Mitigating greenhouse effect in India through gradual shift to renewable energy

Anubhuti Bhatnagar

Carbon dioxide levels in the atmosphere have increased from an average of 6.3 Pg-C year^{-1} during 1990–99 to 7.8 Pg–C year^{-1} during 2000–09. In this context, although the global emissions fell to 0.5% in 2014, there is a need to drastically alter the current path of development because it has been observed that the burden of climate change is disproportionately high on developing countries such as India. Here, the rising global warming predicts a dangerous scenario on agriculture, poverty alleviation efforts and infant mortality rate. The current negative impact of energy generation by fossil fuels can be checked by prudent management of existing resources followed by enhanced use of renewable energy sources to meet the requirements of the world, without emulating the carbon-intensive model of the past. In this study strategies have been proposed for the next 40 years to allow government agencies to observe changes in the climate along with analysing the impact of mitigation measures implemented.

Keywords: Climate change, economic growth, greenhouse effect, mitigation measures, renewable energy.

'Science has spoken. Leaders must act. Time is not on our side.'

–Ban Ki-moon, Secretary-General of the United Nations

AN alteration in the climate that is statistically significant, either in the mean or in the variability of the climate, and has been observed over a few decades (an extended period) is termed climate change[1]. Earth has undergone several glacial cycles in the past, with the seventh glacial retreat occurring some 7000 years ago. Thus, the earth's atmosphere has been warming up and cooling without human intervention since millennia. However, the rapidity of changing climate in the recent decades is drawing attention to the role of human intervention in global warming. The combustion of fossil fuels (coal, oil and natural gas), deforestation, forest fires and changing land-use patterns have led to increase in greenhouse gases (GHGs) such as CO_2, CO, CH_4, NO_x, etc. in the atmosphere resulting in higher global temperature which induces climate change.

Apart from the direct correlation of increasing CO_2 emissions with global warming, other evidences of human-induced climate change are[2]: (i) Decline of oxygen content in line with increasing fossil-fuel combustion. (ii) Observed isotopic signature of carbon from fossil fuel burning (lack of ^{14}C and depleted content of ^{13}C) such as an increase in the $^{13}C/^{12}C$ ratio. (iii) Increase in CO_2 in the northern hemisphere, where fossil combustion is higher.

Due to uptake and distribution of CO_2 throughout carbon sinks – deep oceans, terrestrial ecosystems and atmosphere, the rate of increase of carbon is only half that at which it is actually emitted by the fossil-fuel consumption. But the net balance in uptake of CO_2 is unlikely to remain positive indefinitely[2].

The drought in Sub-Saharan Africa in the 1970s and simultaneous reduction in agricultural yield from the former USSR, China and Latin America have been identified as some of the first incidents occurring due to a shift in climate pattern. Since then, the world has tried to stimulate collective thought regarding reducing emissions through development of indigenous models of economic growth and provision of clean technology transfer in developing countries. Dedicated groups like the Intergovernmental Panel on Climate Change (IPCC), United Nations Framework Convention on Climate Change (UNFCCC), World Climate Conferences, Conference of Parties (COPs), etc. focus on understanding the impact of changing climate patterns, anticipating the damage to life and property, and adapting to the new climate[3].

The objectives of the present study are, first, to assess the impact of climate change and global warming on India; and secondly, to propose a roadmap for policy measures and action plans which could be pursued to mitigate climate change through a gradual shift to renewable and clean energy. This roadmap has been envisioned by taking into account the fact that any strategy for climate change mitigation has to adhere to the timescale relevant

Anubhuti Bhatnagar is in the Energy and Resources Institute, New Delhi 110 003, India. e-mail: anubhuti.bhatnagar@teri.res.in

to effectuate any significant impact on the climate. A period of 40 years chosen for the roadmap proposed here would allow observing the effectiveness of the measures as well as to review the strategies, if required.

Emissions, global warming and the Indian economy

Over geologic history, an ingenious system has evolved, whereby atmospheric CO_2 is redistributed between vegetation, ocean and rocks through a range of pathways called carbon cycle. These pathways had maintained CO_2 concentration in the atmosphere at around 163 ppm for centuries[4,5]. However, burning fossil fuel released on an average 5.4 Pg-C year^{-1} during 1980–89, 6.3 Pg-C year^{-1} during 1990–99, 7.8 Pg-C year^{-1} during 2000–09 (ref. 6) and rose to 9.5 Pg-C in 2011 (ref. 7). The assessment reports released by IPCC expected global temperature to increase from 1°C to 6.4°C as a consequence of increase in the concentration of CO_2 emitted by consumption of fossil fuels in atmosphere by 2100 (ref. 8). The most dramatic impact of such a situation may be the shutdown of the ocean thermohaline cycle which is responsible for the transport of heat from the equator to the northern clines[9], increased food insecurity, poverty and infant mortality[10–15].

It has been calculated[16] that the global total CO_2 emission must be capped at 2.9 Eg to give a 66% chance of avoiding global warming of more than 2°C – regarded as dangerous climate change; hence an almost flat emission curve is a positive sign for climate change advocates. But less than 1 Eg is left to reach the predicted cap and there is a need to drastically cut down the global CO_2 emission.

