this article. The content was independently reviewed by peers in the field and the decision for publication was made by a member of the Editorial Board. Peter's position did not have any conscious influence on this decision. The authors declare that they have no competing interests.

Funding

The lead author would like to acknowledge the support and contribution of the Australian Government Research Training Program (RTP) scholarship and Curtin University research top up scholarship (CRS) during his PhD term.

Author contributions

D.Y. collected the data, conducted the scenario modelling and analysis; D.Y. and V.R drafted the initial paper; P.N. provided additional context and editing for the paper; all authors contributed to structuring, revising and finalising the paper.

Acknowledgements

The technical support and free license for LEAP model (version April 2018 to February 2020) provided by Stockholm Environment Institute, Boston, USA is very much appreciated.

References

1. Schroeder R, Schroeder K. Happy Environments: Bhutan, Interdependence and the West. Sustainability. 2014;6:3521-33.
2. Ura K. The Experience of Gross National Happiness as Development Framework. Manila: Asian Development Bank; 2015. Available from: https://www.adb.org/sites/default/files/publication/177790/gnh-development-framework.pdf.
3. RGoB. The Report of the High-Level Meeting on Wellbeing and Happiness: Defining a New Economic Paradigm. New York: The Permanent Mission of the Kingdom of Bhutan to the United Nations.; 2012. Available from: http://www.newdevelopmentparadigm.bt/wp-content/uploads/2013/06/2-April-Report-of-HLM-on-WH.pdf.
4. Thinley JY, Hartz-Karp J. National progress, sustainability and higher goals: the case of Bhutan's Gross National Happiness. Sustainable Earth. 2019;2(1):11.
5. NEC. National Strategy and action plan for low carbon development. Thimphu, Bhutan: National Environment Commission; 2012.
6. RGoB. Communication of the INDC of the kingdom of Bhutan. In: Commission NE, editor. Thimphu, Bhutan: National Environment Commission; 2015.
7. Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber HJ. A roadmap for rapid decarbonization. Science. 2017;355(6331):1269-71.
8. Robinson M, Shine T. Achieving a climate justice pathway to 1.5 °C. Nature Climate Change. 2018;8(7):564-9.
9. IPCC. Summary for Policy makers. In: V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al., editors. Global warming of 15°C An IPCC Special Report on the impacts of global warming of 15°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. Geneva, Switzerland: Intergovernmental Panel on Climate Change; 2018. p. 3-26.
10. Secretary-General to Global Development Center: 'Energy is the Golden Thread' Connecting Economic Growth, Social Equity, Environmental Sustainability [press release]. New York: United Nations2012.
11. WCED. Report of the World Commission on Environment and Development: Our Common Future. World Commission on Environment and Development; 1987.
12. United Nations. Transforming our world: The 2030 agenda for sustainable development. The United Nations; 2015.
13. Yangka D, Newman P, Rauland V, Devereux P. Sustainability in an Emerging Nation: The Bhutan Case Study. Sustainability. 2018;10(5):1622.
14. Newman P. Decoupling Economic Growth from Fossil Fuels. Modern Economy. 2017;08(06):791-805.
15. Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, Gernaat D, et al. Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change. 2018;8(4):325-32.

