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Article

Bhutan: Can the 1.5 °C Agenda Be Integrated with Growth in Wealth and Happiness?

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Abstract
Bhutan is a tiny kingdom nested in the fragile ecosystem of the eastern Himalayan range, with urbanisation striding at a rapid rate. To the global community, Bhutan is known for its Gross National Happiness (GNH), which in many ways is an expression of the Sustainable Development concept. Bhutan is less known for its policy of being carbon neutral, which has been in place since the 15th session of the Conference of Parties meeting in 2009 and was reiterated in their Nationally Determined Contribution with the Paris Agreement. Bhutan achieves its carbon neutral status through its hydro power and forest cover. Like most emerging countries, Bhutan wants to increase its wealth and become a middle income country by 2020, as well as increase its GNH. This article looks at the planning options to integrate the three core national goals of GNH, economic growth (GDP) and greenhouse gas (GHG). We investigate whether Bhutan can contribute to the 1.5 °C agenda through its 'zero carbon commitment' as well as growing in GDP and improving GNH. Using the Long-range Energy Alternatives Planning model, this article shows that carbon neutral status would be broken by 2037 or 2044 under a high GDP economic outlook, as well as a business as usual scenario. National and urban policy interventions are thus required to maintain carbon neutral status. Key areas of transport and industry are examined under two alternative scenarios and these are feasible to integrate the three goals of GHG, GDP and GNH. Power can be kept carbon neutral relatively easily through modest increases in hydro. The biggest issue is to electrify the transport system and plans are being developed to electrify both freight and passenger transport.

Keywords
Bhutan; carbon neutral; economic growth; electrified transport; emission; energy policy; greenhouse gas; Gross National Happiness; LEAP model; urbanisation; wellbeing

Issue
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1. Introduction

Human society is gradually becoming an urbanised habitat (UN-DESA, 2014) and rapid urbanisation is expected to concentrate energy demand in cities (Newton & Newman, 2013). Urban centres are being recognised as a place for population and economic growth (GDP) (Jiang & O'Neill, 2017). As nations around the world urbanise, reducing greenhouse gas (GHG) emissions will become more critical, which is at the heart of climate policy ever since the establishment of the United Nations Framework Conventions on Climate Change (United Nations, 1992). However, GHG emissions are fully integrated with the economy, hence reducing them is a critical threat to socio-economic development (IPCC, 2014). Recent research argues for net zero emissions between 2045 and

2060 to hold the global temperature rise below 1.5 ºC (Rogelj, Luderer, et al., 2015; Rogelj, Schaeffer, et al., 2015), and the world's nations have committed to begin that journey in the Paris Agreement by making various pledges. Bhutan has pledged for carbon neutrality, which is a heavy commitment for an emerging nation. The question examined in this article is whether such a plan can be achieved along with Bhutan's other major commitments to growth in wealth and the social goals expressed in the unique Bhutan parameter of happiness, measured as Gross National Happiness (GNH).

A carbon budget for a 1.5 °C consistent world is estimated at 365 Gigatonnes (Rogelj, Schaeffer, et al., 2015). For Bhutan that can be considered as a tiny proportion of just 6.3 million tonnes, but the power of Bhutan's ability to integrate GNH, GDP and GHG emissions can send a strong message to the world. The issue examined in this article is whether such integrated goals are possible for an emerging nation like Bhutan.

GDP is well-known globally, but it is also often criticised for undermining socio-environmental issues. GHG is the primary cause of human induced climate change and is seen in most planning to be inconsistent with GDP, though possibilities of decoupling the two are now appearing (Newman, Beatley, & Boyer, 2017). GNH is a development philosophy for which Bhutan is known to the outside world (Brooks, 2013; RGoB, 2012; Schroeder & Schroeder, 2014; Ura, 2015). The term was first pronounced by the 4th king of Bhutan in the 1970s and it seeks to balance material and non-material development through the integration of its four pillars: socio-cultural, economic, environment and good governance (Thinley, 2005; Ura, 2015). Detailed narratives on GNH are provided elsewhere (Alkire, 2015; Centre for Bhutan Studies, 2012, 2016; Thinley, 2005; Ura, 2015) and the importance of GNH to sustainable development and the Sustainable Development Goals (SDG's) is being recognized as well as suggesting potential conflicts with other national goals (Allison, 2012; Brooks, 2013; RGoB, 2012; Schroeder & Schroeder, 2014). How these three goals can be integrated is an important element of Bhutan's planning.

The strong commitment to carbon neutrality is based in the culture of Bhutan. Bhutan is vulnerable to climate change due to low adaptation capacity (Bisht, 2013; NEC, 2011) and being located in the fragile mountainous ecosystem it is highly vulnerable to changes in climate. Thus the bold declaration made by Bhutan during COP15 was to remain carbon neutral for all time to come (NEC, 2011). This was indeed visionary and was reiterated in their Intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change (UNFCCC) (RGoB, 2015). The need to reduce GHG emissions is being acknowledged by Bhutan (GNHC, 2011; RGoB, 2015) and pursuing a low carbon economy is seen as an inevitable choice to achieve economic development in the face of climate change (Mulugetta & Urban, 2010).

The planning scenarios examined in this article to enable the integration of these three goals inevitably must involve urban planning. Most new development in Bhutan, like all emerging countries, is in cities, especially the capital city of Thimphu. Urbanisation in Bhutan is projected to reach 77% by 2040 with many urban growth centres with implications for more travel demand (Asian Development Bank, 2011). Urban planning will need to play a big part in how Bhutan achieves its goal of remaining carbon neutral while improving its GDP and GNH. Increases in the travel demand will lead to a rise in emissions from the transport sector unless travel demand can be carefully managed and there is a shift to carbon neutral fuels. This anticipated issue is of prime concern given that the petroleum products consumed in Bhutan are 100% imported and the transport sector is thus the major consumer of oil. The rising import of automobiles and fuels and their associated congestion and emissions remain a national concern (GNHC, 2011; NEC, 2011; RGoB, 2012) and will need to be addressed. This concern is not just in Bhutan, it is being felt globally. For instance, the need to cut emissions from the transport sector, which contributed to 23% of global GHG emissions is well acknowledged (IEA, 2016a). How to deal with such critical issues are discussed in many forums including IPCC (2014) and Newman, Beatley and Boyer (2017).

The United Nations Environment Programme 2011 recognises that environmental issues arise as a side effect of socio-economic activity in pursuing a desired goal. To this end, the UNEP (2014) acknowledges that there are more options to achieve significant decoupling if the aim is to increase wellbeing rather than just increasing GDP but of course these are all linked. To this end, the focus of the article is about how climate policy commitments may need to be adapted based on scenarios integrating the three key strategies around GHG, GDP and GNH. The article thus examines how Bhutan could leverage technological options and environmentally benign behaviour to achieve carbon neutral development through scenario-based LEAP modelling (see section 4 of this article).

The following sections provide background on the environmental stance and energy situation in Bhutan, the Bhutan-LEAP modelling, model results and discussions, concluding remarks and policy implications.

2. Environment and Human Wellbeing in Bhutan

A range of environmental issues are examined to show how interconnected they are with human wellbeing.

Bhutan's forest policy mandates minimum forest cover of 60%, which is now enshrined in its Constitution (RGoB, 2008) and encouragingly forest cover is being maintained at 71% (Ministry of Agriculture and Forestry, 2017). Research has suggested this regulation as the key to successful conservation in Bhutan (Jadin, Meyfroidt, & Lambin, 2015), while Buch-Hansen (1997) attributes environmental protection in Bhutan to their enlightened leadership and low population. Brooks (2010) applauds Bhutan as a living lab for integrated conservation and development. To this end environmental protection and wild life issues form some of the ecological indicators of the GNH index, which informs policy making in Bhutan. However forest conservation is encroaching on farm land and rising human-wildlife conflict is being faced by the Bhutanese farmers through loss of farm produce to wildlife where there is no formal compensation mechanism in place (Rinzin, 2006; Ura, 2015). The issue of conservation and rural livelihood remains unresolved (Ura, 2015) and the topical discussion warrants separate research.

Taking GNH seriously, Bhutan conducted a national GNH survey over the two periods[1]—2010 and 2015—the GNH index has increased by 1.8% (Centre for Bhutan Studies, 2016) and its Human Development Index (HDI) also increased from 0.572 in 2010 to 0.607 in 2015 (UNDP, 2016). Over the past decades, Bhutan has witnessed an average GDP growth rate of 7.8% (National Statistics Bureau, 2015). Extreme poverty in Bhutan is said to have been eliminated within the living memory of one generation (World Bank, 2014). While Bhutan is a 36% urban population at present, it is expected to reach 77% by 2040 through urban expansion and also due to rural to urban migration (Asian Development Bank, 2011). For instance, the population of Thimphu—the largest urban centre in Bhutan—is expected to increase from 147,000 in 2015 to 300,000 in 2040 (Asian Development Bank, 2011). The Asian Development Bank attributes the rural to urban migration as a consequence of aspirations for a better lifestyle ensuing from better amenities in urban areas, which are called an 'urbanisation bonus' (Lin & Zhu, 2017). However rapid urbanisation along with industrialization were seen as the drivers of GHG emissions in South Asian countries including Bhutan (Shrestha, Ahmed, Suphachalasai, & Lasco, 2013). Furthermore, being in the fragile ecosystem of the Himalayan range, Bhutan is very much vulnerable to the impacts of global climate change (GNHC, 2011; Hoy, Katel, Thapa, Dendup, & Matschullat, 2015; NEC, 2011). Bisht (2013) even suggests that climate change is the key determinant of Bhutan's future development and security. Climate change policy entails reducing GHG emissions. Plans for reducing GHG emissions centres around the energy mix and energy use, lifestyle, economic activities and land use forming the main drivers of anthropogenic GHG emissions (IPCC, 2014). Considering the energy system as one of the key drivers of GHG emissions, a brief background of the current energy system of Bhutan is provided.