With the beginning of the Industrial Revolution in 1750 in Europe, the developed countries were the first to industrialize. The large scale of manufacturing and inefficient use of fossil fuels led to wide-ranging emissions from these countries. This situation has been referred to as 'historical contribution to climate change' and is recognized in the principle of common but differentiated responsibility (CBDR). However, with the present emissions from the developed countries on a downward trend, developing economies are accountable for more than half of the world's carbon dioxide emissions – China being the largest emitter (29%) and India being the fourth largest (6%) emitting nation[17].

It should be noted that while developing economies are being blamed for increasing levels of emission[18], they pay more than they contribute to climate change. In 2006, the cost of a 2°C rise in the global temperature was expected to be equivalent to 1% of the global GDP. But the cost of climate change for India, as estimated by the World Bank in 2006, was found to be 5% (ref. 19). Equitable distribution of the cost of climate change is impractical because the developing countries bear 80% of the world's population and will end up paying the most[20] despite skewed consumption patterns. For instance, India, which is the home to one-sixth of the world population, had an annual per capita emission of only 1.7 MT compared to 17 MT in the US in 2011 (ref. 21).

To plan mitigation policies in the case of India, it is vital to assess the socio-economic aspirations of its citizens. The factors that play a role in human motivation, as explained by Maslow's theory of hierarchy of needs could be reinterpreted to indicate the path to achieve inclusive and sustainable development in India[22]. This theory reveals that people are driven to achieve certain needs starting from the physiological needs – food, water and shelter; to progress towards achieving their full potential called a stage of self-actualization. Maslow explained that the ability to be concerned about welfare of humanity, morality and ethical conduct in society would manifest in a person only after fulfilment of baser desires[23]. In case of governments moving towards sustainable development, the same theory could be applied because all the decisions are based on prioritization (Figure 1).

The physiological needs in the case of a country could be met through provision for energy access, food and water security, shelter, etc. Education, health, employment and economic security would promote dignity and equality in the people, in turn increasing their sense of responsibility. This would enhance their awareness regarding the environment and the need to ascertain the efficient utilization of available resources.

While the catalyst in initial stages of economic development has been conventional energy, the present strategy for India should be to ensure a sustained growth not necessarily through the tried, tested and known to have failed model of 'destruction and growth', but through clean and green economy. This would ensure an economic growth that would be delinked with environmental impact[24,25].

What follows is a discussion on the methods that India can adopt to outlast the dangers of climate change and global warming.

Pathways for mitigating greenhouse effect in India

Fossil fuel consumption contributes up to 65% in the global carbon emission and is the mainstay for energy production in both developing and the developed economies[26]. While increasing consumption of fossil fuels has been identified as a culprit for climate change, the apprehension against climate change mitigation programmes has been the advantages of higher economic growth vis-à-vis the expenditure for climate adaptation policies[27]. However, in developing countries, there is a scope of answering the question of desirability vs feasibility of this economic growth because gross domestic product (GDP) is not a robust indicator of growth. It does not

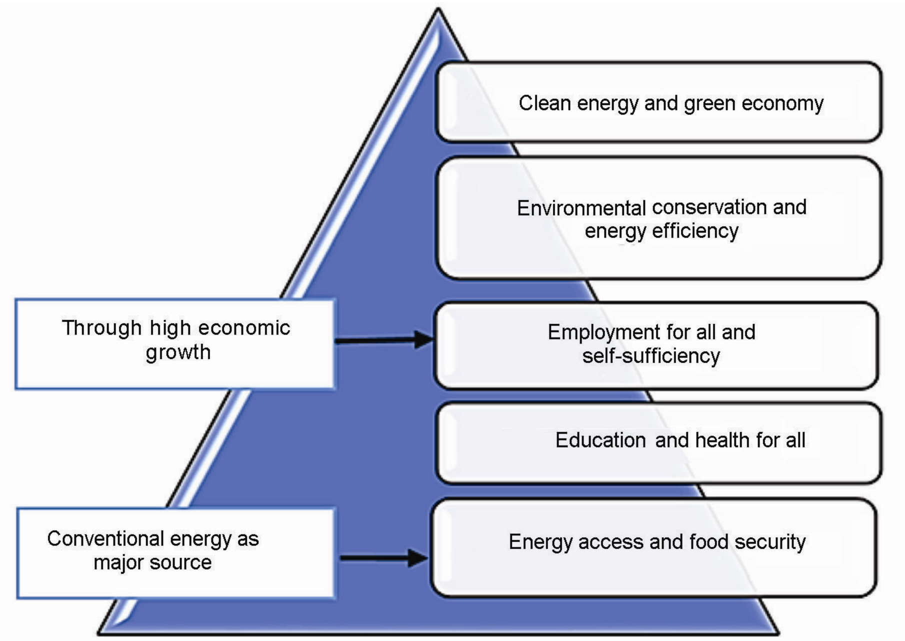

Figure 1. Interpretation of Maslow's hierarchy of needs.

encompass the environmental impact and decreasing availability of resources or the impact on well-being of the people at large[28]. Hence, in order to decouple energy consumption with ecological impact of the fossil fuels, there has been an increasing emphasis on reuse and recycling of resources, and deployment of low carbon technologies on a large scale[27].

