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Transformation of India's steel and cement industry in a sustainable 1.5°C world

Abstract

The anticipated economic and population growth in India will increase demand for material resources, energy and consequently carbon emissions. The global ambition to limit global warming to 1.5°C by the end of the century calls for rapid and unprecedented action. As the most carbon-intensive sectors, India's steel and cement industry will require a more transformative shift, both on the demand and supply side.

Strategies from both supply and demand-side are analysed for steel and cement sector to understand consequences for energy and emissions using two modelling approaches i) energy system and ii) material flow models. A portfolio of technically feasible options to reduce the material, energy and CO_2 intensity is explored under four alternate scenarios spanning till 2050 differentiated by their mitigation ambition and development paradigm.

Results show that current policies in India will provide adequate incentives for achieving the climate targets India has submitted within its Nationally Determined Contribution (NDC) however, dematerialisation, reuse and recycling will be necessary for achieving the global ambition of 1.5^{o}C. The study concludes that a stringent carbon policy in combination with strong sustainability principles can reduce CO_2 emissions by 68% in the steel and cement sector in 1.5oC Scenario compared to NDC Scenario.

Keywords; Material flow model, Energy system model, Scenarios, Industry

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1. Introduction

The Paris Agreement for climate change has enhanced the ambition for mitigation to a global goal of stabilizing temperature below 1.5°C and this call for enhanced contribution from all the sectors of the economy (Rogelj et. al., 2015) including industry. Achieving 1.5°C scenario globally at the lowest mitigation cost is feasible in socio-economic scenarios based on the sustainable paradigm where consumption is oriented toward low material growth and lower resource and energy intensity (Riahi et. al., 2017). With the second largest population globally after China, India would exert a major influence on the demand for energy-intensive materials.

The manufacturing sector in India contributed to 19 % of total CO_2 emissions from fuel combustion in 2010 (GoI (Government of India), 2015). A large share of these emissions is from the production of materials consumed within the economy namely cement, steel, non-ferrous metals, chemicals, paper, textiles, bricks, fertilizers, etc. Steel and cement are the two most energy-intensive sectors and the largest contributors to emissions, together accounting for around half of industry-related CO_2 emissions for India. India's steel sector contributed to 31.9% of industry sector CO_2 emissions from fuel combustion in 2010 (GoI (Government of India), 2015). Cement is the next largest contributor and contributed to 13.5% of industry sector CO_2 emissions from fuel combustion in 2010 (GoI (Government of India), 2015).

In 2015, India's per capita steel consumption at 59.4 kg and per capita cement consumption at 195 kg was well below the global per capita average of 216.6 kg for steel and 520 kg for cement (Garg et. al., 2017). Primarily driven by future growth in the automotive, housing/construction and renewable energy sectors (Prakash, 2018), the business as usual (BAU) pathways will take India's consumption, in the medium term (e.g., by 2050), towards levels reached in developed countries (IEA, 2009).

India's Nationally Determined Contribution (NDC) promises a 33 to 35% reduction in CO_2 intensity by 2030 from the 2005 level and the actions listed within the NDC for achieving the intensity target include energy-intensive sectors and a call for efficient, cleaner and sustainable production and consumption systems (UNFCCC, 2015). Driven by global technology developments, and national policies such as the Perform Achieve and Trade (PAT) for energy-intensive industries, India's industrial sector has seen improvements in energy efficiency (Garg et al., 2017). PAT is a market-based trading scheme designed to improve energy efficiency in energy-intensive sectors through trading in energy efficiency certificates (ESCerts) for designated consumers. ESCerts are issued if designated consumers overachieve the set targets. Achieving 1.5°C will require strong and deep mitigation interventions in both the production and consumption (IPCC, 2018) which, in India's case require multiple transformations at the systemic level (Vishwanathan et al., 2018). The commitment towards achieving the advances in material design, Information Technology (IT) and the sharing economy (UNEP, 2016) have altered the consumption landscape and provide an opportunity for India to achieve rapid economic development and ambitious mitigation. A commitment to achieving sustainable development requires parallel efforts to manage demand in a resource-efficient way. Resource conservation based on the circular economy, therefore, becomes an equally important agenda, along with climate change mitigation (Van der Voet et al., 2018).

In light of multiple global and national climate, energy and sustainability challenges India faces, there is an urgency to find ways to manage this demand. Understand the demand and its drivers in the future is the first step towards this. Several studies have examined emission reductions within steel and cement sector at the global level (Akashi et. al, 2011; Allwood et. al., 2010; IEA, 2009, van Ruijven et. al., 2016). Most of these studies examine changes in technology and fuel choices for steel and cement production and its impacts on CO_2 emissions mitigation. Reduction in CO_2 emissions, for steel and cement at a global level, from changes in product design, recycling and reuse have been analysed (Allwood et. al., 2010). Morrow et. al., (2014) have studied India's steel and cement sectors for the impact of improvements in production technology choices on CO_2 emission. There is a lack of studies for India that explicitly model future demand for steel and cement under alternative policy scenarios and analyse mitigation from these sectors in a holistic way i.e., covering both material efficiency (through product design, recycling and reuse) and energy efficiency (through improvement in production technologies).

The mitigation analysis available for steel and cement sector is for various carbon tax scenarios and the 2°C scenario (van Ruijven et. al., 2016; Akashi et. al, 2011). There are no papers covering a 1.5°C scenario. 1.5°C scenarios would require an accelerated implementation of the mitigation measures (Rogelj et. al., 2015).

This paper addresses the contribution of steel and cement industries, towards mitigation in the 1.5°C scenario. The broad questions addressed in the paper relate to the role of steel and cement sector within the mitigation efforts of India with special attention to demand-side measures. The mitigation that would happen in these sectors would vary with climate policies, therefore, both 2°C and 1.5°C climate stabilisation goals are analysed.