The energy mix in Bhutan comprises: hydropower (28%), biomass (36%) and fossil fuels (37%). At 42.86 kW/capita, Bhutan has the highest theoretical hydropower potential in South Asia (Shrestha et al., 2013). However, the per capita energy consumption at 36 GJ (Department of Renewable Energy, 2015b) is 55% lower than that of the world average at 79 GJ (IEA, 2016b) suggesting there is potential to increase the hydropower side of the economy. The sectoral energy shares are shown in Figure 1 (Department of Renewable Energy, 2015b). Fossil fuels are predominantly used in transport and industry and their associated emissions could undermine any potential future carbon neutral pathway especially in the near future as the economy of Bhutan expands. The need to reduce GHG emissions is being acknowledged by Bhutan (GNHC, 2011; RGoB, 2015) and to this end a National Low Carbon Strategy has been developed (NEC, 2012). However, the strategy document assumes demand saturation in the industry and transport sectors after 2020, thereby underestimating the challenges of the rising energy and emissions from these two sectors, the main contributors of GHG emissions in Bhutan. To this end the following section intends to highlight the challenges and opportunities to reduce GHG emissions in the two sectors- policy directions will be concluded after the scenario analysis.

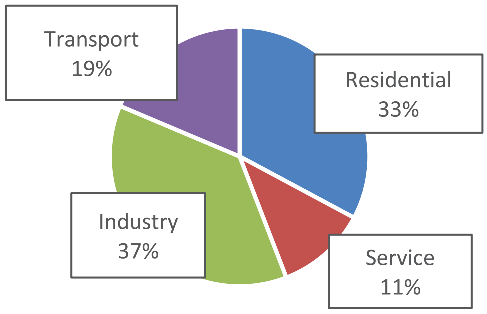

Figure 1. Sectoral energy share (%). Calculated based on Department of Renewable Energy (2015b).

3. Challenges in the Transport and Industry Sectors

Between 2005 and 2014, energy demand in the transport and industry sectors grew at a compound annual growth rate of 9% and 11% respectively, whereas that of service and residential sectors grew at 4% and 1% respectively (Department of Renewable Energy, 2015b; DoE, 2007).[2] At this growth rate, the transport and the industry sectors being major consumers of oil and coal have the potential to derail the carbon neutral pathway of Bhutan. This is the kind of issue faced by many emerging nations.

Furthermore, the transport and the industry sectors are considered to be hard to decarbonize (Rogelj, Luderer, et al., 2015) nonetheless it is not impossible. Industry can be electrified but transport will require a more complex set of urban planning policies.

[1] There was a GNH index for 2008, however the survey conducted in 2007 for that index has been noted as a preliminary survey with fewer questions and covering fewer districts to collect feedback and further expand the questionnaires that were then used for the next two nationwide GNH survey (Centre for Bhutan Studies, 2012).

[2] Authors' calculation based on the referenced sources.

Urban planning has developed an approach to promote pedestrianisation and bus based public transport in the urban areas of Bhutan (Asian Development Bank, 2011) and plans have been developed to electrify both freight and passenger transport in Bhutan (Hargroves, Gaudremeau, & and Tardif, 2017). A study on transport electrification in Nepal (Shakya & Shrestha, 2011), a neighbouring country to Bhutan with similar topography, found there were economic benefits, employment generation, enhanced energy security as well as beneficial environmental outcomes in such a policy. For carbon neutral transport, recent research (Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2017) has highlighted the need for radical changes both at the supply side and the demand side. Empirical studies at the global level have advocated rail based transport to reduce automobile dependence and associated emissions (Newman & Kenworthy, 2015; Newman, Kenworthy, & Glazebrook, 2013). Kołoś and Taczanowski (2016) found light rail to be feasible in medium sized towns in central Europe with a population between 100,000 to 300,000 and there are many cities with population just over 100,000 having such rail systems as a successful mode of transportation (Newman et al., 2013). The above approaches to urban planning will be included in the modelling outlined below.

With this as background the article will now show how the complex integration of GHG, GDP and GNH has been attempted as the basis of generating policy scenarios.

4. Methodology

This study expands on the Bhutan-LEAP model developed by Yangka, Newman and Rauland (2017) but with distinct scenario characterisation not covered in the previous work. LEAP stands for the Long-range Energy Alternative Planning system model, which is a flexible and user-friendly energy-environmental planning tool developed and licensed by the Stockholm Environment Institute (Heaps, 2016). However, LEAP is not a climate simulation model having earth system dynamics, though it is being used to assess climate policy through scenario-based energy system analyses and associated GHG emissions. For instance it is widely used for climate policy assessment and low emission development notably in developing countries (Kumar & Madlener, 2016; Ouedraogo, 2017; Sadri, Ardehali, & Amirnekooei, 2014; Shakya, 2016). The scope of an energy model is inherently vast (Nakata, Silva, & Rodionov, 2011), it is limited by the research questions that are being evaluated and the scenarios that are being formulated to address those queries. Once a database is developed, any pertinent issue can be studied within the scope and limitations of the model. This study used a scenario-based long term energy-economy modelling, which is acknowledged as an important method to explore uncertainties in the future (O'Neill et al., 2017). The alternative scenarios were formulated to address the present research objective.

4.1. Structure of Bhutan-LEAP Model

Bhutan-LEAP model was structured into key assumptions, demand branch, resource branch and non-energy branch. The planning horizon extends from 2014 to 2050. The demand branch is comprised of transport, industry, residential and service sectors to account for energy consumption and associated GHG emissions, and to study plausible policy interventions to contain the rising emission levels. Further disaggregation to sub-sector levels were limited by data availability. For instance, the tourism sector[3] wasn't shown as a separate sector in the model due to lack of data on energy consumption specific to the tourism sector. However, the service sector shown in the model includes the commercial sector (such as hotels and restaurants) which are impacted by the number of tourists (NSB, 2017), suggesting that the energy consumption under the service sector can be assumed to include energy consumption by the tourists visiting Bhutan. Furthermore, energy consumption in air transport can also be assumed to be impacted by the tourists coming to Bhutan given that 2/3rd of the flight passengers are tourists (Asian Development Bank, 2011).

4.2. General Assumptions

In this study a discount rate of 10% was used, consistent with that used in earlier studies and furthermore, a discount rate of 10% is mentioned as a global average opportunity cost of capital in a study on low carbon development for India conducted by World Bank (Gaba, Cormier, & Rogers, 2011). Considering forest cover of Bhutan as a carbon sink, for accounting purposes the emissions from wood-based energy consumption were accounted as positive rather than as a carbon neutral energy source. The emission factors for the demand technologies and the fuels were referred from the Technology and Emission Database of the LEAP model provided by SEI (Heaps, 2016). The emissions from waste disposal and agricultural activities—farming and livestock rearing—were accounted for under 'non-energy'. The amount of waste generation and disposal were assumed to increase along with urbanisation, whereas emissions from agriculture were assumed to remain constant as per the past trend (NEC, 2011). This assumption is plausible due to the ongoing rural to urban migration that is causing decline in the farming activities and livestock rearing. Furthermore, the amount of agricultural land in Bhutan is limited due to topography and forest conservation.

Paucity of data on long term macroeconomic parameters, cost and technological datasets for various demand technologies poses a daunting task, hence surrogate data from the literature were imputed and adapted, with consequent implications for the model results. In this regard,

[3] The brief note on tourism sector was provided to address the comment of a reviewer on the tourist sector being neglected in this article.

higher confidence levels could be placed on the data that were sourced from Bhutan specific studies.

4.3. Distinct Features of Bhutan's Energy System

From a modelling perspective, the energy system in Bhutan is relatively simple in that the energy supply side does not have the complex fossil fuel extraction and conversion processes except for limited coal mining and the hydropower system. Similarly, there is no rail system or transport using water ways and limited domestic air ways. Furthermore, accounting for primary energy supply and final energy consumption are similar except for the transformational losses occurring in the electricity system (Yangka & Diesendorf, 2016). Bhutan neither has oil reserves nor oil refineries, thus petroleum products consumed in the demand sectors are 100% imported.

4.4. Projection of Energy Demand and Energy Prices

Future prices for petroleum products, which are 100% imported from India were assumed to follow the international oil price and thus indexed to the price changes calculated from future oil price projection done by the US-Department of Energy (US Energy Information Administration, 2016). Oil import dependency of India itself is expected to increase from 74% in 2013 to 91% by 2040 (IEA, 2015). 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 (Feuerbacher, Siebold, Chhetri, Lippert, & Sander, 2016). The projected energy prices and end-use energy services in the four sectors are provided in the Annex.