In the case of India, demand for power has increased from 2006 to 2014 at a compounded annual growth rate (CAGR) of 7.72% with thermal energy holding the highest share in electricity generation in this period[29]. Further, being one of the highest emitting countries in the world[17], India has committed to reduce its emissions significantly through increased allocation of funds towards mitigation strategies, changing lifestyle and practices, and creating unambiguous methodologies and policies for energy utilization[30]. Here, renewable energy emerges as a solution because India has a potential of about 900 GW (peak power demand is much lower) from commercially usable sources such as wind, small hydro, biomass and solar energy, and a significant potential from decentralized applications[31].

Agriculture, water, health and livelihood are the most vulnerable sectors in India[30], while power, transport and industry are the major sectors contributing to high emissions[32]. In order to maintain a steady growth rate, India needs to prioritize a shift to renewable energy and enhance climate change resilience capability. The strategies identified in this study are, as mentioned earlier, spread out over duration of 40 years. They are only indicative of the major opportunities available to gradually move to a 'self-actualized' mode of power generation and ultimately towards a greener future.

Enhancing coal efficiency and shift to natural gas

The maximum primary energy demand of India is met by thermal energy. Total consumption of raw coal by industry has increased with a CAGR of 3.73% from 2005–06 to 2012–13 (ref. 29). But with the mounting concern over impact of such carbon-intensive growth, the role of clean coal technology becomes significant. Moving the current average global efficiency rate of subcritical coal-fired power plants from 33% to 40% could cut 2 Pg CO_2 emission, which is close to India's annual CO_2 emission now[33]. Further, a supercritical plant can have a 2% higher efficiency than the present best-case scenario for subcritical with 4% less emission and 20 years more life. Immediate measures regarding improvement in the thermodynamic efficiency, for instance, a 1% point improvement in the efficiency of conventional pulverized coal combustion plant will result in a 2–3% reduction in CO_2 emission as well as reduction in pollutants such as NO_x, SO_x and particulates[33]. The total cost of power generation is based on factors such as land, labour, material and scale of production. Material cost would further depend on fuel availability, transport cost, infrastructure and debt financing[34].

Substituting coal by natural gas, which contains roughly 15 kg C/GJ of energy compared to 26 kg C/GJ of energy for coal, should be a welcome move. At the end of 2012, natural gas-based power generation was 24.2 GW (11th Five Year Plan)[35]. This was used for balancing power and peak demands, while coal power supplied base load[36]. The demand for natural gas has been increasing because of measures undertaken to increase availability, improved distribution infrastructure and environment-friendly

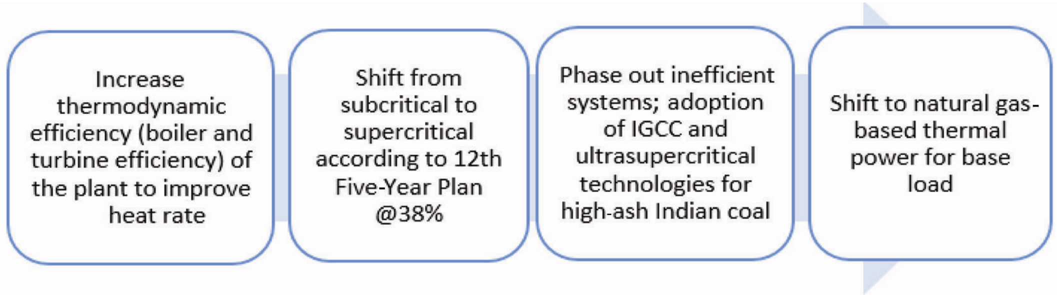

Figure 2. Strategy for thermal power.

characteristics such low emissions per unit of energy generation.

Among the unconventional sources of natural gas is shale. The Ministry of Petroleum and Natural Gas (MoPNG), Government of India (GoI) has been trying to gain experience through international collaboration, and has been scouting for resources of shale gas[37]. India has 63 tcf of recoverable shale gas reserves[38] which could drastically alter the country's power scenario.

Further advantages of natural gas involve lower cost of import, improved quality of life and increased energy security (through discovery of domestic resources) for India[39]. While utilization of shale gas has transformed the American petroleum industry, the issue of land and water availability, and improvement in extraction methodology would require a fiscal policy which could keep pace with the demand and supply dynamics[32]. For instance, while Bengal has been identified as a prospective source of shale, the extraction is curtailed by the pernicious land and water stress[40].

Figure 2 incorporates the aforementioned policy and developmental issues to suggest a road map for improving efficiency of coal-based power generation and ultimately superseding it with natural gas.

As with any policy measure, there is room for iterations in the roadmap to incorporate any technological breakthroughs or set-backs that may occur in the stipulated time period.