16. CBS. An extensive analysis of GNH Index. Thimphu, Bhutan: Centre for Bhutan Studies; 2012. Available from: http://www.grossnationalhappiness.com/wp-content/uploads/2012/10/An%20Extensive%20Analysis%20of%20GNH%20Index.pdf.
17. Wheeler SM. A Carbon-Neutral California: Social Ecology and Prospects for 2050 GHG Reduction. Urban Planning. 2017;2(4):5.
18. Pan H, Page J, Zhang L, Chen S, Cong C, Destouni G, et al. Using comparative socio-ecological modeling to support Climate Action Planning (CAP). Journal of Cleaner Production. 2019;232:30-42.
19. Pan H, Page J, Zhang L, Cong C, Ferreira C, Jonsson E, et al. Understanding interactions between urban development policies and GHG emissions: A case study in Stockholm Region. Ambio. 2020;49(7):1313-27.
20. Heil MT, Selden TM. Carbon emissions and economic development: future trajectories based on historical experience. Environment and Development Economics. 2001;6(1):63-83.
21. Millot A, Krook-Riekkola A, Maïzi N. Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden. Energy Policy. 2020;139:111358.
22. Nakata T, Silva D, Rodionov M. Application of energy system models for designing a low-carbon society. Progress in Energy and Combustion Science. 2011;37(4):462-502.
23. Yang D, Liu B, Ma W, Guo Q, Li F, Yang D. Sectoral energy-carbon nexus and low-carbon policy alternatives: A case study of Ningbo, China. Journal of Cleaner Production. 2017;156:480-90.
24. Yang D, Liu D, Huang A, Lin J, Xu L. Critical transformation pathways and socio-environmental benefits of energy substitution using a LEAP scenario modeling. Renewable and Sustainable Energy Reviews. 2021;135:110116.
25. Geels FW, Sovacool BK, Schwanen T, Sorrell S. The Socio-Technical Dynamics of Low-Carbon Transitions. Joule. 2017;1(3):463-79.
26. Rauland V, Newman P. The Rise of Carbon Neutrality. Decarbonising Cities: Mainstreaming low carbon urban development. Switzerland: Springer International Publishing 2015. p. 95-112.
27. UNEP. A Case for Climate Neutrality—Case Studies on Moving Towards a Low Carbon Economy. Kenya: United Nations Environment Programme; 2011. Report No.: DCP / 1239/NA.
28. Birchall J. New Zealand's abandonment of the Carbon Neutral Public Service programme. Climate Policy. 2014;14(4):525-35.
29. FDRE. The path to sustainable development: Ethiopia's Climate-Resilient Green Economy strategy. In: Authority EP, editor. Federal Democratic Republic of Ethiopia: Environmental Protection Authority; 2011.
30. Flagg J. Aiming for zero: what makes nations adopt carbon neutral pledges? Environmental Sociology. 2015:202-12.
31. Climate Action Tracker. Warming Projections Global Update2019. Available from: https://climateactiontracker.org/documents/698/CAT_2019-12-

10_BriefingCOP25_WarmingProjectionsGlobalUpdate_Dec2019.pdf.

32. Yangka D, editor Application of MARKAL model for understanding the E3 nexus. The E3 conference; 2013; Thimphu, Bhutan: The QED Group.
33. DRE. Bhutan Energy Data Directory. Thimphu, Bhutan: Department of Renewable Energy; 2015.
34. Kero I, Grådahl S, Tranell G. Airborne Emissions from Si/FeSi Production. Jom. 2016;69(2):365-80.
35. DoE. Bhutan Energy Data Directory 2005. Thimphu, Bhutan: Department of Energy; 2007.
36. City of Copenhagen. Copenhagen climate plan: the shorter version. City of Copenhagen; 2009.
37. Yangka D, Newman P. Bhutan: Can the 1.5 °C Agenda Be Integrated with Growth in Wealth and Happiness? Urban Planning. 2018;3(2):94–112.
38. Shrestha RM, Ahmed M, Suphachalasai S, Lasco R. Economics of reducing Greenhouse gas emissions in South Asia: options and cost.pdf. Mandaluyong: Asian Development Bank; 2013.
39. Yangka D, Diesendorf M. Modeling the benefits of electric cooking in Bhutan: A long term perspective. Renewable and Sustainable Energy Reviews. 2016;59:494-503.
40. Sachs J. From Millennium Development Goals to Sustainable Development Goals. The Lancet. 2012;379(9832):2206-11.
41. Rao ND, Min J. Decent Living Standards: Material Prerequisites for Human Wellbeing. Social Indicators Research. 2018;138(1):225-44.
42. Rahut DB, Behera B, Ali A. Household energy choice and consumption intensity: Empirical evidence from Bhutan. Renewable and Sustainable Energy Reviews. 2016;53:993-1009.
43. Glazebrook G, Newman P. The City of the Future. Urban Planning. 2018;3(2):1-20.
44. Newman P, Hargroves KC, Davies-Slate S, Conley D, Verschuer M, Mouritz M, et al. The Trackless Tram: Is it the Transit and City Shaping Catalyst we have been waiting for? Journal of Transportation Technologies. 2019;9:31-55.
45. Nerini FF, Tomei J, To LS, Bisaga I, Parikh P, Black M, et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nature Energy. 2018;3(1):10-5.
46. Raskin P, Gallopin G, Gutman P, Hammond A, Swart R. Bending the curve: towards global sustainability. Development: Springer; 2000. p. 67–74.
47. IEA. Global EV outlook 2016: Beyond one million electric cars. International Energy Agency; 2016.
48. Newman P. Hope in a time of civicide: regenerative development and IPAT. Sustainable Earth. 2020;3(1):13.
49. Yangka D, Rauland V, Newman P. Carbon neutral policy in action: the case of Bhutan. Climate Policy. 2018:1-16.
50. Heaps CG. Long-range Energy Alternatives Planning (LEAP) system. [Software version: 2018.0.7]2018 August 5. Available from: https://www.energycommunity.org.
51. Ouedraogo NS. Africa energy future: Alternative scenarios and their implications for sustainable development strategies. Energy Policy. 2017;106:457-71.