The end-use energy services such as the heating, cooking, passenger travel, freight travel, which drives the corresponding energy demand are projected through the expression builder[4] under the activity variable of the demand module of the LEAP model.

5. Scenario Storyline

This article formulated two base scenarios and two corresponding alternative scenarios. The two base scenarios are: the Business as Usual (BAU) trajectory and a trajectory based on high GDP (HGDP). Their characterisation and key features are provided in Table 1. The two alternative scenarios intend to investigate the future that Bhutan aspires to—societal happiness within net zero greenhouse emissions reflecting carbon neutral development in a GNH state. These alternative scenarios attempt to contain the rising emissions from the BAU and the HGDP scenarios within the carbon sink capacity available for Bhutan. The storyline acknowledges that human settlements are sooner or later expected to be largely urbanised (Jiang & O'Neill, 2017; Newton & Newman, 2015).

The alternative scenarios are designated as Knowledge-Based Society (KBS) and GNH society, which are outlined in sub-sections 5.1 and 5.2 of this article. The GNH scenario is inherited[5] from the BAU scenario, while the KBS scenario is inherited from the HGDP scenario. Under these two alternative scenarios, a case study, with and without light rail transport, was also conducted to examine how light rail can support the carbon neutral pathway of Bhutan.

5.1. Wealthier and Knowledge Based Society (KBS)

This scenario imagines human settlements in Bhutan moving towards a greater proportion knowledge based economic activity in urban society during the later part of the planning horizon and enjoying a high economic outlook as a result of this. The Bhutanese society is likely to embrace such knowledge economy goals which include walking and public transport based on light rail and aggressive expansion of electric vehicles (Newman & Kenworthy, 2015). Such economic activity is less intensive in both energy and emissions. Being a KBS, the contribution of the service sector to the national GDP increases while that from the Industry sector decreases. The specificities of this scenario were outlined under Table 1.

5.2. GNH Based Society

This scenario contemplates a happy society derived from community vibrancy and symbiotic relationships between the human and the natural world, manifesting the essence of GNH—balancing material and spiritual development and co-existing with nature. The economic pathway under this scenario is assumed to follow the GDP growth rate of the BAU scenario (7.8% growth rate in the medium term and sustaining at 5.6% growth rate by 2050). Community vibrancy is defined as the people adopting the walking and public transport system. Harmony with nature is defined as less polluting and with more efficient socioeconomic activities including more knowledge-based activity. These definitions are for modelling purpose only. Similar to the KBS scenario, the specificities of this scenario were outlined under Table 1. While this is an initial attempt to construct scenarios around some key features of the GNH, there is no way to incorporate the entirety of GNH into the modelling work. We expect future work to expand on this.

6. Results and Discussion

The model results for the BAU scenario and the alternative scenarios are presented and synthesised with relevance to the 1.5 °C climate consistent world. The results discussed in the following section do pose a certain level of uncertainty attributable to the assumptions of the key variables, use of data which were adopted from various

[4] A flexible feature in LEAP, which allows user to write mathematical expressions to link various branches (the component of the LEAP structure).
[5] 'Inherited' in LEAP model can be simply understood as 'derived from' or 'built on'.

Table 1. Key features of the four scenarios.

Scenario	Residential sector	Service sector	Transport sector	Industry sector
BAU (GDP growth rate of 5.6% and increasing to 7.8% and sustaining at 5.6% until 2050)	Energy demand increases with the increase in the number of household; Fuelwood usage in all end-uses expected to decline to 23% by 2050 following the declining rural population; Saturation level of households with heating facility increases from 50% in 2014 (NSB & ADB, 2013) to 70% by 2050.	Energy demand increases with value added of the service sector; Fuelwood usage expected to decline.	Energy demand in passenger transport increases with per capita GDP and that for freight increases with the value added of the transport sector; Share of passenger travel demand met by bus increases from 15% to 25% by 2050; Share of passenger travel demand met by air transport increases from 20 to 25% by 2050; Share of freight travel demand met by light diesel truck increases from 17% to 30% by 2050.	Energy demand increases with value added of the industry sector.
GNH state (GDP growth rate assumed to be sufficed with the BAU growth rate)	Firewood and kerosene used in the building sectors reaches zero by 2030 and substituted by electricity and biogas.	The GDP share of the Service sector increases from 33% to 45%.	Walking meets 10% and light rail meets 30% of the passenger travel demand by 2050. Electric vehicles were assumed to penetrate at half the rate specified in IEA (2016a).	The GDP share of the Industry sector decreases from 11.70% in 2014 to 10.70% by 2050; A move towards industrial symbiosis.
HGDP	High economic outlook of 10% in the medium term and declining to 5.6% by 2050.			
KBS—Knowledge based society with high economic outlook	Dirty fuels used in the building sectors reaches zero and substituted by electricity and biogas.	The GDP share of service sector increases from 33% to 45%.	Walking and light rail meets 10% and 30% of the passenger travel demand respectively by 2050; Electric vehicles assumed to reach following share by 2050: 100% for 2-wheelers; 60% for passenger light duty vehicles; 30% for buses and trucks; (this assumptions exceed the rate provided in the IEA (2016a).	The GDP share of industry sector declines from 11.70% in 2014 to 10.70% by 2050; A move towards industrial symbiosis (Liu et al., 2011; Morrow, Hasanbeigi, Sathaye, & Xu, 2014).

sources, the projection methods for energy demand and energy prices. The study also does not analyse possible uncertainties associated with the carbon sink capacity of the forest cover over the planning period.

6.1. Energy Demand and Decarbonisation Rate

Since there are no major differences between the total primary energy supply (TPES) and the total final energy consumption (TFEC) in Bhutan (see sub-section 4.3 of this article), the results and discussion are focussed on TFEC. The final energy consumption exhibits a compound annual growth rate of 5%, 4.3%, 6.4% and 5.3% under the BAU, GNH, HGDP and KBS scenarios respectively. Over the planning period, the energy mix varies among the three major energy groups as shown in Figure 2. The three major energy groups being: 1) fossil energy, 2) biomass, and 3) electricity (which is essentially hydropower). Substantial variations in the energy mix are observed. For instance, in the base year, biomass dominates the fuel mix at 41%, while fossil energy dominates the fuel mix under both the BAU and the HGDP scenarios by 2050. Not surprisingly, hydropower dominates the fuel mix under the GNH and KBS scenarios by 2050 contributing to 48% and 61% of the final energy demand respectively.

The carbon intensity of the final energy demand at 86.41kgCO_2eq/GJ in 2014, which is lower than that of the present world average at 90kgCO_2/GJ (Rogelj, Luderer, et al., 2015) steadily decreases over the planning period under all the four scenarios. For instance, by 2050 the carbon intensity decreases to 52.55kgCO_2eq/GJ under the BAU scenario, further decreasing to 33.71kgCO_2eq/GJ under the KBS scenario. Interestingly under the KBS scenario, the energy system of Bhutan exhibits a decarbonisation rate of 2.6% per year, which is well within the range of 2% to 2.8% per year proposed for a 1.5 °C consistent world (Rogelj, Luderer, et al., 2015).

6.2. Emissions Trajectory

Variations in the energy mix discussed in sub-section 6.1 lead to variations in the emissions levels over the planning period under the four different scenarios; these are shown in Figure 3.

Figure 3 shows that the non-energy sector was the dominant contributor of emissions in 2014, however over the planning horizon oil products and solid fuels become the major contributor to the total CO_2eq emissions. Oil products are mostly consumed in the transport sector, while solid fuels are mostly consumed in the industry sector. This suggest a strong rationale for policy intervention in these two sectors and this article does this with a focus on the transport sector. The two alternative scenarios, KBS and GNH demonstrate the possibility of reducing the dependency on oil products and solid fuels through efficiency improvement in the industry sector and technological changes (switching to electric power) and modal shifting in the transport sector.

The emission trajectories under the four scenarios are shown in Figure 4. The emission level exceeds the sink capacity by 2037 and 2044 under the HGDP and BAU scenarios respectively, indicating the need for policy intervention in order to maintain carbon neutrality as the economy expands over the planning horizon. Under the KBS and GNH scenarios, which are the corresponding emission reduction measures for their parent scenarios, the emissions levels were contained below the sink capacity. Compared to their parent scenarios, cumulative emissions reduce by 34% and 22% under the KBS and GNH scenarios. However, such emissions reduction entails adopting efficient and cleaner technologies in the demand sectors with financial implications, which is discussed under sub-section 6.3 of this article.

