Opportunities for sustainability improvement in aluminum industry

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Abstract
The aluminum consumption in India of 2.5 kg per capita is way below the global average of 11 kg per capita. In the future, India will require additional annual consumption of 16 million tons of aluminum. Due to the energy-intensive nature of aluminum production coupled with its projected growth, there are sustainability concerns for this industrial sector. This paper examines some opportunities available for sustainability improvement in an existing aluminum plant using coal-based electricity. An industrial sustainability index (ISI), as previously developed by the authors, is here to quantitatively evaluate the magnitude of sustainability improvement through a natural gas-based combined cycle (NGCC) power generation. Two modes of sustainability improvement are examined: (a) NGCC with surplus power generation and (b) NGCC with doubling of production capacity. It is observed that the ISI values can be increased by 5 to 6 times through the above modes, as compared to the existing model. The investment required for such sustainability improvement is expected to be less than that required for setting up a totally new plant. The direct carbon emissions for the existing plant are nearly 6.4% of the total carbon emissions, which may be eliminated by adopting new smelting technology now available, with the further possibility of sustainability improvement.

KEYWORDS
aluminum industry, \( \text{CO}_2 \) emissions, industrial sustainability index, socioeconomic benefit

1 | INTRODUCTION

The global annual production of aluminum is 417,712 thousand metric tons, with China contributing to the maximum proportion followed by the Gulf Co-operation Council, North America, and India.\(^1\) Globally, auto and transport account for 23% of aluminum consumption, followed by construction (22%), packaging (13%), electrical (12%), machinery and equipment (8.5%), consumer durables (4.5%), and other segments (4%). To meet the increasing demand for aluminum, there is a continuous rise in its production, which is projected to increase from \( \sim 51 \text{ Mt} \) in 2014 to 89 to 122 Mt in 2050.\(^2\) This increase in aluminum consumption and production will drive significant growth in the industry’s absolute energy use and carbon emission. About 21% of global greenhouse gas (GHG) emissions are contributed by metal industries, of which aluminum industries contribute nearly 1.0%.\(^3\)
As per the economic policy report of the Niti Aayog, Government of India, aluminum consumption in India at 2.5 kg per capita is much below the global average of 11 kg per capita. To reach the global average of 11 kg per capita, India will require additional annual consumption of 16 million tons, thus, making it the second-largest consumer in the world. Even at low consumption, aluminum contributes 2% of manufacturing gross domestic product (GDP) (steel 12%, cement 9%), and this is expected to move up with consumption growth. This growth is critical for India’s industrial vision of achieving 25% of GDP from manufacturing by 2022.

The aluminum industry also has a high direct and indirect employment multiplier creating close to 800,000 jobs in India. Plants are generally based in the hinterlands of the country and aid in generating peripheral employment and development of the region. Going forward the sector will be a key contributor to the government’s key flagship programs like Make in India, National Capital Goods Policy, Development of 100 smart cities and government’s commitment to reach a 100 GW solar capacity by 2022 from 20 GW today. For a comparative assessment, the European non-ferrous metals manufacturing industry is also an essential and strategic sector directly employing 500,000 people and supplying products for numerous crucial downstream industrial sectors, such as public and private transport, energy production, construction, and aeronautics.

There are several studies about GHG emissions from mining and metallurgical industries, and aluminum industries are one of the most energy-intensive industries after steel. International Aluminium Institute reported that per ton of aluminum production on an average consumes 13.56 to 15.75 MWh of electricity. From the aluminum industry, the average world level of GWP in 2009 was 23.96 tons CO₂ per ton of aluminum production. Aluminum smelting contributes 72% of overall GWP, followed by alumina refining and ingot casting. Further, the aluminum production leads to release of greenhouse gases other than CO₂ such as CF₄ and C₂F₆, which pose very high global warming potential (GWP) (7390 and 12 200 times equivalent of CO₂, respectively) with long lifetimes in the atmosphere (50,000 and 100,000 years, respectively). In India’s context, the main environmental concern of the aluminum industry was reported as emissions of GHGs including CO₂, fluorinated compounds, SO₂, etc., which are generated as a result of the anode effects during the process of aluminum production.