In this paper, we first describe the methodology for estimating demand, analysing technology choices and estimating CO_2 emissions (Section 2). The subsequent section presents the results for alternative scenarios. Finally, in Section 4 we discuss the results and conclude with policy implications.

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2. Methodology

Scenarios help understand and analyse alternative futures in a coherent and internally consistent manner (IPCC, 2000) and therefore are a suitable tool for answering the questions related to the future of steel and cement sector. Each of the scenarios constructed in this study includes a qualitative narrative that is then quantified with a detailed set of socio-economic, technological and climate policy assumptions as detailed in Section 2.1. The scenarios are analysed using a model framework that is described in Section 2.2. To fulfil the objective of assessing how the demand varies in these scenarios, the demands for steel and cement are estimated using the methodology in Section 2.3.

2.1. Scenarios

The paper uses scenarios for answering the questions related to the future of steel and cement sector. Scenarios allow to carry out the analysis in a coherent and internally consistent manner (IPCC, 2000). The paper assesses four alternative future scenarios for India from 2010 through 2050. i) NDC Scenario ii) 2°C conventional scenario iii) 2°C sustainable scenario iv) 1.5°C sustainable scenario. The scenarios can be differentiated in terms of i. development paradigm and ii. climate target (Fig 1).

Insert Fig. 1. Scenario Framework

2.1.1. NDC **Scenario**

The NDC scenario considers the achievement of India's NDC target of 33-35% reduction in CO_2 emissions intensity by 2030 relative to 2005 levels (UNFCCC (United Nations Framework Convention on Climate Change), 2016). An analysis of NDC at the global level shows that they will fall short of 1.5°C and 2°C climate target (Rogelj et. al., 2018) and result in a temperature rise of 2.9 to 3.2°C with the implementation of unconditional NDCs (UNEP, 2018). Rapid economic development is the main policy objective of the government as it aims to solve the problems of poverty and unemployment. GDP is projected to grow at a rate of 8% per year during the period 2010-2030 and over 7% for the period 2010-2050. The population projections are consistent with the medium scenario of UN population projections reaching 1513 million by 2030 (UN DESA, 2017). Presently, several policy initiatives are underway overall in the industry, buildings, transportation and urban sectors (See S1, Supplementary Materials for an overview of policies across scenarios). The Perform Achieve and Trade (PAT) scheme, a market-based incentive scheme for reducing emissions from the industry sector has played an important role in bringing about incremental improvements in energy efficiency (Garg et al., 2017). The implementation of policies (including PAT) is expected to continue and intensify in future. However, sustainability measures e.g., remanufacturing and reuse that can reduce demand for materials are not considered. The NDC scenario relies on the implementation of the aforementioned planned policies on renewable energy, energy efficiency and sectoral initiatives. The scenario does not consider any global carbon tax and mitigation actions are mainly due to voluntary actions proposed in India's NDC.

2.1.2. 2°C Conventional Scenario

The 2°C conventional scenario considers strong climate policies, which are operationalised through a global tax on CO_2 for removal of a ton of CO_2 under a global 'cap and trade' regime. The scenario considers a CO_2 price trajectory aligned with Copenhagen pledges planned to take effect post-2020. The CO_2 price trajectory is obtained from an integrated assessment model and increases from 40 USD per tCO_2 in 2020 to 130 USD per tCO_2 by 2050 (Lucas et al., 2013). The increase in CO_2 price renders low carbon technologies more competitive by increasing the cost of fossil fuels corresponding to their CO_2 content. The socio-economic assumptions in this scenario are similar to the NDC Scenario with the difference that the CO_2 tax is expected to result in a GDP loss of around 3% and therefore a lower demand for energy-intensive industries. The scenario does not consider any remanufacturing and reuse beyond the NDC scenario.

2.1.3. 2°C Sustainable Scenario

The 2°C sustainable scenario is similar to the 2°C conventional scenario in its ambition for mitigation as operationalized through a CO_2 budget. This carbon budget is 82 $GtCO_2$ for the period 2010 to 2050 and based on an earlier assessment of 2°C and 1.5°C scenarios for India where the same CO_2 price trajectory was considered for 2°C scenario (Dhar et al., 2018). The scenario differs from the 2°C Conventional Scenario in its assumption that meeting the mitigation targets would not rely on conventional technology-based approaches, but instead on the adoption of a broad range of sustainability actions. The scenario would target to achieve the Sustainable Development Goals (SDG) for energy efficiency (SDG Target 7.3), environmental impacts on cities (SDG Target 11.6), reduce waste generation through prevention, reduction, recycling, and reuse (SDG Target 12.5). A focus on reduction, recycling and reuse would result in lower demand for energy-intensive products like steel, cement, aluminium, paper, etc. relative to the 2°C conventional scenario. Section 2.3 provides a detailed discussion on demands for the steel and cement sectors. The level of remanufacturing and reuse is considered higher than the 2°C conventional scenario.

2.1.4. 1.5°C Sustainable Scenario

A key difference between the 2°C and 1.5°C scenarios is the carbon budget, which at 43 $GtCO_2$ for the 1.5°C scenario is much lower than the 2°C scenario. The methodology for estimating carbon budget for 1.5°C scenarios for India is based on an earlier assessment (Dhar et al.,

2018) and details are provided in S2, Supplementary Material. The significantly constrained carbon emissions space in a 1.5°C world (UNEP (United Nations Environment Programme), 2016) cannot be realized without an overhaul of the existing systems and strong sustainability measures. Therefore, conventional means relying solely on carbon price for achieving the 1.5°C scenario are not explored. The scenario has a wide portfolio of sustainability measures similar to the 2°C sustainable scenario. In the 1.5°C sustainable scenario, the demand for materials and energy-intensive products is lower than 2°C conventional scenario but similar to 2°C sustainable scenario due to dematerialisation, recycling, wastage reduction, and reuse. Moderate level of remanufacturing and reuse is considered.