Efficient transport and alternate fuels

The transport sector in India consumes 22% of the total commercial energy[41], 70% of the diesel produced in the domestic refineries and 99.6% of the petrol[42]. It is an indicator of development in a region. However, since it relies on fossil fuels, there is a consequent rise in GHGs[43], including CO, CO_2, NO_x, photochemical oxidants, particulate matter, poly-aromatic hydrocarbons (PAHs), and benzene, aldehydes and 1,3-butadiene[44].

Figure 3 discusses a four-step strategy for the transport sector in India which could be modelled according to the region.

The first aspect of improvement is in the existing infrastructure and public transport. The Government has proposed policies such as National Highway Development Programme, Pradhan Mantri Gram Sadak Yojna, and Jawaharlal Nehru National Urban Renewal Mission to address the issue of infrastructure[45]. Further, policies related to a clean transport sector enacted in the past decades include Air (Prevention and Control of Pollution) Act, 1981; National Auto Fuel Policy, 2003; National Environment Policy (NEP), 2006; National Transport Development Policy Committee, 2010, etc.[46]. However, national policies can only provide the spine to allow the sector to grow. Vulnerability and economic assessment of individual regions will help frame targeted strategies[46,47]. The rising motor vehicles, CAGR of 10% in cars and two wheelers between 1991 and 2011 (ref. 48), led to increase in congestion on the roads, air pollution and societal strain because of the inability of economically underprivileged population to participate in the rapid growth of mobility[47]. This indicates a need for better traffic engineering, encouraging non-motorized transport through ensuring safety, and provision for better connectivity through public transport to reduce requirement of private car ownership[46].

The next steps could be improvement in energy efficiency and promotion of alternate fuels. For instance, the suggested shift in emission norms from Bharat Stage IV (BS IV) to BS VI in the present decade[49] would require gasoline-driven cars and other light-duty vehicles to have better air–fuel management system and catalytic converters, and diesel-run vehicles to reduce emissions through the use of diesel particulate filter (DPF) technology, in-cylinder exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) method. This step also requires constant monitoring and needs to involve manufacturers without whom compliance to any policy would be unachievable[50].

Here, alternate fuels like compressed natural gas (CNG), ethanol, methanol, dimethyl ether (DME), biodiesel, hydrogen, electricity, etc. could 'de-carbonize' the transport sector by substituting gasoline/diesel[47]. CNG has a high octane rating, does not generate ash during combustion, has low NO_x, SO_x and hydrocarbon emissions

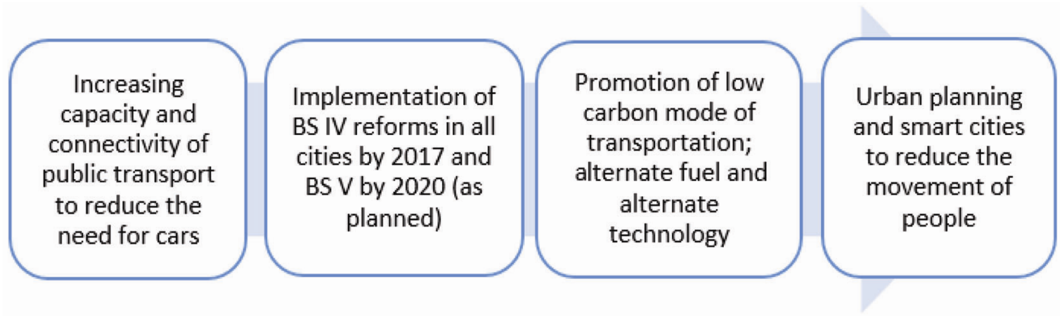

Figure 3. Strategy for efficiency in transport.

and almost half the CO_2 emissions as gasoline, making it an excellent fuel for light-duty vehicles[51]. Through National Biofuel Policy, 2008, 10% ethanol blending with petroleum was mandated. It was also proposed that a 20% biodiesel blending would be achieved by 2017 (ref. 52). Further, absence of GHG emissions from engine exhaust give hybrid energy vehicles (HEVs) and fuel cell energy vehicles (FCEVs) a major advantage over gasoline/diesel-operated vehicle[47]. In 2013, the National Electric Mobility Mission Plan was launched with a vision of 7 million hybrid vehicles by 2020 and a spending of Rs 13,000–14,000 crores for the same[50]. Expenditure in upgrade of vehicles, in keeping with all the Government mandates, is worth undertaking in a scenario where these high standards lead to positive financial feedback, through reduced expenditure on pollution control, GHG mitigation and an improved quality of life[47].

Global urban transport energy consumption is likely to double by 2050 (ref. 53). In India, the Ministry of Urban Development, GoI, along with state and city-level governments, has come up with roadmaps and programmes to identify cities in which core infrastructure could be modified to address issues of efficient urban mobility and public transport, electricity and water supply, sanitation, etc. to create 'smart cities'[54].

Thus, GHG reduction in transport would be an indirect outcome of improvements suggested in this section.