Although the total emissions increases, the carbon intensity of the Bhutanese economy steadily declines

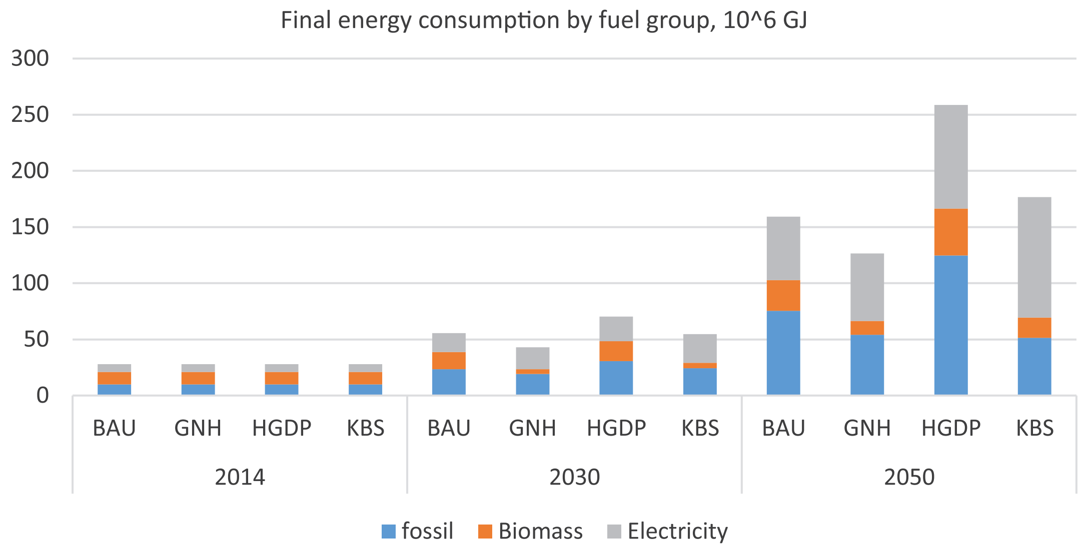

Figure 2. Energy consumption by major fuel group under four different scenarios. Note: BAU (Business as Usual); GNH (Scenario following GNH principle); HGDP (high economic outlook); KBS (knowledge-based society).

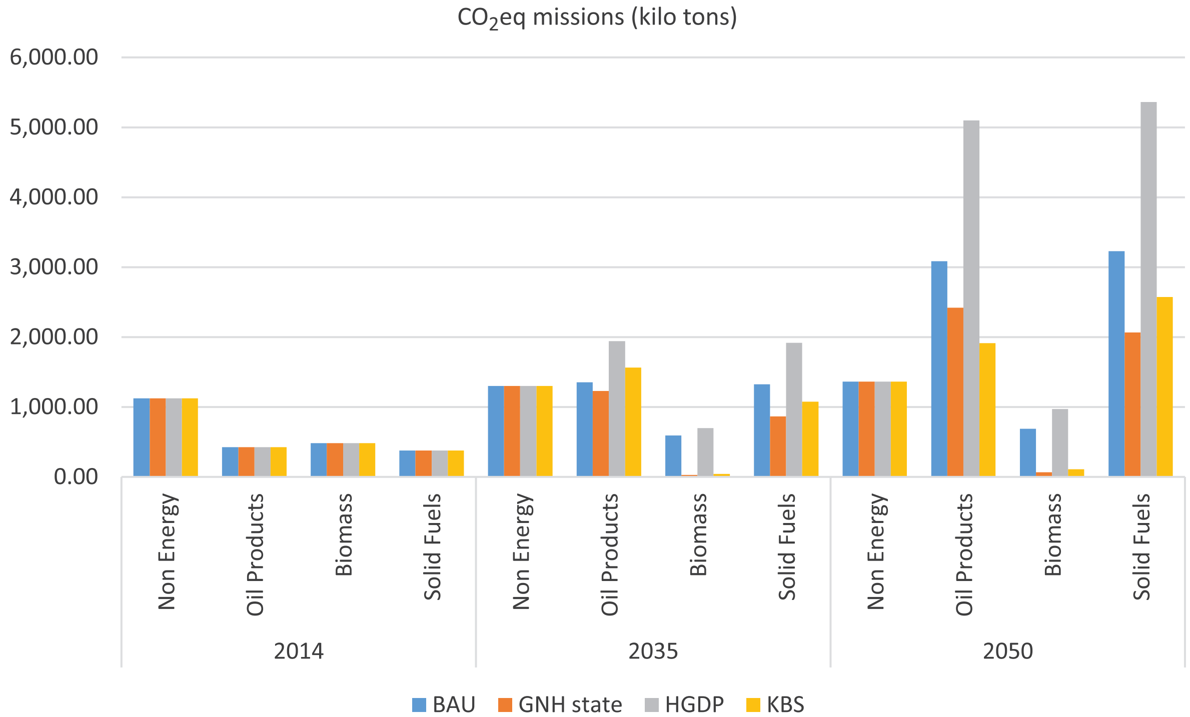

Figure 3. Emission variation by source under different scenarios.

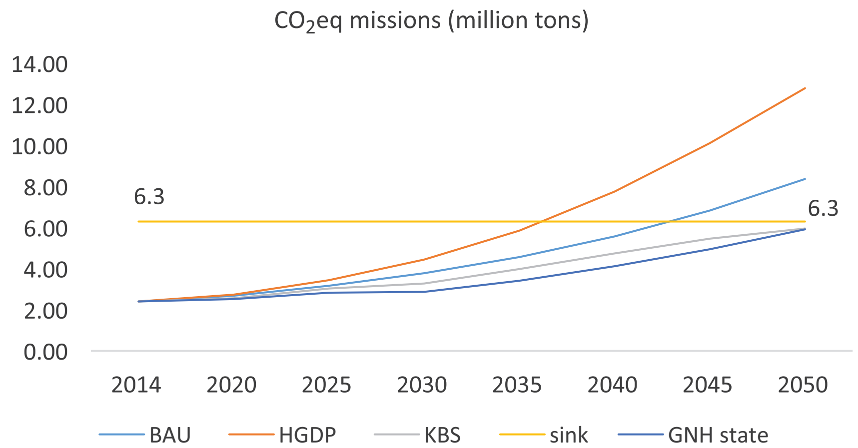

Figure 4. Scenario based CO_2eq emission in Million tonnes.

as shown in Figure 5, demonstrating the potential for a relative decoupling of GDP from environmental pressure, though absolute decoupling will require entirely replacing fossil fuels with renewables-based transport and industry. For instance, under the KBS scenario the carbon intensity of the economy decreases from 2.68kgCO_2eq/US$ in 2014 to 0.47kgCO_2eq/US$ by 2050, showing an improvement of 4.7%/year over the planning period. Such rapid reduction in the carbon intensity is following global trends (Newman, Beatley, & Boyer, 2017) as well as including new technologies in the energy mix as discussed in Sub-Section 6.1.

6.3. The Cost of Taming the Rising Carbon

As discussed in Sub-Section 6.2, the KBS scenario limits the total CO_2eq emission below the sink capacity despite high economic growth, similarly the GNH scenario holds the emission levels from a BAU pathway below the sink capacity. However, they entail transitioning to an efficient industrial production and preferences towards gradual electrification of the transport sector. But it comes with financial implications; there is a cost of carbon mitigation under the KBS scenario and savings from carbon mitigation under the GNH scenario relative to their parent scenarios, which were obtained from the cost-benefit summary report in the result module of LEAP. Table 2 shows the total discounted system cost and the cumulative CO_2eq emissions under the four scenarios. The system cost comprises a demand cost, transformation cost and the net resource cost (cost of export less cost of import). Relative to their parent scenarios, under the two alternative scenarios cost incurred in the demand sector increases, while the cost of resource

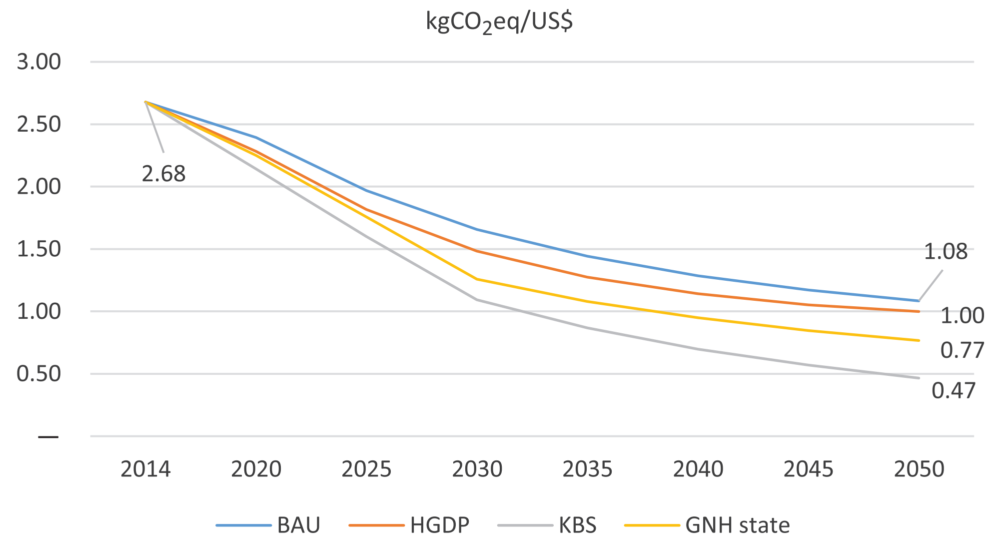

Figure 5. Carbon intensity of the Bhutanese economy.

import decreases. This leads to financial saving of US\$ 15.05/tCO_2eq under the GNH scenario relative to its parent scenario, BAU. This portion of the result indicates that Bhutan can live up to its carbon neutral pledge with cleaner and advanced technological choices at no cost.