2.2. Model framework for analysis

The questions addressed in this paper are related to consequences for energy and emissions from the steel and cement sector. These have been analysed using energy system models (Akashi et. al, 2011; IEA, 2009, van Ruijven et. al., 2016) or models dealing with material flows (Allwood et. al., 2010). The key driving forces for energy systems models are population and GDP (Bhattacharyya and Timilsina, 2010) and the analysis is primarily related to the existing stock of technologies and future changes within the respective sectors that result in changes in energy and emissions. Analysing alternative scenarios for material demand is not a strength of these models. On the other hand, models looking at material flows have a framework for an analysis of material demand and strategies for reducing the demand but lack a detailed representation of technologies.

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Fig. 2. Model Framework

The overall framework in this paper for analysing CO_2 emission reductions from the steel and cement sector, therefore, uses a hybrid approach (Fig 2). This approach modifies the framework used in the energy system models (Bhattacharyya and Timilsina, 2010; van Ruijven et al., 2016) through the addition of material flow modelling in the modelling steps. A detailed modelling of material demand will provide inputs to an energy system model to analyse technological choices. These inputs, in addition to the demand for steel and cement, also include the amount of scrap produced, amount of material reused, and dematerialisations.

The model framework is based on the Kaya identity. The Kaya identity provides a relationship between energy-related CO_2 emissions with population, economic development, energy intensity and carbon intensity. Recently, the Kaya identity has been used to decompose overall emissions at regional level (Wang et al., 2017) and at the sectoral level for the industry, buildings (Ma and Cai, 2018) and transport sectors. The Kaya identity for the whole economy can be described using the following equation (based on Schandl et. al., 2016)

$$CO_2 = Pop * \frac{GDP}{Pop} * \frac{Energy}{GDP} * \frac{CO_2}{Energy}$$

Where, CO_2 = Total CO_2 emissions in the economy

Pop = Population

$\frac{GDP}{Pop}$ = Per capita Gross Domestic Product or a measure of national income

$\frac{Energy}{GDP}$ = Energy Intensity of economic activity

$\frac{CO_2}{Energy}$ = CO_2 intensity of the energy

The above Kaya identity can be modified for industry-related emissions as follows

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$$CO_2Ind = \sum_{i=1}^{n} Pop * \frac{GDP}{Pop} * \frac{Material_i}{GDP} * \frac{Energy_{Ind_i}}{Material_i} * \frac{CO_{2\ Ind_i}}{Energy_{Ind_i}}$$

Where

$\frac{GDP}{Pop}$ = Per capita GDP

$\frac{Material_i}{GDP}$ = Intensity of material i consumption in the economy measured in terms of material consumption per unit of GDP

$\frac{Energy_{Ind_i}}{Material_i}$ = Energy intensity of manufacturing per unit quantity of material i

$\frac{CO_{2\ Ind_i}}{Energy_{Ind_i}}$ = CO_2 intensity of energy used for manufacturing material i

2.3. Modelling material demand

Material demand has grown with industrial development and typically, industrialised societies have historically operated in an open system transforming resources into products and discarding them at the end of the useful life (Allwood et. al., 2011). This approach is defined in the present study as the conventional approach for material use and forms the basis for material demand in the NDC and 2°C Conventional scenario. This conventional approach imposes enormous environmental costs for land, water and emissions including CO_2 (Allwood et. al., 2011). A more sustainable approach, which aims at reduction in material use through material efficiency improvements, forms the basis of sustainable scenarios (2°C and 1.5°C).

2.3.1. Conventional Scenario

Insert Fig. 3. Correlation of Material Demand with GDP a) Steel Demand b) Cement Demand

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The demand for steel and cement, for India, has been highly correlated with GDP (Fig 3) however despite rapid growth in demand in the post-reform period in India (1990), the per capita demand is still much below the world average (Garg et. al., 2017). This demand is expected to grow in the near term and stabilise in the longer term at levels close to those witnessed in the developed countries. Earlier studies have used GDP as the main driver of demand for steel and cement and a variety of functional forms have been used (van Ruijven et al., 2016). In this study, we use the industrial GDP instead of overall GDP since the correlation is stronger with industrial GDP. Using the following linear regression models form the elasticity of demand for steel and cement were estimated.

$$\ln(Demand_t) = \alpha + \beta * lnGDP\_IND_t$$

The value of elasticity was 1.09 in case of cement and 1.07 in case of steel, i.e., if industry grew at 1% the demand for cement will grow at 1.09% and demand for steel will grow at 1.07%.

The Industrial GDP is estimated using a logistic regression function. The share of industrial GDP at any future time is estimated from the following logistic regression.

$$Ind\_GDP_t = Ind\_GDP_a * \left\{\frac{e^{(a+bt)}}{1+e^{(a+bt)}}\right\}$$

where a and b are estimated from the logistic regression and Ind_GDP_a is the asymptotic value of the share of industrial GDP which is taken as 40% in the NDC scenario and 2°C conventional scenario. The asymptotic value assumes that India will follow a manufacturing-led growth path to create jobs for a large working-age population similar to China where the share of industrial sector GDP has remained above 40% for a long time.

2.3.2. Sustainable Scenario

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Insert Fig. 4. Framework for analysing demand reductions for energy-intensive materials

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Allwood et al., (2010) describe four strategies for improving material efficiency i) using less material for same service ii) extending product life and using more intensively iii) remanufacturing and reuse of components iv) recycling. All four strategies are applied in case of the sustainable scenarios (both 2°C and 1.5°C scenario) to estimate the demand reductions. Fig 4 provides a framework for analysing the four strategies and materials flow in the economy. The material flows coming out at each stage are characterised by α's.