Carbon capture and storage

The use (efficient or inefficient) of fossil fuels is carbon-intensive, which necessitates a parallel system to capture the generated CO_2. Physical sequestration naturally occurs in oceans and saline aquifers which take up CO_2 from the atmosphere to form carbonates. Enhanced oil recovery using CO_2 is being practised in Weyburn oil-field, Canada, and CO_2 is also being proposed for release of methane from methane hydrates[55].

Among the biological sequestration methods for carbon are the terrestrial ecosystems such as forests and soil.

Forests hold a huge capacity of carbon absorption through photosynthesis. But the forest ecosystem also becomes a source of carbon emission through fires, deforestation and alteration in land-use patterns. Much higher losses of CO_2 from soil were reported[56] in the world after deforestation for shifting cultivation (0.093–0.223 Pg-C year^{-1}) than other arable (0.063 Pg-C year^{-1}) or pasture soil (0.092 Pg-C year^{-1}). Globally loss of primary production by fire is estimated[57,58] to be 2-5 Pg-C year^{-1}. While shifting cultivation, as observed in eastern and North East India, has led to loss of soil carbon and has been proven an unsustainable practice, it is extant because it is a traditional system of agriculture[59]. This reinstates the point made earlier that any sustainable practice introduced would encounter the issue of socio-cultural acceptability[60].

Carbon can be sequestered in the soil as both organic and inorganic carbon. The global soil has a C sink capacity of ~78 Pg (ref. 61). This carbon holds the moisture and maintains a ratio of carbon to other elements (N, S, metals, etc.) which are vital to the growth of the plant. A change in land-use patterns or inefficient management of soil, including ploughing, drainage and excessive fertilizer input, leads to loss of soil carbon which reduces crop productivity[62]. A solution to improve soil sink capacity is through application of biochar augmented with microbes which help in the uptake of nutrients by the crop[63,64]. The avoided GHG emission through this method would translate into reduced fertilizer application due to improvement in soil fertility[65].

Considering the impact of soil carbon, the strategy proposed in Figure 4, could be divided into immediate measures such as prevention of further deforestation and mitigation of emissions due to change in land use.

To promote afforestation, GoI proposed a Green India Mission. The immediate implementation period of the programme from 2010 to 2020 was projected to cost Rs 46,000 crores and include institution-building, sensitization, land identification and field operations[66]. This would need to be transformed into a long-term mitigation measure to enhance carbon sink and ecological adaptation to climate change.

The ultimate stage for carbon sequestration would be long-term storage such that CO_2 stored should not leak into the atmosphere. This requires injection of CO_2 at a

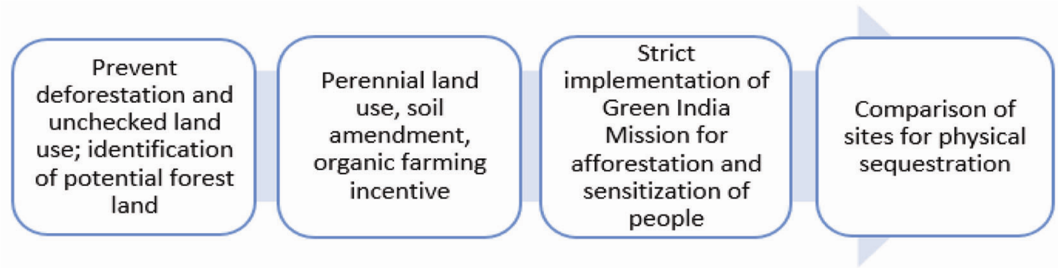

Figure 4. Roadmap for carbon capture and storage in India.

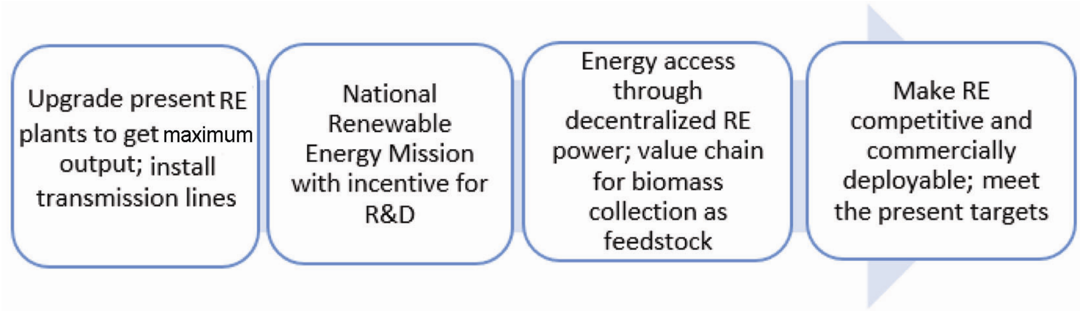

Figure 5. Renewable energy pathway for India.

depth of 800 m (ref. 67). Geological carbon storage capacity in India has been estimated to be 500–1000 Gt of CO_2 (ref. 67). These sites may be found in the Gangetic (north, northeast), Brahmaputra (northeast, Bangladesh border) and Indus (northwest, Pakistan border) river plains, and along the immediate offshore regions on the Arabian Sea (southwest coast) and the Bay of Bengal (southeast coast)[68]. However, the prospect of physically storing carbon for India is limited due to the economic viability.