Some recent research on product sustainability on a life cycle basis has been reported as follows: Bin et al review the latest technologies in sustainable product design methods and tools from an environmental, economic, and social perspective. A systematic product carbon footprint model across a sustainable supply chain for the product life cycle was proposed by Bin et al. The water and fertilizer irrigation machine is used to demonstrate the proposed methodology. In another study, Bin et al have estimated product environmental footprints (PEF) for the product life cycle. PEF assessment process of an agricultural picking robot was used to demonstrate the effectiveness of the proposed methodology. Wan et al have used the concept of environmental performance index (EPI) and industrial structure entropy (ISE), which were applied to analyze the current environment pressure and industrial conditions.

Liu et al reported on a unit basis, a ton of aluminum production requires ~126 GJ of energy. In another study of Liu et al., for the Henan province of China, 18 aluminum smelters were examined for energy efficiency in the aluminum production process. Through simulation studies, it was estimated that the energy consumption of the aluminum industry will decrease by 19% to 29% compared to 2014 level. In India’s context, the Bureau of Energy Efficiency (BEE) reported energy consumption of Indian aluminum industries as about 7.71 million tons of oil equivalent/year in the period of 2007 to 2010. With the use of PAT (perform, achieve, and trade) cycle, the energy savings of 0.456 million tons of oil equivalent/year is expected to be achieved, which is around 7% of the total national energy-saving. The energy conservation studies conducted by the authors in dairy and pulp and paper industries show limited energy and carbon-saving potential through process improvement and co-generation technologies.

Going beyond the process level improvement, which generally leads to a marginal reduction in energy and emissions, this study examines the potential of significant energy and emission reduction in the representative Indian aluminum industry. This may be feasible by fuel substitution and more efficient on-site power generation required by the industry. The objective of this study is to look for energy-saving opportunities beyond what is generally achieved through process improvement. Hence, a system’s approach has been used to explore the possibility of significantly large reductions in energy and emissions from the aluminum industry by examining an existing aluminum production plant located in northern India.

2 METHODOLOGY

Industrial sustainability is an important factor for socioeconomic development and environmental protection across the world. As per sustainable development goal (SDG 09), industrial sustainability has to address all the three aspects, that
is, social, economic, and environmental. Out of the three aspects, industrialization is closely related to economic growth, job creation, resources consumption, and environment pollution.

The commonly used metric for assessing energy performance in the industrial sector has been the specific energy consumption (SEC). However, the SEC is variable depending upon the type of industrial product as well as the scale of industrial production. Further, the metric SEC presents the problem of allocation of energy use in multi-product manufacturing. Another parameter developed for industrial sustainability is called eco-efficiency. It considers only economic output and carbon emissions to estimate the product’s impact. It is a ratio of the value of a product to the environmental impact of the product. It suffers from two drawbacks: (a) physical resource inputs are not considered and (b) social sustainability is not addressed.

To overcome the deficiencies mentioned above of SEC and eco-efficiency, a new industrial sustainability index (ISI) was proposed by the authors. It is meant to address all the three sustainability goals (social, economic, and environmental) and it can also compare different types of industries such as small, medium, or large scale as well as for any kind of product. The problem of allocation of energy use in multi-product manufacturing is also avoided by ISI. The concept of ISI was further applied by the authors for quantitatively examining the impact of industrial symbiosis on sustainability for a chemical industry.

The ISI is a simplified tool, which represents the socioeconomic benefit of any type of industry per unit of its carbon emissions. Carbon emissions could be direct and indirect. The direct carbon emissions may be due to the inherent nature of the production process, while the indirect emissions are caused due to energy consumption in the production process. The ISI as proposed assesses social, economic, and environmental goals of any type or types of industries (ie, small, medium, or large scale). The concept of ISI is illustrated through Figure 1.

The expression of the ISI is as follows:

\[
\text{ISI} = \frac{(\text{RVA}) \times (\text{EMP})}{\text{CO}_2 \text{ emissions}}.
\]

Here, the term “RVA” represents the resource value addition (ie, the difference of the total annual economic values of material and energy outputs [products] and that of inputs); it is represented here as million Rs per year. The limitation of RVA using Indian currency (Rs) can be overcome if the RVA is expressed in US dollars with purchasing power parity (ie, PPP $). The use of purchasing power parity can make the RVA units universal in nature rather than being country-specific.

The term “EMP” represents the total number of persons employed by the industry in a year. This refers to manpower with full-time employment (FTE, ie, 8 hours per day). The manpower employed for less than 8 hours per day can be proportionately converted to the equivalent FTE. For example, employment for 4 hours per day would be equivalent to 0.5 FTE.

The term “CO₂ emissions” represents the total annual carbon dioxide emissions (direct and indirect) by the industry during its production process (in tCO₂ per year). Thus, the ISI value is expressed in terms of million Rs persons per tCO₂ emissions, henceforth expressed as “units.”