The total amount of finished steel or cement manufactured from various plants available for consumption in different industries is expressed as Y_o. The production of steel and cement has been assumed equivalent to the demand for steel in the economy since historically the net exports of steel and cement have ranged mostly within 5% of the production (Refer Supplementary Material, S3). The focus of the policy is to promote manufacturing in India and therefore a large shift towards imports is not expected and neither is a large shift towards exports expected on account of the large domestic demand that is fuelled by a growing population with increasing incomes.

In the first step, finished steel Y_o is fed as input to industries manufacturing secondary products e.g., cars, appliances, house construction, etc. The scrap generation during fabrication within these industries is a fraction of incoming materials and is expressed as α_3. The remaining material embedded in the manufactured products is, therefore, equal to $(1-\alpha_3)*Y_o$.

The outputs from the industry cater to the new demand or replacement of stocks. The fraction of the steel added as new stock in the economy is designated as α_1. The old stocks removed from circulation and are measured with reference to the steel supplied from industries during that year. The old stock retired is expressed as $1-\alpha_1$. The amount of stock retired will depend inherently on the stock of material in the economy and how intensively they are used and how long they are used and these dynamics are captured within the coefficient α_1. Within this fraction, some amount is partly recycled, partly reused and partly lost. α_4 is a fraction of retired stock that is reused and α_2 denotes the fraction of retired stock that is lost. The remaining retired stock is recycled and together with scrap generated in manufacturing becomes the total scrap available for steel production.

The coefficients α_1, α_2, and α_3 for the base year 2010 India are established through a review of the literature (Allwood et al., 2010), government reports and expert interviews (Table 1). Future coefficients vary in line with the storylines for conventional and sustainable scenarios.

Insert Table 1 Coefficients for material use

The first strategy can be achieved through light weighting of components, upgrading of material properties and material substitution. Light weighting includes e.g., the substitution of steel with alternate materials such as high strength steel, aluminium and more recently carbon fibre composites. This has been found to quite prevalent in case of components made from casting and injection moulding however, materials, which are machined, the potentials are limited. Studies show that it is possible to reduce steel and aluminium requirements by 25–30% by applying lightweight design principles (Seyfried et al., 2015). Substitution of low energy materials in construction (roofing, flooring, columns, and load-bearing walls) could reduce cement consumption by 5%. Substitution of fly-ash in cement as a substitute or fly-ash blocks in construction could reduce cement consumption without compromising the strength requirement. In overall, this strategy is reflected in the material demand reduction (Table 1) and we assume due to greater application of light-weighting and material substitution the demand coming from products would be 10% lower for steel w.r.t conventional and 15% lower for cement in 2050.

The second strategy involves extending material life and using materials more intensively. In general, the trend in developed countries is that useful product lives are getting shorter due to rapid technological change (Allwood et al., 2011). Product life is the shortest of physical life (product breaks down and it is not viable to repair), functional life (the need for product ceases) and technical life (the product becomes obsolete) (Allwood et al., 2011). In developing countries lack on investment and maintenance in building and infrastructure is shortening product lives. However, prolonging the lifetime of buildings and infrastructure through reinvestment is a useful strategy for reducing steel and cement consumption and CO_2 emissions (Shi et al., 2012). The growth of the sharing economy offers possibilities for reducing ownership and using products more intensively. In overall, these dynamics and the stock of the product in the economy are reflected in the coefficient α_1 (Table 1). The α1 value for steel and cement start at 0.85 and 0.95 respectively in 2010 signifying a low level of stock in the economy and large demand for new things e.g., infrastructures, buildings, cars, appliances, etc. As the economy matures and per capita ownership of appliances and vehicles increase a large part of production will go towards replacing the stocks and therefore α1 decline to 0.20 by 2050 in the conventional scenario. The value of 0.20 is taken from Allwood et. al., 2010 who estimated this value for 2050. However, the extension of material life and intensive use of materials reduces the amount of the material to be replaced and therefore the α1 value is taken as 0.22 in the sustainable scenario."

The third strategy involves remanufacturing and reuse of materials. Remanufacturing happens when components of a product can be used again in the new products e.g. some auto manufacturers are promoting reusing of components of old cars in new cars. Reuse happens when a product can be used without physical change for some other application e.g. using old batteries from electric vehicles for energy storage. Remanufacturing and reuse are prevalent to a limited extent in the informal economy within the developing economies. However, wide-scale use within the formal economy has not been observed. These dynamics are reflected in the coefficient α_4 (Table 1). The sustainable scenario would imply higher reuse and remanufacturing in the steel sector with 15% of retired stock getting back into products by 2050. For the cement sector, 5% of the retired stock would form part of the new stock.

The fourth strategy involves higher recycling of materials. Recycling happens at multiple points within the material cycle. Recycling involves the use of scrap materials produced during fabrication in the user industry or of the material recovered from products at the end of the product life cycle. The scrap is used in fresh material production and can substitute raw material from natural resources. Since the cement is converted to concrete in an irreversible chemical process, it cannot be recycled. In the case of steel, the recycling will depend on scrap generated during fabrication in the user industry (α_3) and the amount of steel retired. During the forming of steel slag, sludge, mill scale and dust are generated and these are recycled.

These would be recycled even in the conventional scenario and therefore not considered as an additional reduction strategy for sustainable scenarios.

2.4. Modelling reduction in energy and CO_2 emissions

The outputs from material demand modelling are provided as an input for scenario analysis related to energy, fuel mix and CO_2 using ANSWER MARKAL, a bottom-up energy system model. ANSWER MARKAL has a detailed description of technologies, energy sources, and costs and has been successfully adopted for the industrial sector of India (Lucas et. al., 2013; Dutta & Mukherjee, 2010). The model optimises the overall energy system costs while keeping consistency with system constraints such as energy supply, demand, investment and emissions (Loulou, R., Goldstein, G., Noble, 2004).