Thus, the roadmap for the next few decades indicates the importance of carbon sequestration as a mitigation strategy for GHG emission.

Gradual shift to renewable energy

As mentioned in the beginning of this study, the most important requirement for global sustainable development is to have a sustainable form of energy or renewable energy (RE). An addition of more than 1000 GW has been made to the renewable power capacity globally between 2000 and 2014, with the figure of 1829 GW in 2014 being a paragon of this shift[69]. The developing countries invested US$ 131.3 billion in RE in 2014 (up by 36% from 2013) with the share being maximum for China in the world and amongst the emerging economies. In addition, investments in RE increased in Brazil (US$ 7.6 billion), India (US$ 7.4 billion), South Africa (US$ 5.5 billion), and Indonesia, Chile, Mexico, Kenya and Turkey invested up to US$1 billion (ref. 70).

India has an installed capacity of 260 GW (all sources combined) and a peak power demand of around 140 GW (ref. 71). The shortages in supply are due to inaccessibility of fuel, both thermal power and nuclear. Here, RE can be a promising solution for integrating and managing the intermittent supply in the first stage. GoI, in the past decade, has taken many initiatives to promote RE in the mainstream power generation market, such as National Action Plan on Climate Change (NAPCC) of 2009 ensuring 15% of total electricity consumption from RE by 2020; Energy Act, 2003, and National Tariff Policy, 2006, which provide guidelines for state and Central Government to ensure a percentage of power is obtained from renewable incentives[32], and other initiatives. Further, the government is also providing incentives such as accelerated depreciation (AD), generation-based incentive (GBI), viability gap funding (VGF), and capital subsidy.

Moving forward, India should have a clear vision for RE-based power generation. As shown in Figure 5, an immediate consideration for RE plants should be the ability to accommodate an energy mix from different feeds and ensure a flexible grid. With a potential of 900 GW for renewable energy[31], the present plants could be upgraded through adoption of better technologies to achieve higher production[70]. RE should no longer be treated as an option. It should be aggressively turned into a necessity with a wholesome policy initiative with equivalent thrust on deployment, use of indigenous technology and financing research for future improvements[71]. Since RE could be employed as off-grid systems, it could provide energy access to all sections of society while addressing the issue of GHG mitigation in increasing energy consumption. The major challenges in decentralized energy are related to policy, technology, finance, public participation and understanding of demand–supply chain[72].

While RE is continuously becoming cost-effective, in order to replace conventional energy it would be required to make RE completely cost-competitive, which is the final stage of the indicated roadmap in this study.

RE has advantages in terms of providing energy independence, no fuel cost or price variability and reduction in pollution. However, challenges to be addressed in RE scale-up are related to resource assessment, best-fit technology or technology mix for different scenarios, storage of excess power and grid integration, land and logistics required (especially for solar, thermal and wind) and variability in power generation.

Despite all these measures, businesses are apprehensive of RE due to either lack of understanding of the incentives or lack of confidence in the competency of RE technology. Thus, a holistic dialogue between stakeholders and policy makers will encourage RE investment in India.

Conclusion

The above discussion underscores the need for scientific and political intervention to bring the impact of climate change to a manageable level in developing countries like India. Here, it is important to consider that even though the mitigation measures require huge political will and monetary input, they may be achievable through a gradual shift in technology and perception of viewing growth.

For India, the target discussion should cease to be about the ability of RE to meet the gap in power generation and focus on promoting it as a choice for the new power system with indigenous solutions formulated by Indian researchers for the specific problems pertaining to the country. This is vital because 'survival of the fittest' is not only limited to living species, but is relevant for survival of economies and civilizations as a whole.