52. ESMAP. Planning for a low carbon future: Lessons learned from seven country studies. Washington: Energy Sector Management Assistance Program, Program ESMA; 2012. Contract No.: 73508.
53. Nilsson M, Heaps C, Persson Å, Carson M, Pachauri S, Kok M, et al. Energy for a Shared Development Agenda: Global Scenarios and Governance Implications. Stockholm: Stockholm Environment Institute; 2012.
54. Thuy VTH, Limmeechokchai B. Analyses of Energy use and CO2 Emission in Residential Sector: Case Studies in Thailand and Vietnam. Energy Procedia. 2015;79:290-5.
55. Shakya SR. Benefits of Low Carbon Development Strategies in Emerging Cities of Developing Country: a Case of Kathmandu. Journal of Sustainable Development of Energy, Water and Environment Systems. 2016;4(2):141-60.
56. Kumar S, Madlener R. CO2 emission reduction potential assessment using renewable energy in India. Energy. 2016;97:273-82.
57. Subramanyam V, Kumar A, Talaei A, Mondal MAH. Energy efficiency improvement opportunities and associated greenhouse gas abatement costs for the residential sector. Energy. 2017;118:795-807.
58. Emodi NV, Emodi CC, Murthy GP, Emodi ASA. Energy policy for low carbon development in Nigeria: A LEAP model application. Renewable and Sustainable Energy Reviews. 2017;68:247-61.
59. Mirjat NH, Uqaili MA, Harijan K, Walasai GD, Mondal MAH, Sahin H. Long-term electricity demand forecast and supply side scenarios for Pakistan (2015–2050): A LEAP model application for policy analysis. Energy. 2018;165:512-26.
60. Nieves JA, Aristizábal AJ, Dyner I, Báez O, Ospina DH. Energy demand and greenhouse gas emissions analysis in Colombia: A LEAP model application. Energy. 2019;169:380-97.
61. NEC. Second National Communication to the UNFCCC. Thimphu, Bhutan: National Environment Commission; 2011.
62. MoAF. National Forest Inventory Report: Stocktaking Nation's forest resources. In: Department of Forests and Park Services, editor. Thimphu, Bhutan: Ministry of Agriculture and Forestry; 2017.
63. Department of Industry. Bhutan Industry report 2015. Thimphu, Bhutan: Department of Industry; 2015.
64. DRC. Bhutan Trade Statistics. Thimphu, Bhutan: Deapartment of Revenue and Customs, Bhutan RGo; 2015.
65. DRE. Bhutan Building energy efficiency study-Part 1 (Main Report). Thimphu, Bhutan: Department of Renewable Energy; 2015.
66. Druk Green Power Corporation. Annual Report 2014. Thimphu, Bhutan: Druk Green Power Corporation Limited, Limited DGPC; 2014.
67. IPCC. Scenario driving forces. In: Nakićenović N, editor. Special Report on Emissions Scenarios: A special report of working group III of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge Cambridge University Press; 2000.