In this study due to material flow modelling besides overall demand for material, data on the amount of scrap produced, amount of material reused, and dematerialisation was included. The amount of scrap steel produced was helpful in deciding the share of steel making technologies that can use scrap (Table 2). In India since amount of scrap available is limited, due to lower stock of steel in the economy, the Electric Arc Furnace (EAF) technology was also given the choice of producing steel without scrap, in which case hot briquetted iron (HBI) produced using the Direct Reduction route was provided as an input to EAF.

3. Results and Discussion

Global studies show that there is considerable scope to mitigate CO_2 emissions from steel and cement industries under strong climate policy scenarios (van Ruijven et al., 2016). The four scenarios in this paper examine reductions in CO_2 emissions from both a carbon tax and broader sustainability measures.

The analysis examines the contribution of material intensity, energy intensity and CO_2 intensity of fuel according to the Kaya identity. An important piece of the Kaya framework is also the impact of per capita incomes e.g., slower income growth could deliver emissions reductions. For this study, per capita incomes are similar across the four scenarios.

3.1. Steel Sector

Insert Fig. 5 CO_2 Emissions from the Steel Sector across scenarios

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Steel sector emissions would increase in the NDC scenario and reach around 1000 Million tCO_2 by 2050. These results are comparable to an earlier study where the authors estimated steel sector emissions to be 930 MT by 2050 (Jajal and Mishra, 2018). The carbon tax in the 2°C scenario would reduce the growth in CO_2 emissions however unable to achieve the peaking of the emissions. Sustainable (2°C and 1.5°C) scenario would achieve a peaking of emissions. A more detailed analysis is provided using the Kaya framework.

Material intensity

The four scenarios have a different set of material demands. The NDC and 2°C Conventional scenario conform to the conventional development paradigm and for these scenarios; the aggregate demand for steel will increase almost ten-folds from 69 Mt in 2010 to 617 Mt in 2050. A large part of this demand for steel would be met from recycled steel (Fig. 6a) since the stock of steel held in the economy would continue to increase. In the 2°C Sustainable and the 1.5°C Sustainable scenarios implementation of measures that extend the life of steel in the economy, through reuse, reducing losses and promoting alternative materials the steel demand increases from 69 Mt to 456 Mt of steel in 2050, 26% lower than the conventional scenario (Fig. 6b). These demand projections at 617 Mt in the NDC scenario are consistent with the projections of the International Energy Agency (IEA) which estimates around 700 Mt in 2050 in the high growth scenario (IEA (International Energy, 2009).

Insert Fig. 6 Demand of steel a) NDC and 2°C Conventional Scenario = Conventional b) 2°C Sustainable Scenario and 1.5°C Sustainable Scenario = Sustainable

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The material intensity measured as steel per unit of GDP declines across all the scenarios. The material intensity in the NDC and 2°C Conventional scenario declines from 50 kg steel per 1000 USD to 24 kg of steel per 1000 USD in 2050 (Fig. 7). For the sustainable scenarios, both 2°C Sustainable Scenario and 1.5°C Sustainable Scenario, the decline is steeper from 50 kg of steel per 1000 USD in 2010 to 20 kg of steel per 1000 USD.

Insert Fig. 7 Material Intensity Vs Energy Intensity across scenarios for steel sector

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Energy Intensity and Technology choice

Energy intensity measured as energy per ton of steel declines in all the four scenarios with the 1.5°C Sustainable scenario displaying the most rapid decline from 0.6 toe per ton of steel in 2010 to 0.25 toe per ton of steel in 2050 (Fig. 7). The energy intensity reductions in NDC scenario is least progressive with energy intensity at 0.37 toe per ton of steel in 2050. The variations in energy intensity across the scenarios are due to two factors i) the share of scrap available for steel making and ii) the faster diffusion of more efficient technologies. An overview of technologies for steel making is provided in Table 2.

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Insert Table 2 Technologies for Steel Making and their energy intensity (toe per ton of steel)

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The share of steel produced from scrap (Fig. 8) is much higher in the sustainable scenarios (2°C and 1.5°C) and since producing steel from scrap requires the lowest energy (Table 2) these two scenarios have lower energy intensity. Another factor that results in relatively rapid improvement of efficiency is the early retiring of inefficient steel making capacities e.g., integrated steel plant (ISP) running on the conventional technology are retired by 2030 in all except the NDC scenario.

Insert Fig. 8 Technology mix for steel sector

CO_2 intensity of steelmaking

CO_2 intensity of steelmaking (measured as tCO_2 per toe of energy used for steel production) declines rapidly in all the three climate scenarios relative to NDC scenario (Fig. 9). The decline in 2°C conventional scenario is lower than the two sustainability scenarios (2°C and 1.5°C Sustainable). In all the three scenarios a large portion of reduction happens in combination with carbon capture and storage and by 2050 all the ISP BOF process is together with CCS in all the scenarios. However, the rate of diffusion of CCS is fastest in the 2°C Conventional scenario. The deep CO_2 mitigation in the 2°C Conventional scenario is mainly driven by the global carbon price whereas in 2°C Sustainable scenario it is dematerialisation, reuse and recycling combined with a lower global carbon price that achieves equivalent CO_2 mitigation. Additional mitigation in 1.5 °C is achieved with deep sustainability transitions as well as a substantial increase in CCS. Global carbon price or a cap on CO_2 emissions drives decarbonisation mainly through increased uptake of CCS and enhanced energy efficiency. In the steel sector, deep decarbonisation of electricity also plays a major role in decarbonisation. Strong carbon policies in the form of a global carbon price or a cap on CO_2 emissions will drive decarbonisation mainly through increased uptake of CCS and enhanced energy efficiency.