However, under the KBS scenario, the cost of carbon mitigation relative to its parent scenario (i.e., HGDP scenario) amounts to US\$ 2.67/t CO_2eq. This translates to an additional cost of US\$ 5.55 million per year over the planning period, forming 0.043% of the GDP in 2050, which is lower than that estimated for India at 1.5% (GoI, 2014). The reason for the difference could be attributable to various assumptions in the model development and scenario characterisation. Notwithstanding this, pursuing a low carbon economy in India requires decarbonising their electricity sector, which is predominantly coal based, while in Bhutan clean hydropower is already the baseline electricity generation. With regard to the marginal abatement cost of carbon, a previous study conducted by the Asian Development Bank (Shrestha et al., 2013) for the South Asian countries showed that it varies from a saving of \$72.8/tCO_2eq to a cost as high as \$417.7/tCO_2eq depending on the fuel and the technology being substituted by their cleaner and more efficient counterparts. The additional cost under the KBS scenario suggests allocating the limited financial resources towards the carbon neutral goal that could compete with the budget for other pertinent socio-economic developmental needs. The result supports the viewpoint of Flagg (2015), who calls the carbon neutral pledge as a 'generous public good' (p. 209). However, in a carbon constrained world, where emission reduction targets are being accelerated following the Paris Agreement (UN Framework Convention on Climate Change, 2016), such additional costs could be met through the global carbon market.

6.4. Cost of Mitigation Measures in the Transport Sector

The KBS and the GNH scenarios assume that light rail meets 30% of passenger travel demand by 2050. However, electric vehicles were assumed to follow a different penetration rate in the two scenarios (see Table 1) to contain the corresponding emissions level below the sink capacity. In the GNH scenario, without calling in policies like developing an electric transport system, efficiency improvement in the four industry subsectors along with phasing out of dirty fuels in the residential and service sectors were found inadequate to limit the emissions level within the sink capacity. This is therefore suggesting the crucial role of electrifying the transport sector in Bhutan to live within their net zero carbon budget.

To examine the possible role of light rail transport in supporting the carbon neutral goal, model runs with a 'no LRT case' and 'LRT case' were compared under both the KBS and the GNH scenarios. The model results show that in the 'LRT case' there is a cost saving of US\$51.42/tCO_2eq and US\$ 5.07/tCO_2eq under the KBS and GNH scenarios respectively, while maintaining the emissions level below the sink capacity. This also

Table 2. Social Cost and CO_2eq emission.

Scenario	BAU	GNH	HGDP	KBS
Total discounted system cost, 10^9 US$	52.78	52.24	66.70	66.90
CO_2eq emission, Million tons	167.43	131.33	219.04	143.67
Mitigation cost (US$/t CO_2eq) relative to BAU	—	(−15.05)	—	—
Mitigation cost (US$/t CO_2eq) relative to HGDP	—	—	—	2.67

demonstrates the attractiveness of light rail transport, attributable to its longer operational life and higher passenger carrying capacity despite its high upfront cost. The results show the promises of light rail transport in decarbonising the transport sector thereby leveraging the carbon neutral goal of Bhutan. Furthermore, with a dedicated right of way, light rail can decongest road traffic. A prefeasibility study initiated by UNCRD also found light rail to be promising for urban Bhutan (Hargroves et al., 2017). Furthermore, a detailed project level costs and feasibility are being undertaken in an on-going parallel research activity. LRTs were also found to become cheaper than bus based transport when travel demand grows (IUT India, 2012). The case of transport electrification can also be useful for other emerging countries where oil imports represent a high burden on their GDP.

7. Concluding Remarks and Policy Implications

The long term Bhutan-LEAP modelling exercise provided crucial insights into the carbon neutral goal of Bhutan and its implications for urban planning. The results showed that if Bhutan follows the 2014 BAU energy-economy pathway, the associated emissions will exceed the sink capacity by 2044 and the aspiration for a high economic outlook can potentially derail Bhutan's carbon neutral path as early as 2037 if a similar BAU energy economic system gets locked-in. This is suggesting the need for policy intervention if Bhutan is to live within its carbon neutral budget.

The urban planning implications are that electrification of transport is needed and this requires some interventions such as those outlined by (Newman, Davies-Slate, & Jones, 2017). The model results indicate that there is economic benefit arising from introducing environmentally beneficial policies to maintain its carbon neutral status following a BAU pathway. Furthermore, even under the high economic outlook, the cost of carbon mitigation to hold the rising emissions is US$ 2.67/tCO_2eq only. Nonetheless, Bhutan's hydropower-based electricity generation along with extensive forest cover seem to be the comparative advantage at present and together provide a future bastion of hope to uphold its carbon neutral goal. The hydropower provides clean electricity and the forest cover provide ecosystem support as well as acting as a carbon sink. These features will need to be preserved into the future.

This study could be useful for the Bhutanese policy makers as the country strives to mainstream its low carbon strategy while it pursues a GNH paradigm and aspires to a better living standard. The article could be useful for emerging countries with similar aspirations to that of Bhutan to grow their economy with less emissions, though Bhutan pursuing GNH is unique in that it has shaped its policy making towards social and environmental goals as well as economic development. This article shows that GDP, GHG and GNH can be integrated under scenarios that also invite intervention, especially with electrified transport options. The article suggests there are hopeful scenarios that can be developed for emerging nations like Bhutan to meet the 1.5 °C agenda along with the SDG's.

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Conflict of Interests

The authors declare no conflict of interests.

References

Alkire, S. (2015). *Well-being, happiness, and public policy*. Thimphu: The Centre for Bhutan Studies & GNH Research.

Allison, E. (2012). Gross national happiness. In Ray C. Anderson (Ed.), *The Berkshire encyclopedia of sustainability: Measurements, indicators, and research methods for sustainability* (vol. 6/10; pp. 180–184). Great Barrington, MA: Berkshire Publishing Group.

Asian Development Bank. (2011). *Bhutan transport 2040 integrated strategic vision*. Metro Manila: Asian Development Bank. Retrieved from https://www.adb.org/sites/default/files/publication/30268/bhutan-transport-2040.pdf

Bisht, M. (2013). Bhutan and climate change: Identifying strategic implications. *Contemporary South Asia*, *21*(4), 398–412. doi:10.1080/09584935.2013.859658

Brooks, J. S. (2010). Economic and social dimensions of environmental behavior: Balancing conservation and development in Bhutan. *Conservation Biology*, *24*(6), 1499–1509. doi:10.1111/j.1523-1739.2010.01512.x

Brooks, J. S. (2013). Avoiding the limits to Growth: Gross national happiness in Bhutan as a model for sustainable development. *Sustainability*, *5*(9), 3640–3664. doi:10.3390/su5093640

Buch-Hansen, M. (1997). Environment. A liability and an asset for economic development: Some views on environmental protection with economic development in Bhutan. *International Journal of Sustainable Development & World Ecology*, *4*(1), 17–27. doi:10.1080/13504509709469938

Centre for Bhutan Studies. (2012). *An extensive analysis of GNH Index*. Thimphu: Centre for Bhutan Studies. Retrieved from http://www.grossnationalhappiness.com/wp-content/uploads/2012/10/An%20Extensive%20Analysis%20of%20GNH%20Index.pdf

Centre for Bhutan Studies. (2016). *A compass towards a just and harmonious society: 2015 GNH survey report*. Thimphu: Centre for Bhutan Studies. Retrieved from http://www.grossnationalhappiness.com/wp-content/uploads/2017/01/Final-GNH-Report-jp-21.3.17-ilovepdf-compressed.pdf

Department of Renewable Energy. (2015b). *Bhutan energy data directory*. Thimphu: Department of Renewable Energy.

DoE. (2007). *Bhutan energy data directory 2005*. Thimphu: Department of Energy.

Feuerbacher, A., Siebold, M., Chhetri, A., Lippert, C., & Sander, K. (2016). Increasing forest utilization within Bhutan's forest conservation framework: The economic benefits of charcoal production. *Forest Policy and Economics*, *73*, 99–111. doi:10.1016/j.forpol.2016.08.007

Flagg, J. A. (2015). Aiming for zero: What makes nations adopt carbon neutral pledges? *Environmental Sociology*, *1*(3), 202–212. doi:http://dx.doi.org/10.1080/23251042.2015.1041213

Gaba, K. M., Cormier, C. J., & Rogers, J. A. (2011). *Energy of the Indian economy: Path to low carbon development*. Washington, DC: World Bank. Retrieved from http://documents.worldbank.org/curated/en/753461468041481044/India-Energy-intensive-sectors-of-the-Indian-economy-path-to-low-carbon-development

GNHC. (2011). *Bhutan national human development report: Sustaining progress. Rising to the climate challenge*. Thimphu: Gross National Happiness Commission. Retrieved from http://planipolis.iiep.unesco.org/sites/planipolis/files/ressources/bhutan_nhdr_2011.pdf

GoI. (2014). *The final report of the expert group on low carbon strategies for inclusive growth*. New Delhi: Government of India Planning Comission.