1. Raman, V. V., Iniyan, S. and Goic, R., A review of climate change, mitigation and adaptation. *Renew. Sustain. Energy Rev.*, 2012, **16**, 878–897.
2. Prentice, I. C. *et al.*, The carbon cycle and atmospheric carbon dioxide. In *Climate Change 2001: The Scientific Basis* (eds Pitelka, L. and Rojas, A. R.), Cambridge University Press, New York, 2001.
3. Hecht, A. D., Past, present and future: urgency of dealing with climate change. *Atmos. Climate Sci.*, 2014, **4**, 779–795.
4. Bolin, B. *et al.* (eds) SCOPE 13 Report. In *The Global Carbon Cycle*, John Wiley, Chichester, UK, New York, 1979, p. 491.
5. Degens, E. T., Womg, H. K. and Kempe, S., Factors controlling global climate of the past and the future. In *Some Perspectives of the Major Biogeochemical Cycles* (ed. Likens, G. E.), John Wiley and Sons, Chichester, UK, 1981, pp. 3–24.
6. Stocker, T. F. *et al.* (eds) Climate change 2013: the physical science basis. In *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2013.
7. Peters, G. P. *et al.*, The challenge to keep global warming below 2°C. *Nature Climate Chang.*, 2013, **3**, 4–6.
8. Pachauri, R. K., Projected climate change and its impacts. In *Climate Change 2007:Synthesis Report for IPCC Fourth Assessment Report* (ed. Reisinger, A.), Cambridge University Press, Cambridge, UK, 2007, p. 104.
9. O'Neill, B. C. and Oppenheimer, M., Dangerous climate impacts and the Kyoto Protocol. *Science*, 2002, **296**, 1971–1972.
10. Masters, G., Baker, P. and Flood, J., Climate change and agricultural commodities. CABI Working Paper II, 2010, p. 38.
11. Dev, S. M. and Sharma, A. N., Food security in India: performance, challenges and policies. In *Oxfam India Working Papers Series*, 2010, p. 46.
12. Ramasamy, J. and Moorthy, P., Managing food insecurity and poverty in India in the era of globalization. *Int. J. Multidiscip. Res.*, 2012, **2**, 1–12.
13. Oluoko-Odingo, A., Determinants of poverty: lessons from Kenya, *GeoJournal.*, 2009, **74**, 311–331.
14. Parry, M., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G., Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environ. Change*, 2004, **14**, 53–67.
15. Giorgi, F. and Hewitson, B., Regional climate information – evaluation and projections. In *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (eds Mietus, M. and Zillman, J.), Cambridge University Press, Cambridge, 2001, pp. 583–638.
16. Evans, S., Two degrees: will we avoid dangerous climate change? *Carbon Brief*, 2014.
17. Olivier, J. G. J., Janssens-Maenhout, G., Muntean, M. and Peters, J. A. H. W., *Trends in Global CO_2 Emissions*, PBL Netherlands Environmental Assessment Agency, The Hague, 2015, pp. 4–7.
18. Trudeau, N., Tam, C., Graczyk, D. and Taylor, P. *Energy Transition for Industry: Indiaand the Global Context*, International Energy Agency, Paris, 2011, p. 24.
19. Developing countries and global warming: a bad climate for development, *The Economist*, 2009.
20. CO_2 emissions (metric tons per capita), World Bank: Data Indicator, 2015.
21. CO_2 emissions (metric tons per capita) data. World Bank: Data Indicator, 2011.
22. Yawson, D. O., Armah, F. A. and Pappoe, A. N. M., Enabling sustainability: hierarchical need-based framework for promoting sustainable data infrastructure in developing countries. *Sustainability*, 2009, **1**, 946–959.
23. Maslow, A. H., A theory of human motivation. *Psychol. Rev.*, 1943, **50**(4), 370–396.
24. Kaivo-Oja, J., Vehmas, J. and Luukkanen, J., A note: de-growth debate and new scientific analysis of economic growth. *J. Environ. Prot.*, 2014, **5**, 1477–1481.
25. Shahbaz, M., Ozturk, I., Afza, T. and Ali, A., Revisiting the environmental Kuznets curve in a global economy. *Renew. Sustain. Energy Rev.*, 2013, **25**, 494–502.
26. Global greenhouse gas emissions data, US EPA, 2016.
27. Victor, P. A., Growth, degrowth and climate change: a scenario analysis. *Ecol. Econ.*, 2012, **84**, 206–212.
28. Bleys, B. and Whitby, A., Barriers and opportunities for alternative measures of economic welfare. *Ecol. Econ.*, 2015, **117**, 162–172.
29. Reserves and potential for generation. Energy Statistics, Ministry of Statistics and Programme Implementation, Government of India (GoI), 2015.
30. Mitra, A., Damassa, T., Fransen, T., Stolle, F. and Mogelgaard, K., 5 key takeaways from India's New Climate Plan (INDC), World Resources Institute, GoI, Bengaluru, 2015.
31. Annual Report 2014–15, Ministry of New and Renewable Energy, GoI, 2015, p. 5.