The ISI metric as formulated shows only annual carbon emissions (direct and indirect) from an industrial enterprise. Certainly, there are other environmental impacts from the industry, for example, non-CO₂ GHG emissions, water use, land use, solid and liquid wastes, etc., which may be included in a comprehensive environmental impact assessment.
of an industry. However, in the present study, only direct and indirect CO₂ emissions have been considered given their predominant role in causing global warming, which is currently the most crucial global environmental issue.

Further modifications in the ISI metric may be incorporated, for example, by replacing CO₂ emissions with (a) GHG emissions (CO₂e) or (b) ecological footprint (EF in gha) to account for water use, land use, emissions, and other wastes.

The ISI tool has been used in this study to identify the potential of sustainability improvement in an existing aluminum plant, which currently uses coal as a fuel for on-site power generation with huge carbon emissions. The study undertaken proposes the use of natural gas based combined cycle (NGCC) power generation for environmental benefits, as well as for additional power generation for increasing the aluminum production capacity for economic benefits. An increase in production capacity is also likely to provide other employment, thereby enhancing social benefits. Such a holistic approach has been proposed and analyzed in this study to significantly improve the sustainability of the aluminum sector in the country.

3 | SURVEY AND DATA COLLECTION FOR THE CASE STUDY

3.1 | The aluminum production process

In nature, aluminum does not exist in a pure state. The production of primary aluminum metal commences with bauxite ore, which is composed of hydrated aluminum oxide (40%-60%) mixed with silica and iron oxide. Roughly 4 to 5 tons of bauxite ore are refined to produce approximately 2 tons of alumina. This alumina (2 tons) is smelted to produce around 1 ton of aluminum. Production of aluminum is a very capital and energy-intensive process. Alumina, power, and labor account for 75% to 80% of the total cost of aluminum depending on the region where it is produced. The major resources required for aluminum production are bauxite, carbon, aluminum fluoride, cryolite, and electrical power. The resource requirement for 1 kg aluminum production is depicted in Figure 2.

The Bayer process of alumina production from bauxite is illustrated through the process flow diagram (Figure 3). Figure 4 provides the process flow diagram of alumina reduction (Hall-Heroult process) for aluminum production. It may be pointed out here that CO₂ is released during the electrolytic reduction process of alumina because of the reaction of oxygen with carbon at the anode. For the prebaked anode, such direct CO₂ emissions are reported to be approximately 1.8 ton per ton of aluminum production. Hence, there are both direct and indirect CO₂ emissions during aluminum production.
3.2 Technical details of the plant

The case study taken for this work is an existing aluminum industry (Hindalco Industries Ltd. Unit-Mahan Aluminium) located at Singrauli, Madhya Pradesh, India. The primary raw material, that is, alumina, is procured from Hindalco’s Utkal and Muri alumina refineries. The aluminum production plant consists of 0.36 MTPA (million tons per annum) smelter and 900 (6 × 150) MW power plant. The 360 kA electrolysis process technology of Alcan Inc. (AP36 from Pechiney, France) is used for the aluminum smelter. The smelting technique is based on Hall-Heroult process of electrolytic reduction of alumina to aluminum metal. Alumina is dissolved in molten cryolite (bath) at a temperature of about 950°C to 960°C and DC current is passed through molten electrolyte for the reduction of alumina to form liquid aluminum at the cathode and oxygen collects at the anodes, where it combines with carbon to form CO₂ gas. The aluminum production plant has four major outputs: I-20K aluminum ingots, aluminum ingots, aluminum billets, and aluminum wire rods.
**Table 1** Material inputs and outputs and energy consumption in existing system

| S. No. | Item (input/output) | Quantity in metric ton (MT) per annum | Price/costrate (Rs) | Total price/cost (million Rs) |
|--------|----------------------|--------------------------------------|---------------------|------------------------------|
| 1      | Coal (input)         | 5,464,800 MT                         | 4,000 MT            | 21,859                       |
| 2      | Furnace oil (input)  | 90 MT                                | 55,830 MT           | 5                            |
| 3      | Light diesel oil (input) | 9.5 MT     | 46,725 MT            | 0.4                          |
| 4      | Electricity import (marginal) from grid (input) | 43,800,000 kWh | 8.00 kWh            | 350.4                        |
| 5      | Alumina (input)      | 850,000 MT                           | 1,500 MT            | 1,275                        |
| 6      | Aluminum fluoride (input) | 69,000 MT  | 100,000 MT           | 6,900                        |
| 7      | Cryolite (input)     | 6900 MT                              | 25,000 MT           | 172.5                        |
| 8      | Carbon for smelter (input) | 143,175 MT  | 16,000 MT           | 2,291                        |
| 9      | I-20K aluminum ingots (output) | 125,000 MT  | 145,000 MT           | 18,125                       |
| 10     | Aluminum ingots (output) | 65,000 MT     | 140,000 MT           | 9,100                        |
| 11     | Aluminum billets (output) | 55,000 MT     | 130,500 MT          | 7,178                        |
| 12     | Aluminum wire rods (output) | 100,000 MT  | 125,500 MT           | 12,550                       |