Hargroves, K., Gaudremeau, J., & Tardif, F. (2017). *Prefeasibility study to investigate potential mass transit options for bhutan* (Report to the United Nations centre for regional development and the royal government of Bhutan). Perth: Curtin University.

Heaps, C. G. (2016). Long-range energy alternatives planning (LEAP) system. (Software version: 2017.0.7). Somerville, MA: Stockholm Environment Institute. Retrieved from https://www.energycommunity.org

Hoy, A., Katel, O., Thapa, P., Dendup, N., & Matschullat, J. (2015). Climatic changes and their impact on socioeconomic sectors in the Bhutan Himalayas: An implementation strategy. *Regional Environmental Change*, *16*(5), 1401–1415. doi:10.1007/s10113-015-0868-0

IEA. (2015). India energy outlook: World energy ooutlook special report. *World Energy Outlook*. Retrieved from www.worldenergyoutlook.org/india

IEA. (2016a). Global EV outlook 2016: Beyond one million electric cars. *International Energy Agency*. Retrieved from www.iea.org

IEA. (2016b). Key World energy statictics. *International Energy Agency*. Retrieved from http://www.iea.org/statistics

IPCC. (2014). *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, edited by R. K. Pachauri and L.A. Meyer). Geneva: Intergovernmental Panel on Climate Change.

IUT India. (2012). *Life cycle cost analysis of five urban transport systems*. New Delhi: Institute of Urban Transport. Retrieved from http://ficci.in/spdocument/20301/LIGHT-RAIL-TRANSIT-White-paper.pdf

Jadin, I., Meyfroidt, P., & Lambin, E. F. (2015). Forest protection and economic development by offshoring wood extraction: Bhutan's clean development path. *Regional Environmental Change*, *16*(2), 401–415. doi:10.1007/s10113-014-0749-y

Jiang, L., & O'Neill, B. C. (2017). Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, *42*, 193–199. doi:10.1016/j.gloenvcha.2015.03.008

Kołoś, A., & Taczanowski, J. (2016). The feasibility of introducing light rail systems in medium-sized towns in Central Europe. *Journal of Transport Geography*, *54*, 400–413. doi:10.1016/j.jtrangeo.2016.02.006

Kumar, S., & Madlener, R. (2016). CO2 emission reduction potential assessment using renewable energy in India. *Energy*, *97*, 273–282. doi:10.1016/j.energy.2015.12.131

Lin, B., & Zhu, J. (2017). Energy and carbon intensity in China during the urbanization and industrialization process: A panel VAR approach. *Journal of Cleaner Production*, *168*, 780–790. doi:10.1016/j.jclepro.2017.09.013

Liu, X., Zhu, B., Zhou, W., Hu, S., Chen, D., & Griffy-Brown, C. (2011). CO2 emissions in calcium carbide industry: An analysis of China's mitigation potential. *International Journal of Greenhouse Gas Control*, *5*(5), 1240–1249. doi:10.1016/j.ijggc.2011.06.002

Ministry of Agriculture and Forestry. (2017). *National forest inventory report: Stocktaking nation's forest inventory report launched* (Press release). Retrieved from http://www.dofps.gov.bt/wp-content/uploads/2017/07/National-Forest-Inventory-Report-Vol1.pdf

Morrow, W. R., Hasanbeigi, A., Sathaye, J., & Xu, T. (2014). Assessment of energy efficiency improvement and CO2 emission reduction potentials in India's cement and iron & steel industries. *Journal of Cleaner Production*, *65*, 131–141. doi:10.1016/j.jclepro.2013.07.022

Mulugetta, Y., & Urban, F. (2010). Deliberating on low carbon development. *Energy Policy*, *38*(12), 7546–7549.

Nakata, T., Silva, D., & Rodionov, M. (2011). Application of energy system models for designing a low-carbon society. *Progress in Energy and Combustion Science*, *37*(4), 462–502. doi:10.1016/j.pecs.2010.08.001

National Statistics Bureau. (2015). *Statistical year book of Bhutan 2015*. Thimphu: National Statistics Bureau.

NEC. (2011). *Second national communication to the UNFCCC*. Thimphu: National Environment Commission. Retrieved from www.nec.gov.bt/climate/snc http://www.nec.gov.bt/nec1/wp-content/uploads/2012/11/Bhutan-SNC-final-sm.pdf

NEC. (2012). *National strategy and action plan for low carbon development*. Thimphu: National Environment Commission.

Newman, P., Beatley, T., & Boyer, H. (2017). *Resilient cities: Overcoming fossil fuel dependence* (2nd ed.). Washington DC: Island Press.

Newman, P., Davies-Slate, S., & Jones, E. (2017). The entrepreneur rail model: Funding urban rail through majority private investment in urban regeneration. *Research in Transportation Economics*. doi:10.1016/j.retrec.2017.04.005

Newman, P., & Kenworthy, J. (2015). *The end of automobile dependence: How citites are moving beyond car-based planning*. Washington DC: Island Press.

Newman, P., Kenworthy, J., & Glazebrook, G. (2013). Peak car use and the rise of global rail: Why this is happening and what it means for large and small cities. *Journal of Transportation Technologies*, *3*(4). doi:10.4236/jtts.2013.

Newton, P., & Newman, P. (2013). The geography of solar photovoltaics (PV) and a new low carbon urban transition theory. *Sustainability*, *5*(6), 2537–2556. doi:10.3390/su5062537

Newton, P., & Newman, P. (2015). Critical connections: The role of the built environment sector in delivering green cities and a green economy. *Sustainability*, *7*(7), 9417–9443. doi:10.3390/su7079417

NSB. (2017). *National accounts statistics*. Thimphu: National Accounts Statistics. Retrieved from http://www.nsb.gov.bt/publication/files/pub4pe1310cn.pdf

NSB, & ADB. (2013). *Bhutan living standards survey 2012 report*. Thimphu: National Accounts Statistics. Retrieved from http://www.nsb.gov.bt/publication/files/pub1tm2120wp.pdf

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., . . . Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. doi:10.1016/j.gloenvcha.2015.01.004

Ouedraogo, N. S. (2017). Africa energy future: Alternative scenarios and their implications for sustainable development strategies. *Energy Policy*, *106*, 457–471. doi:10.1016/j.enpol.2017.03.021

RGoB. (2008). *The constitution of the kingdom of Bhutan*. Thimphu: The Royal Government of Bhutan. Retrieved from http://www.nationalcouncil.bt/assets/uploads/files/Constitution%20%20of%20Bhutan%20English.pdf

RGoB. (2012). *Bhutan: In pursuit of sustainable development* (National report for the United Nations conference on sustainable development 2012). Thimphu: Royal Government of Bhutan.

RGoB. (2015). *Communication of the INDC of the kingdom of Bhutan*. Thimphu: National Environment Commission.

Rinzin, C. (2006). *On the middle path: The social basis for sustainable development in Bhutan*. Utrecht: Netherlands Geographical Studies. Retrieved from https://dspace.library.uu.nl/handle/1874/15167

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., . . . Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, *5*, 519–527.

Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K., . . . Hare, W. (2015). Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters*, *10*(10), 105007. doi:10.1088/1748-9326/10/10/105007

Sadri, A., Ardehali, M. M., & Amirnekooei, K. (2014). General procedure for long-term energy-environmental planning for transportation sector of developing countries with limited data based on LEAP (long-range energy alternative planning) and EnergyPLAN. *Energy*, *77*, 831–843. doi:10.1016/j.energy.2014.09.067

Schroeder, R., & Schroeder, K. (2014). Happy environments: Bhutan, interdependence and the West. *Sustainability*, *6*, 3521–3533.

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2017). 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*, *141*, 237–247. doi:10.1016/j.jclepro.2016.09.064

Shakya, S. R. (2016). 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*, *4*(2), 141–160. doi:10.13044/ j.sdewes.2016.04.0012

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

Shrestha, R. M., Ahmed, M., Suphachalasai, S., & Lasco, R. (2013). *Economics of reducing greenhouse gas emissions in South Asia: Options and cost*. Mandaluyong: Asian Development Bank.

Thinley, J. Y. (2005). *What does gross national happiness (GNH) mean?* Paper presented at the Rethinking Development 2nd International Conference on GNH, Halifax, Canada.

UN-DESA. (2014). *World urbanization prospects: The 2014 revision, highlights*. New York, NY: United Nations. Retrieved from https://esa.un.org/unpd/wup/publications/files/wup2014-report.pdf

UN Framework Convention on Climate Change. (2016). *Decisions adopted by the conference of the parties* *session 21*. United Nations. Retrieved from http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

UNDP. (2016). *Human development report 2016: Human development for everyone*. Retrieved from http://hdr.undp.org/sites/default/files/2016_human_development_report.pdf

UNEP. (2014). *Decoupling 2: Technologies, opportunities and policy options* (DTI/1795/PA). Retrieved from www.unep.org/resourcepanel

United Nations. (1992). *United Nations framework convention on climate change*. United Nations. Retrieved from http://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf

Ura, K. (2015). *The experience of gross national happiness as development framework*. Metro Manila: Asian Development Bank. Retrieved from https://www.adb.org/sites/default/files/publication/177790/gnh-development-framework.pdf

US Energy Information Administration. (2016). *International energy outlook 2016*. Washington, DC: U.S. Energy Information Administration. Retrieved from www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf.