68. Kaya Y. Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios. Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris. 1990.
69. US EIA. International Energy Outlook 2016. US Energy Information Administration, Administration EI; 2016. Contract No.: DOE/EIA-0484(2016).
70. Anandarajah G, Gambhir A. India's CO2 emission pathways to 2050: What role can renewables play? Applied Energy. 2014;131:79–86.
71. Shafiei E, Davidsdottir B, Leaver J, Stefansson H, Asgeirsson EI. Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity. Journal of Cleaner Production. 2017;141:237-47.
72. Yophy H, Jeffrey BY, Chieh-Yu P. The long-term forecast of Taiwan's energy supply and demand: LEAP model application. Energy Policy. 2011;39(11):6790-803.
73. Feuerbacher A, Siebold M, Chhetri A, Lippert C, Sander K. Increasing forest utilization within Bhutan's forest conservation framework: The economic benefits of charcoal production. Forest Policy and Economics. 2016;73:99-111.
74. IEA. World Energy Outlook special report: India Energy Outlook: . Paris: International Energy Agency; 2015.
75. BPC. BPC Power Data Book 2015. Thimphu, Bhutan: Bhutan Power Corporation Limited; 2015.
76. Morrow WR, Hasanbeigi A, Sathaye J, Xu T. Assessment of energy efficiency improvement and CO2 emission reduction potentials in India's cement and iron & steel industries. Journal of Cleaner Production. 2014;65:131-41.
77. NEC, TERI. Energy Efficiency imporvements in the industry sector in Bhutan. National Environment Commission; 2016.
78. ETSAP. Technology brief 103: Cement Production. Energy Technology System Analysis Programme: International Energy Agency; 2010. Contract No.: Technology Brief 103.
79. Liu X, Zhu B, Zhou W, Hu S, Chen D, Griffy-Brown C. CO2 emissions in calcium carbide industry: An analysis of China's mitigation potential. International Journal of Greenhouse Gas Control. 2011;5(5):1240-9.
80. IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland: Intergovernmental Panel on Climate Change,; 2014.