**Table 2** Annual CO₂ emissions from energy inputs in the existing system

| S. No. | Item | Quantity in metric ton (MT) per annum | Specific emission factor (kg CO₂/kg fuel) | CO₂ emissions (t CO₂) |
|--------|------|--------------------------------------|------------------------------------------|----------------------|
| 1      | Coal | 5,464,800 MT                         | 1.66                                     | 9,071,568            |
| 2      | Furnace oil | 90 MT | 3.31 | 297 |
| 3      | Light diesel oil | 9.5 MT | 2.68 | 25 |
| 4      | Electricity from grid | 43,800,000 kWh | 0.88 kg CO₂ per kWh | 38,544 |
| 5      | Direct emissions from production process | 345,000 MT (total aluminum production) | 1.8 t CO₂ per ton aluminum | 621,000 |

Note: Total emissions = 9,731,434 t CO₂.

Hindalco Industries has an on-site coal-fired power plant of 900 MW total capacity. It has 6 units, each of 150 MW capacity with single reheat and regenerative feed heating. The turbine is designed for steam inlet parameters of 140 bar pressure and 540°C (±5°C) temperature, reheat steam temperature of 540°C (±5°C), and condenser pressure of 0.1 bar.

The input and output materials and energy consumption in the plant are listed in Table 1. The detailed input resource consumption and product outputs of Hindalco plant were collected from the Data and Record Center Office of the industry. This data has been used for evaluating the ISI for the existing system.

**4 | ISI EVALUATION WITH EXISTING AND IMPROVED ENERGY SYSTEMS**

**4.1 | ISI evaluation for the existing system**

From Table 1, the direct and indirect (energy linked) CO₂ emissions evaluated for the existing plant are listed in Table 2.

The ISI for the existing plant is evaluated as follows:

RVA is estimated as 14,100 million Rs; EMP is 3,971 persons for a year; the total annual CO₂ emissions are estimated as 9,731,434 t CO₂. The direct CO₂ emissions are about 6.4% of the total emissions. Hence, ISI for the existing system is evaluated as 5.8 units, that is, approximately 6 units.
The possibility of ISI improvement in the existing plant has been analyzed by considering fuel substitution (natural gas in place of coal) as well as combined cycle power generation for higher efficiency by “repowering” of existing steam turbines. Such repowering involves the use of gas turbine cycle as a topping unit and the existing steam cycle as a bottoming unit; with the replacement of existing boiler by waste heat recovery boiler (WHRB) of the same capacity. Such a repowering of old steam turbines generally requires less investment compared to the installation of a new combined-cycle unit, elaborated as follows.

In a repowering arrangement, usually, the coal-fired boiler is replaced by the heat recovery steam generator (HRSG) so as to recover the gas turbine exhaust heat from the topping unit. The following equipment is not required to be replaced: (a) steam turbine; (b) electrical generator, controls, and auxiliaries; (c) condenser; (d) cooling tower and water treatment units; and (e) main transformer and high voltage equipment.

In view of the above, there are significant advantages in terms of reduced capital investment compared to the case when an entirely new NGCC plant is proposed. The proposed natural gas fired combined cycle (NGCC) power generation is illustrated through a schematic diagram shown in Figure 5. Two modes of NGCC operations have been considered in the present study for possible improvement in ISI as elaborated below:

Mode I: A natural gas fired gas turbine of 450 MW capacity (as topping unit) with bottoming steam turbine unit of 150 MW is considered. The capacity of the gas turbine (450 MW) has been selected to provide sufficient waste heat recovery from the topping unit to run the bottoming steam turbine of 150 MW.