World Bank. (2014). *Kingdom of Bhutan green growth opportunities for Bhutan* (Policy Note). Danvers, MA: World Bank. Retrieved from http://documents.worldbank.org/curated/en/537221468205739263/pdf/ACS103290P1443560Box385344B00PUBLIC0.pdf

Yangka, D., & Diesendorf, M. (2016). Modeling the benefits of electric cooking in Bhutan: A long term perspective. *Renewable and Sustainable Energy Reviews*, *59*, 494–503. doi:10.1016/j.rser.2015.12.265

Yangka, D., Newman, P., & Rauland, V. (2017). *Energy future for carbon neutral Bhutan*. Manuscript submitted for publication.

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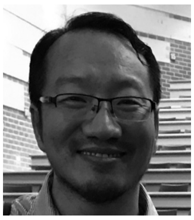

Dorji Yangka is a PhD student at the Curtin University Sustainability Policy Institute (CUSP), Curtin University, Western Australia. He has an M.E in Energy Economics and Planning from the Asian Institute of Technology, Thailand. He is from Bhutan, a carbon neutral and a GNH country. His PhD research is on how Bhutan can uphold its carbon neutral pledge as it aspires to be wealthier and happier. His PhD research is a journey through the complex tri-junction of GDP, GNH and GHG. His research hopes to connect the three goals of Bhutan with the wider literature. He is interested in carbon neutrality, low carbon development, energy policy and modelling, environmental intensity of human wellbeing and sustainability.

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Annex

A1. Data source

The base year energy consumptions were referred from the Bhutan Energy Data Directory (Department of Renewable Energy, 2015b). In case of techno-economic parameters of demand technologies, Bhutan specific data were used wherever available and the remaining data requirements were surrogated and adapted from the wider literature. For instance, data for transport sector were adapted from: City Bus Service (2015), Department of Renewable Energy (2015b), DoE (2010), Kołoś & Taczanowski (2016), the Ministry of Information and Communications (2015), Shafiei et al. (2017) and Zhu, Patella, Steinmetz and Peamsilpakulchorn (2016). Data for industry sector were obtained from: DoI (2015), Huisingh, Zhang, Moore, Qiao and Li (2015), Kero, Grådahl and Tranell (2016), Liu et al. (2011); Morrow et al. (2014), and NEC & TERI (2016). Similarly data for residential and the commercial sectors were sourced and adapted from: Department of Renewable Energy (2012, 2015a, 2015b) and UNDP (2012). Techno-economic data for existing hydropower plants and on-going hydropower projects were obtained from relevant stakeholders (Druk Green Power Corporation, 2014; Indian Embassy, 2016; MHPA, 2016). Data for wind power plant was imputed from Bhutan Power Corporation Limited (Personal communication, November 21, 2016) and for solar it was imputed from TERI (2015). Learning rates were imputed from Rubin, Azevedo, Jaramillo, and Yeh (2015) and Shafiei et al. (2017).

A2. Data sets for Bhutan-LEAP model

Table A1. Electricity sector key feature, based on BPC (2015).

Particulars	GWh		US cents/kWh*
Export	5179.3		3.36
Import	187.6		3.77
Generation	7166.3		
T&D loss		3.87%	

Notes: *authors' calculation based on BPC (2015). T&D stands for transmission and distribution.

Table A2. GDP and population projection under the BAU scenario.

Year	GDP, 10^6 US$*	Population**
2014	902	745,153
2020	1,324	809,397
2025	1,822	850,976
2030	2,508	886,523
2035	3,453	931,745
2040	4,753	979,273
2045	6,542	1,029,226
2050	9,005	1,081,727

Notes: US$ stands for the U.S. dollar. *See table 1 in the main text for the assumed growth rate; **data for 2014–2030 is from the National Statistical Bureau (2015); from 2035 to 2050, 1% growth rate was assumed.

Table A3. Power plant techno-economic data.

Plant	Capacity, MW	Capital cost (US$/kW)*	Data source
Existing hydropower plant			
CHP	360	646.57	Druk Green Power Corporation, 2014; Department of Renewable Energy, 2015b
Kurichu	60	1517.62	
Basochu	64	828.51	
Tala	1020	657.72	
Dagachu	126	1577.75	
Hydro_Micro	8.20	6952.00	
Candidate hydropower plant			
PHPA I	1200	1270.40	Indian Embassy (2016)
PHPA II	1020	1162.22	
MHPA	720	1088.16	MHPA (2016)
Tangsibji	118	1648.06	Druk Green Power Corporation. (2014)
KHP	600	1048.51	
Mega_hydro	4000	1173.60	This study
Other power plant			
Solar	0.12	1626	Department of Renewable Energy (2015b); TERI (2015)
Wind	0.60	4848.85	BPC, Personal Communication, November 21, 2016
Diesel Generator Set	10.7	2500	Department of Renewable Energy (2015b); Oladokun & Asemota (2015)
WTE	3.4	2746	Department of Renewable Energy (2015b)

Note: *authors' calculations based on the available data sources.

Table A4. Monthly electricity generation and consumption in 2014 based on Druk Green Power Corporation (2014) and BPC, Personal Communication, January 2017.

Month	Generation (GWh)	% Peak Generation*	Consumption (GWh)
Jan	243.7	20.3%	169.8
Feb	178.9	14.9%	154.6
Mar	211.4	17.6%	161.7
Apr	232.6	19.4%	166
May	458.9	38.2%	172.5
Jun	785.1	65.4%	167.6
Jul	1187.5	98.9%	155.9
Aug	1200.8	100.0%	164.3
Sep	1162.6	96.8%	157
Oct	767.9	63.9%	168.7
Nov	411.5	34.3%	175.1
Dec	306.1	25.5%	191.7

Note: *authors' calculations to construct hydropower availability curve.

Table A5. Cooking and heating end-use technology in the residential and service sectors UNDP (2012); Yangka & Diesendorf (2016).

Device	US$/device	Life (years)	Efficiency
Wood cook stove	5.69	5	10
Efficient wood cook stove	135.45	5	25
LPG/biogas stove	46.34	5	85
Electric stove	43.9	5	90
Efficient wood heating stove	189.66	5	75
Electric heater	57.98	5	90
Kerosene heater	203.25	5	45
Wood heating stove	56.90	5	12

Table A6. Household electric appliances, based on Department of renewable Energy (2015a, 2015b).

Device	US$/Device*	Life
Fridge 2-star	268.29	5 years
Fridge 3-star	284.55	5 years
Washing m/c semi-auto	240.65	5 years
Washing m/c auto	256.91	5 years
60Watt incandescent lamp	0.16	1200 hours
14Watt CFL	1.95	10000 hours
42Watt Fluorescent lamp	4.55	10000 hours
7Watt LED	7.31	50000 hours

Notes: *authors' calculation derived from the referred data sources. CFL — compact fluorescent lamp; LED stands for light emitting diode.

Table A7. Cost of passenger vehicle (IUT India, 2012*; RSTA, Personal Communication, October 19, 2016; Zhu et al., 2016).

Vehicle	Cost (US$)
Electric-cars	20,488
Light vehicle_gasoline	7,073.17
Light vehicle_diesel	29,268.29
Electric-bike	945.59
Diesel bus	39,204.75
Electric-bus	300,000.00
Light rail* (30 years life; 0.3MJ/pkm; 242 persons/coach)	1.62 million US$

Table A8. Transport sector technology characteristics, based on DoE (2010), Ministry of Information and Communications (2015), Yangka and Diesendorf (2016) and Zhu et al. (2016).

Passenger transport				
Vehicle type	**Fleet**	**km/litre**	**Occupancy (person/vehicle)**	**mp-km/year**
2-wheeler	9988	53.8	1.6	36.1
Taxi	4109	15	2.93	297.6
Light	41924	15	2.55	524.8
Bus	354	3.27	18.85	696.0
Freight transport				
Vehicle type	**Fleet**	**km/litre**	**Average capacity (tonnes/vehicle)**	**mt-km/year**
Heavy	8120	3.7	6	1933.78
Medium	1392		3	392.73

Note: mt-km stands for million tonnes kilometre; mp-km stands for million passenger kilometre.

Table A9. Freight transport technology, based on DoE (2010) and ETSAP (2010).

Freight vehicle	Diesel heavy truck	Heavy electric-truck*	Diesel light truck	Light electric-truck*
MJ/vehicle-km	7.46	−76%	3.92	−77%
Capital cost	32,000	406%	20,292	297%
kWh/vehicle-km		0.49		0.49
O&M cost	0.13	−82%	0.0561	−76%

Note: *authors' calculation based on ETSAP (2010).

Table A10. Transformation processes other than power generation, data imputed based on DoI (2015), Department of renewable Energy (2015a) and DRE & UNDP (2014).