Figures

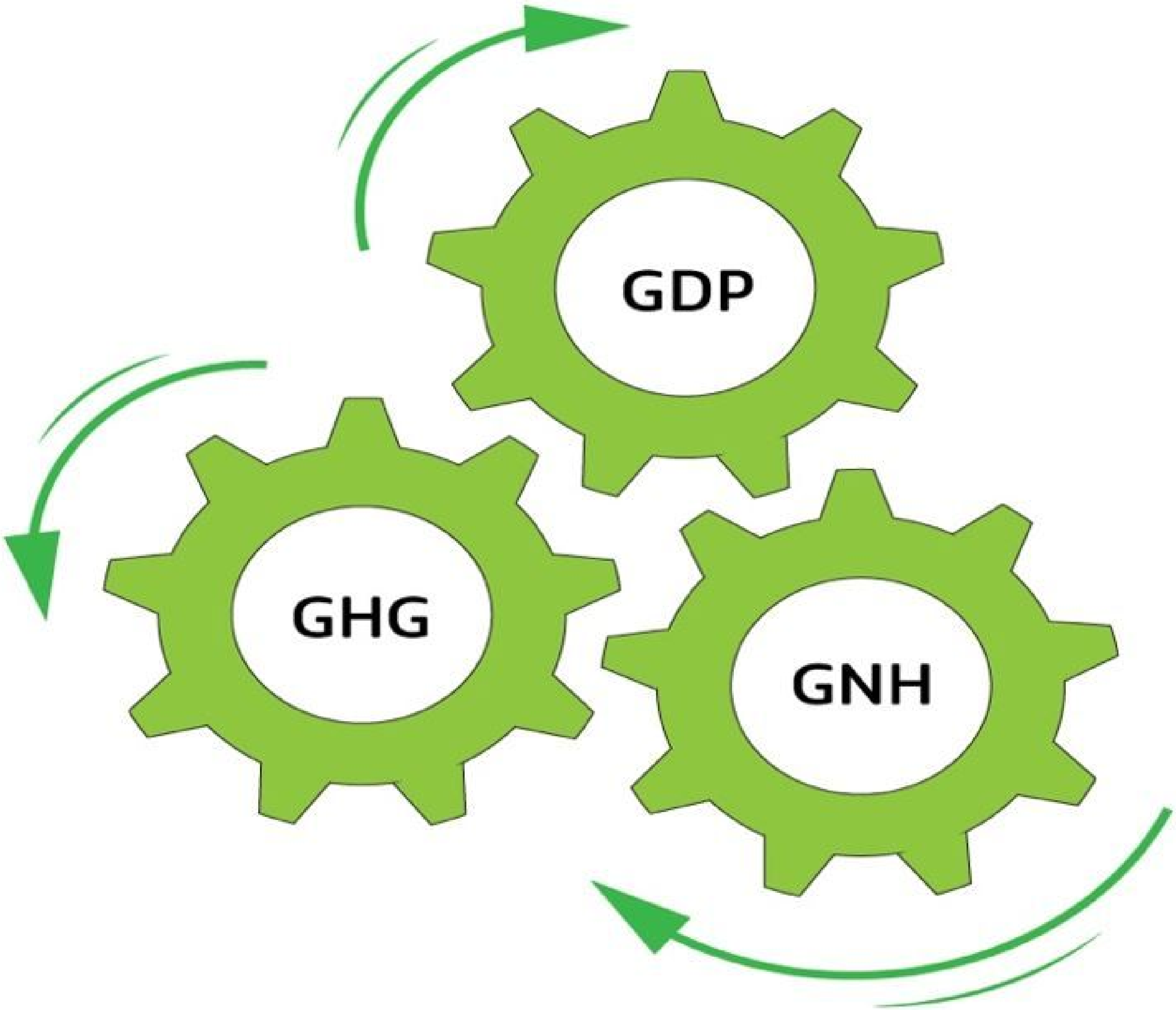

Figure 1

The three G's – the interconnected goals. Adapted from [11] (GDP – gross domestic product; GNH – gross national happiness; GHG – greenhouse gas)