Hence, two such combined cycle units (600 MW ×2) can not only fulfill the 900 MW electricity requirement of the existing plant but can also generate surplus 300 MW for sale to the electricity grid. The remaining four steam turbine plants, therefore, need not be operated. Detailed specifications of the proposed gas turbine are depicted in Table 3.
### TABLE 4  Annual material and energy consumption for mode I

| S. No. | Item (input/output)                                | Quantity in metric ton (MT) per annum | Price/costrate (Rs) | Total price/cost (million Rs) |
|--------|---------------------------------------------------|---------------------------------------|---------------------|-------------------------------|
| 1      | Natural gas (input)                               | 1639 872 MT                          | 10 000 MT³⁶         | 16 399                        |
| 2      | Electricity import (marginal) from grid as per regulations (input) | 43 800 000 kWh                   | 8.00 kWh            | 350.4                         |
| 3      | Alumina (input)                                   | 850 000 MT                           | 1500 MT             | 1275                          |
| 4      | Aluminum fluoride (input)                         | 69 000 MT                            | 100 000 MT          | 6900                          |
| 5      | Cryolite (input)                                  | 6900 MT                              | 25 000 MT           | 172.5                         |
| 6      | Carbon for smelter (input)                        | 143 175 MT                           | 16 000 MT           | 2291                          |
| 7      | Electricity supply to grid (output)               | 2 628 000 000 kWh                    | 8.00 kWh            | 21 024                        |
| 8      | I-20K aluminum ingots (output)                    | 125 000 MT                           | 145 000 MT          | 18 125                        |
| 9      | Aluminum ingots (output)                          | 65 000 MT                            | 140 000 MT          | 9100                          |
| 10     | Aluminum billets (output)                         | 55 000 MT                            | 130 500 MT          | 7178                          |
| 11     | Aluminum wire rods (output)                       | 100 000 MT                           | 125 500 MT          | 12 550                        |

### TABLE 5  Annual CO₂ emissions from energy inputs for mode I

| S. No. | Item                                | Quantity in metric ton (MT) per annum | Specific emission factor (kgCO₂/kg fuel)³⁴ | CO₂ emissions (tCO₂) |
|--------|-------------------------------------|---------------------------------------|-------------------------------------------|----------------------|
| 1      | Natural gas                         | 1639 872 MT                          | 2.67                                      | 4 378 458            |
| 2      | Electricity from Grid               | 43 800 000 kWh                       | 0.88 kg CO₂ per kWh                       | 38 544               |
| 3      | Direct emissions from production process | 345 000 MT (total aluminum production) | 1.8 tCO₂ per ton aluminum²⁹ | 621 000               |

Note: Total emissions = 5 038 002 tCO₂

Mode II: Here, three of the existing steam turbine units are proposed to be converted to NGCC mode, which can generate a total of (600 MW ×3) 1800 MW power. This amount of power can be utilized for doubling the aluminum production capacity of the existing plant by installing another smelter. The remaining three steam turbine units need not be operated in this mode. It may be pointed out here that Hindalco industries are already planning for doubling its production capacity by setting up another plant in the state of Odisha, India.³⁴

### 4.2.1  ISI evaluation in mode I (same production capacity with surplus power)

For the existing aluminum production capacity, the energy analysis of mode I was carried out by MATLAB program for the two required combined cycle units of 600 MW each. In this mode, the surplus electricity sale to the grid (300 MW) helps in increasing the RVA. Further, carbon emissions are significantly reduced not only due to the use of a cleaner fuel, that is, natural gas, but also due to the reduced heat rate of the combined cycle unit as compared to the steam cycle for equivalent power generation. The employment provided in mode I is assumed to be the same as in the existing plant. The annual energy and material inputs and outputs for mode I is provided in Table 4. The corresponding carbon emissions are provided in Table 5.

The following data was used to evaluate the improved ISI in mode I: CV of natural gas is 48 MJ/kg³³; total CO₂ emissions are 5 038 002 tCO₂; RVA is 40 589 million Rs; and EMP is 3971 persons for a year.