32. Renewable energy. In Emerging Opportunities and Challenges: India Energy Congress, Pricewaterhouse Coopers Private Limited, 2012, p. 61.
33. High efficiency low emission coal. In *Reducing CO_2 Emissions*, World Coal Association, 2015; http://www.worldcoal.org/reducing-co2-emissions/high-efficiency-low-emission-coal
34. Coal and gas power stations. In *User Guide for India's 2047 Energy Calculator*, Niti Aayog, New Delhi, 2015, p. 12.
35. Load Generation Balance Report 2014–15, Central Electricity Authority, New Delhi, 2014.
36. Annual Report 2013–14, Planning Commission, New Delhi, 2013, pp. 93–95.
37. 'Vision 2030': Natural gas infrastructure in India, Industry Group For Petroleum and Natural Gas Regulatory Board, New Delhi, 2013, p. 8.
38. India's massive untapped natural gas reserves could help free up $306 million a day on imported oil. *GE Bulletin: Quartz*, 2015.
39. Mukundan, S., Make in India… unmatched scope and scale in oil and gas! Cheap, clean and continued energy at my doorstep, British Petroleum, 2015.
40. Sengupta, D., Shale gas extraction faces numerous challenge in India: SudhirVasudeva, CMD, ONGC, *The Economic Times*, 2013.
41. Schipper, L., Fabian, H. and Leather, J., Transport and carbon dioxide emissions: forecasts, options analysis, and evaluation. In ADB Sustainable Development Working Paper Series, 2009.
42. All-India study on sectoral demand of diesel and petrol report: petroleum planning and analysis cell, Nielson India, New Delhi, 2013, pp. 9–14.
43. Ramachandra, T. V., Emissions from India's transport sector: state wise synthesis. *Atmos. Environ*., 2009, **43**, 5510–5517.
44. Status of the vehicular pollution control programme in India. In Programme Objective Series, Central Pollution Control Board, New Delhi, 2010, pp. 11–25.
45. Ahmad, S. and Choi, M. J., Urban India and climate change: mitigation strategies towards inclusive growth. *Theor. Empir. Res. Urban Manage*., 2010, **6**, 60–73.
46. Verma, A., Harsha, V. and Shah, M., Urban transport policies in India in context to climate change: an international perspective. In 10th Annual Conference of Knowledge Forum, National Institute of Advanced Studies, Bangaluru, 2015.
47. Ribeiro, K. *et al*., Transport and its infrastructure. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Metz, B. *et al.*), Cambridge University Press, Cambridge, UK, 2007, pp. 325–380.
48. Transport Sector. In *User Guide for India's 2047 Energy Calculator,* Niti Aayog, New Delhi, 2015, pp. 4–7.
49. Auto Fuel Vision and Policy – 2025, Ministry of Petroleum and Natural Gas, GoI, 2014.
50. Bansal, G. and Bandivadekar, A., Overview of India's vehicle emissions control program, International Council on Clean Transportation, 2013.
51. Semin, R. A. B., A technical review of compressed natural gas as an alternative fuel for internal combustion engines. *Am. J. Eng. Appl. Sci.,* 2008, **1**, 302–311.
52. Bandyopadhyay, R. K., Biofuel promotion in India for transport: exploring the grey areas. In *Policy Brief*, TERI Press, New Delhi, 2015.
53. A Tale of Renewed Cities, International Energy Agency, Paris, 2013, pp. 8–16.
54. Smart Cities: Mission Statement and Guidelines, Ministry of Urban Development, GoI, 2015, pp. 5–7.
55. Resources to Reserves, International Energy Agency, Paris, 2013, pp. 25–48.
56. Kimble, J. M., Levine, E. R. and Bobby, A., Agricultural activities and greenhouse gas emission from soil of tropics. In *Soil Management and Greenhouse Effect*, CRC Press, 1995, pp. 293–307.
57. Hao, W. and Liu, M., Spatial and temporal distribution of tropical biomass burning. *Global Biogeochem. Cycles*, 1994, **8**, 495–503.
58. Crutzen, P. J. and Andreae, M. O., Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. *Science*, 1990, **250**, 1669–1678.
59. Ranjan, R. and Upadhyay, V. P., Ecological problems due to shifting cultivation. *Curr. Sci*., 1999, **77(**10), 1246.
60. Rahman, S. A., Rahman, M. F. and Sunderland, T., Causes and consequences of shifting cultivation and its alternative in the hill tracts of eastern Bangladesh. *Agrofor. Syst*., 2012, **84**, 141–155.
61. Lal, R., Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience,* 2010, **60**, 708–721.
62. Forster, P. *et al.,* Changes in atmospheric constituents and in Radiative forcing. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon, S. *et al.*), Cambridge University Press, Cambridge, UK, 2007, pp. 129–234.
63. Quilliam, R. S., Glanville, H. C., Wade, S. C. and Jones, D. L., Life in the 'charosphere' – does biochar in agricultural soil provide a significant habitat for microorganisms? *Soil Biol. Biochem*., 2013, **65**, 287–293.
64. Kolton, M. *et al.*, Impact of biochar application to soil on the root-associated bacterial community structure of fully developed greenhouse pepper plants. *Appl. Environ. Microbiol*., 2011, **77**, 4924–4930.
65. Gaunt, J. L. and Lehmann, J., Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environ. Sci. Technol*., 2008, **42**, 4152–4158.
66. National Mission for a Green India, Ministry of Environment and Forest, GoI, 2015, pp. 13–18.
67. CO_2 Capture and storage: a key carbon abatement option, International Energy Association, Paris, 2008, p. 7.
68. https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf
69. IRENA renewable energy capacity statistics, International Renewable Energy Agency, 2015, p. 2.
70. Renewables 2015: Global Status Report, REN21, 2015, pp. 17–25.
71. Report on India's renewable electricity roadmap 2030: towards accelerated renewable electricity deployment, NITI Aayog, New Delhi 2015, pp. 11–24.
72. Kulkarni, S. H. and Anil, T. R., Rural electrification through renewable energy sources – an overview of challenges and prospects. *Int. J. Eng. Res*., 2014, **3**, 384–389.

ACKNOWLEDGEMENTS. I thank all the journal repositories for providing the information needed to undertake this work and of Dr Praveen Kumar (ICAR), Dr Piyali Das (TERI) and Sujai Banerji (JNU) for their innumerable inputs which helped improve the manuscript.

Received 4 January 2016; revised accepted 28 July 2016

doi: 10.18520/cs/v111/i11/1765-1772