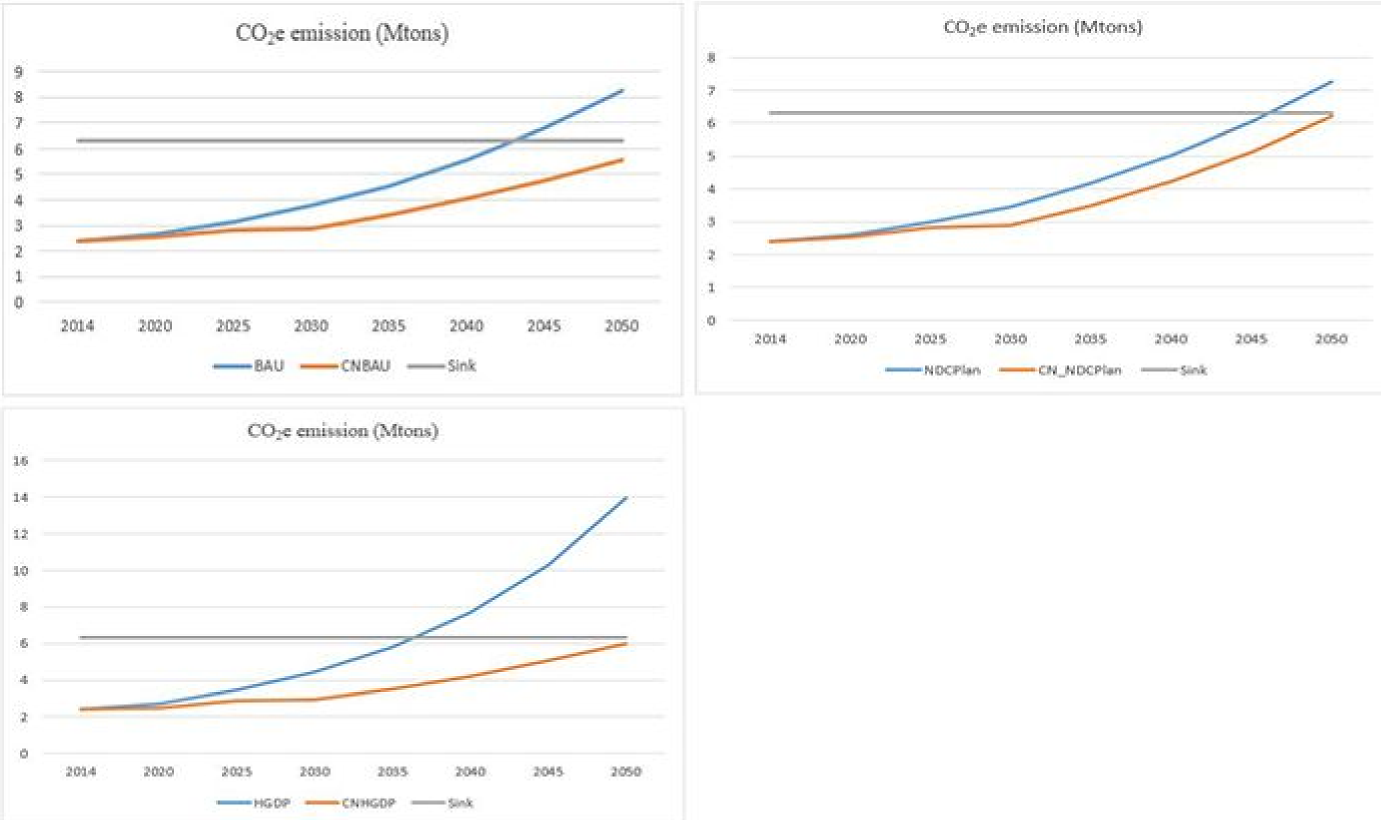

Figure 2

Carbon Neutral scenarios under different growth pressures a) BAU and its carbon neutral counterpart b) NDC Plan and its carbon neutral counterpart c) HGDP and its carbon neutral counterpart