Insert Fig. 9 CO_2 Intensity Vs Energy Intensity for steel making

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A major contributor to the decarbonisation of fuel use is firstly the larger share of electricity due to a greater diffusion of electric arc furnace (EAF) technology for steel making (Figure 8) and secondly the rapid decarbonisation of electricity (Table 3) in the climate stabilisation scenarios. The MARKAL model has a complete representation of the energy system and CO_2 intensity of electricity are endogenously estimated in the model and available for steel making technologies.

Insert Table 3 CO_2 intensity of electricity production across the four scenarios (kg CO_2 / kWh)

Contribution to NDC

Steel is the largest contributor to CO_2 emissions from industry and in the NDC scenario, the CO_2 emissions from fuel combustion continue to increase reaching 465 Mt CO_2 in 2030 from 183 MtCO_2 in 2010. The NDC does not specify individual commitments for the steel sector, but its contribution can be analysed in terms of reductions in emission intensity. The emission intensity for steel sector with respect to GDP shows a declining trend from 131 kg CO_2 per '000 USD in 2010 to 72 kg CO_2 per '000 USD in 2030, well beyond the 32-33% reductions between 2005 and 2030 committed by India at an overall level in the NDC.

3.2. Cement Sector

Insert Fig. 10 CO_2 Emissions from cement sector across scenarios

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Cement sector emissions would increase in the NDC scenario and reach around 380 Million tCO_2 by 2050. The carbon tax in the 2°C conventional scenario would reduce the growth in CO_2 emissions through a wide-scale deployment of carbon capture and storage (CCS) in the cement sector and by 2050 45% of cement plants would be with CCS. Sustainable actions in the 2°C sustainable scenario achieve a similar result but with a limited share of CCS and by 2050 only 16% of plants are with CCS. In the 1.5°C scenario, a decoupling of emissions is achieved from economic growth. A more detailed analysis is provided using the Kaya framework.

Material intensity

Driven by economic growth and urbanisation, the demand for cement will increase substantially in future. The demand increases five times between 2010 and 2050 in the NDC and conventional scenarios (Figure 11a). The sustainable scenarios include a combination of strategies both on the supply and demand side. Reducing demand including recycling of construction waste, raw material blending including the substitution of fly ash, and substitution of concrete with other building materials. A more sustainable urban form and lower floor area per household would reduce the per capita floor area in the sustainable scenarios. The demand increase is therefore 25% lower in 2050 in the sustainable scenarios compared to the NDC and conventional 2°C scenarios (Figure 11b).

Insert Fig. 11 Demand of cement in a) NDC and 2°C Conventional = Conventional and b) 2°C Sustainable Scenarios and 1.5°C Sustainable Scenarios = Sustainable

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Material intensity i.e. the material consumed per unit of GDP for cement shows a declining trend across all the scenarios. The material intensity in the NDC and 2°C Conventional scenario declines from 150 kg cement per 1000 USD to 61 kg of cement per 1000 USD in 2050 (Fig. 12). For the sustainable scenarios, both 2°C Sustainable Scenario and 1.5°C Sustainable Scenario, this decline is steeper at 51 kg of steel per 1000 USD in 2050. Expectedly, in the NDC and conventional scenarios, the demand for both the materials increases significantly- nearly a ten-fold increase between 2010 and 2050.

Insert Fig. 12 Material Intensity Vs Energy Intensity across scenarios for cement sector

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Energy Intensity and technology choice

Energy intensity similar to material intensity shows a declining trend across all the four scenarios and reach an almost similar level of 0.055 toe per ton of cement in 2050 (Fig. 12) however, the pathways differ across the scenarios. The reductions in energy intensity vary across the scenarios mainly due to two factors i) rate of adoption of efficient dry technology ii) share of CCS in cement making (Table 4). All the scenarios have entirely retired the inefficient wet process for cement clinker production and the technology available to cement plants for cement clinker production is the efficient dry process, which we refer as standard dry. Additional efficiency gains of around 25% can happen due to the adoption of more efficient practices that relate to both technology and housekeeping (van Ruijven et al., 2016) and these are considered in the efficient dry technology. An additional factor that determines the energy efficiency of cement sector is the share of blended cement since blended cement has a lower share of clinker (Hanle et. al., 2006) and a higher share of blending materials such as fly ash, limestone, etc.

Insert Table 4 Technology Shares across the four scenarios for cement production

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In the 2°C conventional and more in the 1.5°C sustainable scenario there is a wide-scale diffusion of CCS. This is not very helpful for energy efficiency since CCS plants have around 10% more energy consumption (van Ruijven et al., 2016) and as a result the energy intensity declines in both 2°C conventional and 1.5°C sustainable scenario after 2040.

CO_2 Intensity of cement making

CO_2 intensity of cement making (measured as tCO_2 per toe of energy used for cement production) declines rapidly in all the three climate scenarios relative to NDC scenario. The decline in 1.5°C sustainable scenario is the largest where CO_2 intensity falls from 5.4 tCO_2 per toe in 2010 to 1.7 tCO_2 per toe. The reductions in CO_2 intensity are firstly due to large scale adoption of more efficient dry cement technology (including a higher share of blended cement) and secondly due to a large scale diffusion of CCS in the 2°C conventional and the 1.5°C sustainable scenarios (Table 4). Electricity decarbonisation, unlike steel sector, plays only a minor part in the decarbonisation of the cement sector.

Insert Fig. 13 CO_2 Intensity vs Energy Intensity for cement making

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Word Count : 6952 (minus abstract, references)

Contribution to NDC

As the second-largest contributor to industrial CO_2 emissions the CO_2 emissions from cement in the NDC scenario continues to increase from 89 MtCO_2 in 2010 to 184 Mt CO_2 in 2030 (Fig. 9). The NDC does not specify commitments specific to the cement sector, but its contribution can be analysed in terms of reductions in emission intensity. The emission intensity for cement shows a declining trend from 64 kg CO_2 per '000 USD in 2010 to 28 kg CO_2 per '000 USD in 2030, well beyond the overall 33-35% reductions between 2005 and 2030.