Process	Capital cost	O&M cost	Life (years)	Production in 2014 (tonnes)	Resource potential
Coal Mining	49.59 (US$/ton)	82.62 (US$/ton)	50	121,891.00	1.9 Mt
Biogas production	18.96 (US$/GJ)	NA	30	898.45	633,756.19 GJ
Briquette making	4.05 (US$/GJ)	5% of capital cost	20	367.40	6,832.80 GJ

Table A11. Industry sector techno-economic data.

			US$/tonnes*			
Industry	**SEC (kWh/tonnes)**	**Production (tonnes)**	**Capital cost**	**O&M cost**	**Life (years)**	**Data source**
Cement	132.71	525,240.00	113.04	60.39	20	DoI (2015),
BCCL	5,340.58	32,340.48	812.38	842.76	20	Department of
Steel	825.50	196,172.22	46.07	335.40	20	Renewable Energy
Ferro Alloys	9,000.00	105,050.00	660.98	895.05	20	(2012, 2015a)

Note: *authors' calculation based on the listed data sources.

A3. Demand Projection

LEAP expression builder allows creating expressions for linking one branch to the other. For instance, the following expression syntax

GrowthAs(Branch:Variable, Elasticity)

relates the current branch (containing the above expression syntax) to the other branch which contains the independent variable that is assumed to drive the growth of the dependent variable in the current branch within the elasticity value specified by the modeller. In the Bhutan LEAP model, the above expression syntax translates to the following equation when invoked to project demand in the demand branches.

$$\text{Demand}(t) = \frac{\text{Demand}(t-1) * \text{driver}(t)}{\text{driver}(t-1)} \qquad \text{(Eq. (A.1))}$$

The driver is the chosen macroeconomic parameter (such as GDP, per capita GDP, population, number of households, etc.) provided under the 'key assumption' branch.

Table A12. Projected demand.

Sector	Unit	2014	2020	2025	2030	2035	2040	2045	2050
Transport sector									
Passenger travel	bp-km	1.93	2.84	3.91	5.39	7.43	10.24	14.11	19.45
Freight travel	bt-km	2.34	3.67	5.34	7.77	11.31	16.46	23.97	34.89
Industry sector									
BCCL	kt	32.3	40	57.6	81.7	113.7	155.7	209.4	276.9
Ferro Alloys	kt	106.8	132.1	190.4	269.7	375.6	514.1	691.6	914.5
Iron and Steel	kt	196.2	242.7	349.7	495.4	689.8	944.2	1,270.30	1,679.80
Cement	kt	525.2	649.8	936.3	1,326.30	1,847.00	2,528.10	3,401.30	4,497.60
Residential and Service sector									
Residential	Thousand HH	164.13	175.27	185.12	195.53	206.52	218.13	230.4	243.35
Service	Million US$	320.56	502.57	731.63	1,065.08	1,550.52	2,257.20	3,285.98	4,783.64

Table A13. Fuel price projection, based on Department of Renewable Energy (2015a) and US Energy Information Administration (2016).

Fuel	Unit	2014	2020	2025	2030	2035	2040	2045	2050
Diesel	US$/lt	0.82	1.29	1.49	1.74	2.00	2.31	2.67	3.09
Gasoline	US$/lt	0.95	1.49	1.72	2.01	2.31	2.67	3.08	3.56
Kerosene (Domestic)	US$/lt	0.21	0.34	0.39	0.46	0.52	0.61	0.70	0.81
Kerosene (Department of Industry)	US$/lt	0.77	1.22	1.41	1.64	1.89	2.18	2.52	2.92
Aviation Turbine Fuel	US$/lt	1.00	1.58	1.82	2.12	2.44	2.82	3.26	3.77
LPG	US$/kg	0.42	0.67	0.77	0.90	1.03	1.19	1.38	1.59

References

BPC. (2015). *BPC power data book 2015*. Thimphu: Bhutan Power Corporation Limited.

City Bus Service. (2015). *Bhutan: City Bus service technical assistance report*. Thimphu: City Bus Service.

Department of Industry. (2015). *Bhutan industry report 2015*. Thimphu: Department of Industry.

Department of Renewable Energy. (2012). *Bhutan energy efficiency baseline study*. Thimphu: Department of Renewable Energy.

Department of Renewable Energy. (2015a). *Bhutan Building energy efficiency study-Part 1 (Main Report)*. Thimphu, Bhutan: Department of Renewable Energy.

Department of Renewable Energy. (2015b). *Bhutan energy data directory*. Thimphu: Department of Renewable Energy.

DoE. (2010). *Integrated energy master plan for Bhutan*. Thimphu: Department of Energy.

DoI. (2015). *Bhutan Industry report 2015*. Thimphu, Bhutan: Department of Industry.

DRE, & UNDP. (2014). *Feasibility study on sawdust briquetting for sawmills in Bhutan*. Thimphu: Department of Renewable Energy.

Druk Green Power Corporation. (2014). Annual report 2014. *Drukgreen*. Retrieved from https://www.drukgreen.bt/images/yootheme/Publication/Annual_Reports/Annual_Report_2014.pdf

ETSAP. (2010). Technology brief 103: Cement production. *ETASAP*. Retrieved from www.etsap.org

Huisingh, D., Zhang, Z., Moore, J. C., Qiao, Q., & Li, Q. (2015). Recent advances in carbon emissions reduction: Policies, technologies, monitoring, assessment and modeling. *Journal of Cleaner Production*, *103*, 1–12. doi:10.1016/j.jclepro.2015.04.098

Indian Embassy. (2016). Ongoing hydropower projects. *Embassy of India*. Retrieved from https://www.indianembassy thimphu.bt/pages.php

IUT India. (2012). *Life cycle cost analysis of five urban transport systems*. New Delhi: Institute of Urban Transport. Retrieved from http://ficci.in/spdocument/20301/LIGHT-RAIL-TRANSIT-White-paper.pdf

Kero, I., Grådahl, S., & Tranell, G. (2016). Airborne emissions from Si/FeSi production. *Jom*, *69*(2), 365–380. doi:10.1007/s11837-016-2149-x

Kołoś, A., & Taczanowski, J. (2016). The feasibility of introducing light rail systems in medium-sized towns in Central Europe. *Journal of Transport Geography*, *54*, 400–413. doi:10.1016/j.jtrangeo.2016.02.006

Liu, X., Zhu, B., Zhou, W., Hu, S., Chen, D., & Griffy-Brown, C. (2011). CO2 emissions in calcium carbide industry: An analysis of China's mitigation potential. *International Journal of Greenhouse Gas Control*, *5*(5), 1240–1249. doi:10.1016/j.ijggc.2011.06.002

MHPA. (2016). *Status report* (September). Thimphu: Mangdechu Hydroelectric Project. Retrieved from http://www.mhpa.gov.bt/document/MHPASTATUSREPORTSEPT2016.pdf

Ministry of Information and Communications. (2015). *Annual info-comm and transport statistical bulletin*. Thimphu: Ministry of Information and Communications

Morrow, W. R., Hasanbeigi, A., Sathaye, J., & Xu, T. (2014). Assessment of energy efficiency improvement and CO2 emission reduction potentials in India's cement and iron & steel industries. *Journal of Cleaner Production*, *65*, 131–141. doi:10.1016/j.jclepro.2013.07.022

National Statistics Bureau. (2015). *Statistical year book of Bhutan 2015*. Thimphu: National Statistics Bureau.

NEC., & TERI. (2016). *Energy Efficiency imporvements in the industry sector in Bhutan*. National Environment Commission.

Oladokun, V. O., & Asemota, O. C. (2015). Unit cost of electricity in Nigeria: A cost model for captive diesel powered generating system. *Renewable and Sustainable Energy Reviews*, *52*, 35–40. doi:10.1016/j.rser.2015.07.028

Rubin, E. S., Azevedo, I. M. L., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy*, *86*, 198–218. doi:10.1016/j.enpol.2015.06.011

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2017). 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*, *141*, 237–247. doi:10.1016/j.jclepro.2016.09.064

TERI. (2015). *Reaching the Sun with Rooftop Solar*. Delhi: TERI and Shakti Sustainable Energy Foundation.

UNDP. (2012). Bhutan sustainable rural biomass energy project. *UNDP Buthan*. Retrieved from http://www.bt.undp.org/content/bhutan/en/home/operations/projects/ccmprojectlist/srbe

US Energy Information Administration. (2016). *International energy outlook 2016*. Washington, DC: U.S. Energy Information Administration. Retrieved from www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf.

Yangka, D., & Diesendorf, M. (2016). Modeling the benefits of electric cooking in Bhutan: A long term perspective. *Renewable and Sustainable Energy Reviews*, *59*, 494–503. doi:10.1016/j.rser.2015.12.265

Zhu, D., Patella, D. P., Steinmetz, R., & Peamsilpakulchorn, P. (2016). *Bhutan electric vehicle initiative: Scenarios, implications and economic impact*. Washington, DC: International Bank for Reconstruction and Development/The World Bank. Retrieved from http://documents.worldbank.org/curated/pt/395811467991008690/pdf/104339-PUB-PUBLIC-ADD-doi-isbn.pdf