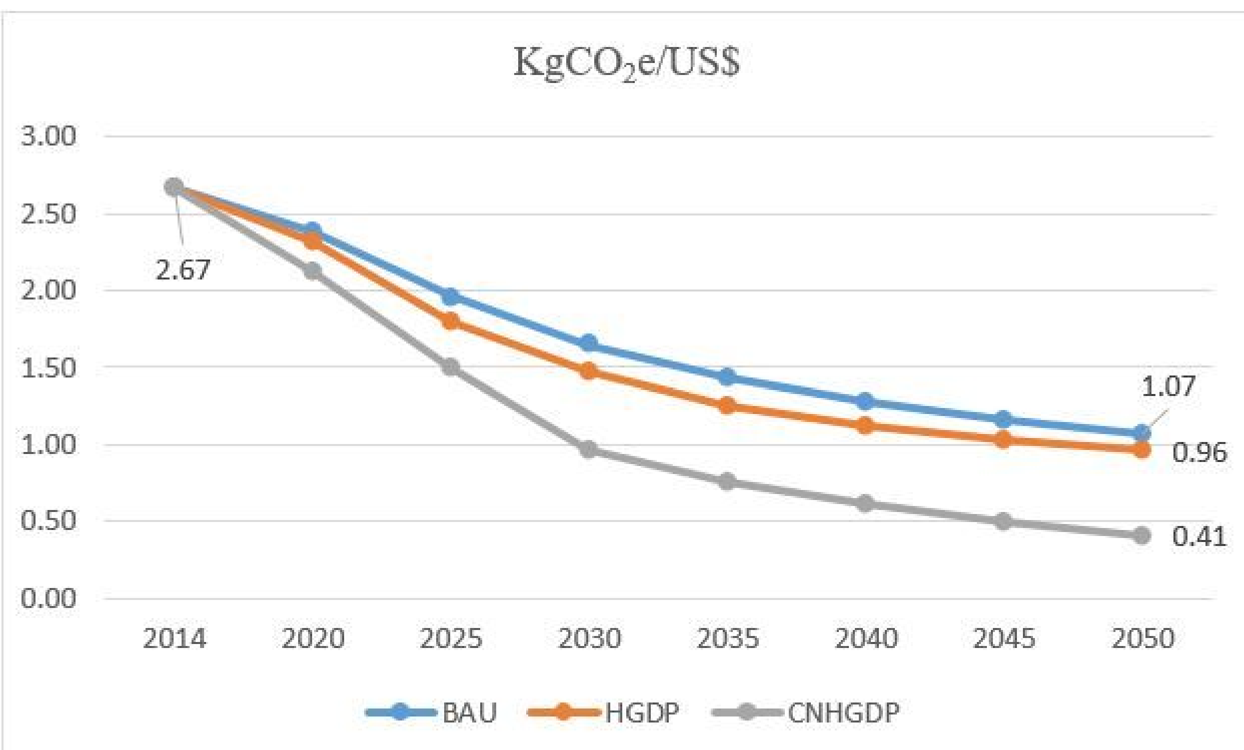

Figure 3

Carbon intensity of the Bhutanese economy

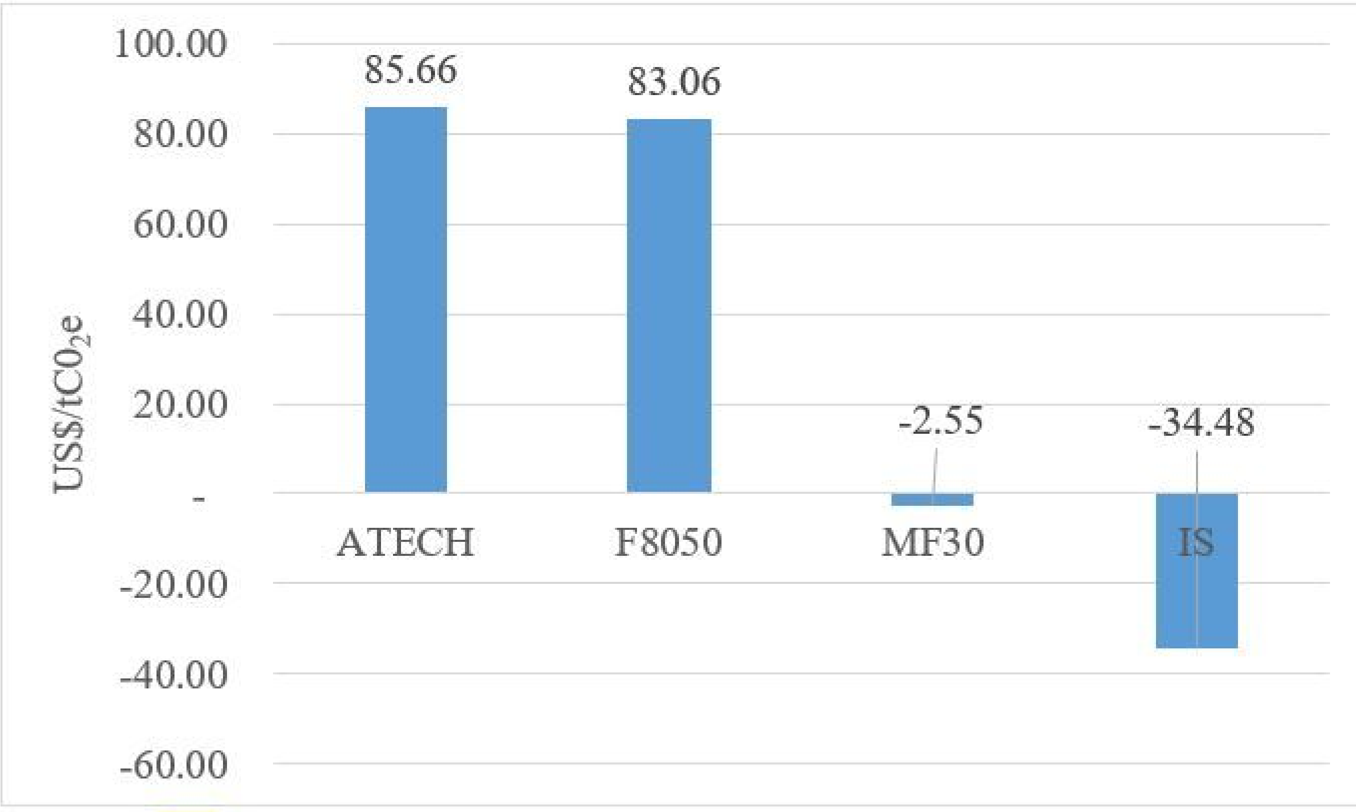

Figure 4

The cost of aggregated carbon neutral measures (US$/tCO2e)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendixfinal.docx