4. Conclusion and Policy Implications

Indian economy is the world's third-largest CO_2 emitter. India's economy is passing through a high growth phase that is conventionally associated with the rapid rise of CO_2 intensive infrastructure materials industries such as steel and cement. The historical coincidence of global climate change challenge with India's high growth economic development phase poses unique threats and opportunities for aligning India's CO_2 emissions with Paris Agreement's ambition 'to limit global temperature rise to well below 2 degrees Celsius above pre-industrial levels and pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. An important contribution of this paper is to develop an understanding of the responses of India's two most energy-intensive sectors to meet the global mitigation ambition as aspired by the Paris Agreement. The analysis in the paper shows that reduction in all components of the Kaya factor - namely materials intensity of the economy, energy intensity of material and CO_2 intensity of energy - is essential to achieving sizable reductions in CO_2 emissions. While recognizing that NDC targets can make inroads into reducing energy, emissions and material intensity; these are highly inadequate to achieve deep decarbonisation.

An important outcome of our analysis is that the implementation of bottom-up sustainability measures is key to reducing materials intensity of the economy. Both steel and cement sector have a huge untapped mitigation potential in terms of demand-side reduction. Compared to the NDC and conventional scenarios, the sustainable scenarios display a significant reduction in material intensity. The study points towards a national 'circular economy' framework that can be translated at the regional level through subsidies, policy goals and incentives. At a sectoral level, this implies specific policies to encourage dematerialisation, reuse, recycling and material substitution specifically in the buildings, construction and automobile industry. For example, building codes or construction guidelines could mandate the use of fly ash in construction. Similarly, formalizing and incentivizing the informal scrap industry can help in more systematic reuse and recycling of automobile components for not only the informal spare part market but within the production of new vehicles.

In India, PAT Scheme has created the right incentive structure for improvement in energy efficiency, which has led to a reduction in energy intensity of steel and cement. The assessment of NDC scenario evidently shows the continuation of the resulting gains in energy efficiency. Significant additional improvement in energy intensity can happen in the steel sector if a high share of scrap steel is used. In case of the cement sector, improvements in energy beyond what is achieved in NDC scenario is difficult and on the contrary, large-scale adoption of CCS in 1.5°C and 2°C scenarios would impose energy penalty that increases energy intensity.

Electricity will play an important role in the steel sector. Therefore, decarbonisation of steelmaking will rely on decarbonisation of electricity. Indian electricity generation relies heavily on coal and is very carbon-intensive. In order to reduce reliance on coal and promote renewable energy, the government has put a tax of Rs 400 per tonne of coal (US $ 6 per tonne of coal) which translates to a CO_2 price of US 11.5 per tonne of CO_2 which is a fifth of the CO_2 price in a conventional scenario. A large-scale transformation towards low carbon electricity therefore would require a coal tax at least 4 times of the current. A high coal price would also drive energy efficiency within the steel and cement sector.

Reduction in CO_2 intensity of energy in steel and cement will also depend on the uptake of Carbon Capture and Storage (CCS). Stringent carbon policy, in the form of a high carbon tax or a cap on CO_2 emissions, will be needed for the uptake of CCS. CCS however as a technology is still not commercialised and therefore a demonstration of the technology in India within cement and steel sector is needed to gain experience.

Achieving a sustainable 1.5^{o}C transition as specified in this study would require integrated policymaking across sectors. Establishing linkages between the manufacturing and construction industry policies can upscale a number of demand-side reductions. Intervention points such as national and sub-national building codes and urban building bye-laws could specify waste management policies such as the use of fly ash from power plants to brick and cement manufacturing industry. At the national level, this requires resource and supply chains mapping and implementing industrial ecology principles regionally. Stakeholder engagement to ensure buy-in from the private sector, especially small and medium producers will ensure a wide-scale implementation of sustainability actions to deliver results at the national scale.

An important area for the future would be to refine the results through a deeper dive into industry specific data to characterize contributions of individual interventions and their co-benefits. Additional studies to quantify cost savings and co-benefits could support decision-making, especially to push for deeper targets and early adoption of clean industry policies.

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References

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper. Resour. Conserv. Recycl. 55, 362–381. https://doi.org/10.1016/J.RESCONREC.2010.11.002

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. Environ. Sci. Technol. 44, 1888–1894. https://doi.org/10.1021/es902909k

Akashi, O., Hanaoka, T., Matsuoka, Y., & Kainuma, M. 2011. A projection for global CO_2 emissions from the industrial sector through 2030 based on activity level and technology changes. Energy, 36(4), 1855-1867. https://doi.org/10.1016/j.energy.2010.08.016

Bhattacharyya, S.C., Timilsina, G.R., 2010. A review of energy system models. Int. J. Energy Sect. Manag. 4, 494–518. https://doi.org/10.1108/17506221011092742

Dhar, S., Pathak, M., Shukla, P.R., 2018. Transformation of India's transport sector under global warming of 2 °C and 1.5 °C scenario. J. Clean. Prod. 172, 417–427. https://doi.org/10.1016/j.jclepro.2017.10.076

Dutta, M. & Mukherjee, S. 2010. An outlook into energy consumption in large scale industries in India: The cases of steel, aluminium and cement. Energy Policy, 38(11): 7286-7298. https://doi.org/10.1016/j.enpol.2010.07.056

Garg, A., Dhar, S., Kankal, B., & Mohan, P., 2017. Good Practice and Success Stories on Energy Efficiency in India. Copenhagen: Copenhagen Centre on Energy Efficiency, UNEP DTU Partnership.

GoI, 2015. First Biennial Update Report to the United Nations Framework Convention on Climate Change. Ministry of Environment Forests and Climate Change, Government of India, New Delhi, India (www.moef.gov.in/sites/default/files/indbur1_0.pdf) (Accessed 31 May 2016).

Hanle, L., Maldonado, P., Onuma, E., Tichy, M., & Oss, H. G. v. 2006. Chapter 2 Mineral Industry Emissions Volume 3: Industrial Processes and Product Use: Intergovernmental Panel on Climate Change.

IEA, 2009. Cement Roadmap, International Energy Agency (https://www.iea.org/publications/freepublications/publication/Cement_Roadmap_Foldout_WEB.pdf) (Accessed 25 June 2018).

IPCC, 2018. Summary for Policymakers, in: Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, Maycock, M. Tignor, and T.W.

(Ed.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change,. World Meteorological Organization, p. 32.

IPCC, 2000. Summary for Policymakers IPCC Special Report on Emissions Scenarios. Intergovernmental Panel on Climate Change.

Jajal, P., Mishra, T., 2018. Potential climate change mitigation of Indian Construction Industry through a shift in energy efficient technology by 2050. Adv. Geosci. 45, 155–162. https://doi.org/10.5194/adgeo-45-155-2018

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL Family of Models.

Lucas, P.L., Shukla, P.R., Chen, W., van Ruijven, B.J., Dhar, S., den Elzen, M.G.J., van Vuuren, D.P., 2013. Implications of the international reduction pledges on long-term energy system changes and costs in China and India. Energy Policy 63, 1032–1041. https://doi.org/10.1016/j.enpol.2013.09.026

Ma, M., Cai, W., 2018. What drives the carbon mitigation in Chinese commercial building sector? Evidence from decomposing an extended Kaya identity. Sci. Total Environ. 634, 884–899. https://doi.org/10.1016/J.SCITOTENV.2018.04.043

Morrow, W. R., Hasanbeigi, A., Sathaye, J., & Xu, T. 2014. Assessment of energy efficiency improvement and CO_2 emission reduction potentials in India's cement and iron & steel industries. Journal of Cleaner Production, 65: 131-141. https://doi.org/10.1016/j.jclepro.2013.07.022

Prakash, R., 2018. Energy and Material Constraints in India’s Economic Growth. Springer, Cham, pp. 343–349. https://doi.org/10.1007/978-3-319-69844-1_31

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 1.5oC. Nature Clim. Change, 5(6), 519-527. https://doi.org/10.1038/nclimate2572

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Seferian, R., & Vilario, M. V. 2018. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In V. Masson-Delmotte, H.-O. Partner, J. Skea, A. Pirani, R. Pidcock, Y. Chen, E. Lonnoy, W. Moufouma-Okia, S. Connors, X. Zhou, T. Maycock, M. Tignor, T. Waterfield, P. Zhai, D. Roberts, P. R. Shukla, C. Pean, J. B. R. Matthews, & M. I. Gomis (Eds.), An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty: Intergovernmental Panel on Climate Change.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenader, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., & Tavoni, M. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42: 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., & Owen, A. 2016. Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. Journal of Cleaner Production. 132, 45-56. https://doi.org/10.1016/j.jclepro.2015.06.100

Seyfried, P., Taiss, E.J.M., Calijorne, A.C., Li, F.-P., Song, Q.-F., 2015. Light weighting opportunities and material choice for commercial vehicle frame structures from a design point of view. Adv. Manuf. 3, 19–26. https://doi.org/10.1007/s40436-015-0103-8

Shi, F., Huang, T., Tanikawa, H., Han, J., Hashimoto, S., Moriguchi, Y., 2012. Toward a Low Carbon-Dematerialization Society. J. Ind. Ecol. 16, 493–505. https://doi.org/10.1111/j.1530-9290.2012.00523.x

Shukla, P. R., & Dhar, S. 2015. Energy policies for low carbon sustainable transport in Asia. Energy Policy, 81, 170-175. http://dx.doi.org/10.1016/j.enpol.2015.02.021

UN DESA, 2017. World Population Prospects The 2017 Revision Key Findings and Advance Tables. World Popul. Prospect. 2017 1–46. https://doi.org/10.1017/CBO9781107415324.004

UNEP, 2018. Emissions Gap Report 2018. United Nations Environment Programme, Nairobi.

UNEP, 2016. The Emissions Gap Report 2016, United Nations Environment Programme, Nairobi.

UNFCCC, 2015. India's Intended Nationally Determined Contribution. United Nations Framework Convention on Climate Change (http://www4.unfccc.int/submissions/INDC/Published Documents/India/1/INDIA INDC TO UNFCCC.pdf) (Accessed 30 November 2016).

UNFCCC , 2016. Paris Agreement Pre 2020 Action., United Nations Framework Convention on Climate Change (www.ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm) (Accessed 31 January.2016).

Van der Voet, E., Van Oers, L., Verboon, M., Kuipers, K., 2018. Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. J. Ind. Ecol. https://doi.org/10.1111/jiec.12722

van Ruijven, B.J., van Vuuren, D.P., Boskaljon, W., Neelis, M.L., Saygin, D., Patel, M.K., 2016.

Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. Resour. Conserv. Recycl. 112, 15–36. https://doi.org/10.1016/J.RESCONREC.2016.04.016

Vishwanathan, S.S., Garg, A., Tiwari, V., Shukla, P.R., 2018. India in 2 °C and well below 2 °C worlds: Opportunities and challenges. Carbon Manag. 1–21. https://doi.org/10.1080/17583004.2018.1476588

Wang, C., Wang, F., Zhang, X., Yang, Y., Su, Y., Ye, Y., Zhang, H., 2017. Examining the driving factors of energy related carbon emissions using the extended STIRPAT model based on IPAT identity in Xinjiang. Renew. Sustain. Energy Rev. 67, 51–61. https://doi.org/10.1016/J.RSER.2016.09.006