The RVA is much higher in mode I compared to the existing case due to the surplus power generation of 300 MW, which is being exported to the grid at Rs 8 per kWh. The sale of surplus power to the electricity grid is 2 628 000 000 kWh providing extra revenue of 21 024 million Rs. Therefore, RVA in mode I will be much higher than in the existing case.
TABLE 6  Annual material and energy consumption for mode II

| S. No. | Item (input/output)                        | Quantity in metric ton (MT) per annum | Price/costrate (Rs) | Total price/cost (million Rs) |
|--------|-------------------------------------------|--------------------------------------|---------------------|-------------------------------|
| 1      | Natural gas (input)                       | 2 459 808 MT                         | 10 000 MT$^{38}$    | 24 598                        |
| 2      | Electricity import (as per regulations) from grid (input) | 43 800 000 kWh                      | 8.00 kWh            | 350.4                         |
| 3      | Alumina (input)                           | 1 700 000 MT                         | 1500 MT             | 2550                          |
| 4      | Aluminum fluoride (input)                 | 138 000 MT                           | 100 000 MT          | 13 800                        |
| 5      | Cryolite (input)                          | 13 800 MT                           | 25 000 MT           | 345                           |
| 6      | Carbon for smelter (input)               | 286 350 MT                           | 16 000 MT           | 4582                          |
| 7      | I-20K aluminum ingots (output)           | 250 000 MT                           | 145 000 MT          | 36 250                        |
| 8      | Aluminum ingots (output)                 | 130 000 MT                           | 140 000 MT          | 18 200                        |
| 9      | Aluminum billets (output)                | 110 000 MT                           | 130 500 MT          | 14 355                        |
| 10     | Aluminum wire rods (output)              | 200 000 MT                           | 125 500 MT          | 25 100                        |

TABLE 7  Annual CO2 emissions from energy inputs for mode II

| S. No. | Item                                      | Quantity in metric ton (MT) per annum | Specific emission factor (kgCO2/kg fuel)$^{33}$ | CO2 emissions (tCO2) |
|--------|-------------------------------------------|--------------------------------------|-----------------------------------------------|---------------------|
| 1      | Natural gas                               | 2 459 808 MT                         | 2.67                                          | 6567 687            |
| 2      | Electricity from grid                     | 43 800 000 kWh                       | 0.88 kg CO2 per kWh                            | 38 544              |
| 3      | Direct emissions from production process | 690 000 MT (total aluminum production) | 1.8 tCO2 per ton aluminum$^{35}$                | 1242 000            |

Note: Total emissions = 7 848 231 tCO2.

Employment is assumed to be the same after repowering as two of the existing steam turbine plants would still exist. The manpower used in the four redundant steam plants is assumed to be transferred to gas turbine units for NGCC based power generation.

Thus, ISI for mode I is evaluated as 32 units, which is nearly 5 times more than the ISI for the existing unit.

4.2.2  ISI evaluation in mode II (double production capacity without surplus power)

For doubling the aluminum production capacity, the power generation required is 1800 MW. The energy analysis of mode II was carried out by MATLAB program for the three required combined cycle units of 600 MW each, without any surplus power. In this mode, the doubling of aluminum production output helps in increasing the RVA, though the material input quantities are also doubled. Similar to mode I, carbon emissions are significantly reduced. The annual energy and material inputs and outputs for mode II are provided in Table 6. The corresponding carbon emissions are provided in Table 7.

The following data was used to evaluate the improved ISI for mode II: total CO2 emissions are 7 848 231 tCO2; RVA is evaluated at 47 681 million Rs; it may be noted here that there is no surplus power generation (exported to the grid) in mode II unlike mode I; EMP is assumed to increase to around 6000 persons on an annual basis due to expansion in the production capacity; and thus, ISI for mode II is evaluated as 36 units, thus providing 6 times improvement in ISI as compared to the existing plant.

4.3  Investment analysis for modes I and II

For investment analysis, price estimates for gas based power generating plants are provided in Table 8.$^{37}$
| S. No. | Type of generation plant                  | Total plant cost (US$/kW net)          |
|--------|------------------------------------------|----------------------------------------|
| 1      | Gas turbine combined cycle plant         | U.S.-1410 India-1170 Romania-1140      |
| 2      | Gas turbine simple cycle plant           | U.S.-860 India-720 Romania-710         |

**TABLE 8** Pricing estimates for selected generation technologies

| S. No. | Aluminum industry system configuration | ISI |
|--------|----------------------------------------|-----|
| 1      | Existing system (coal-fired steam power)| 06  |
| 2      | Modified system (NGCC with surplus power) | 32  |
| 3      | Modified system (NGCC with doubling of production capacity) | 36  |

**TABLE 9** Summary of ISI evaluations

### 4.4 | Investment analysis for mode I

The power generation required for the existing mode is 900 MW. From the price data in Table 8, the 900 MW gas turbine combined cycle plant investment cost is estimated as Rs million 7371.

For mode I, two of the existing steam turbines (150 MW × 2) are proposed to be repowered by adding two topping units (simple cycle gas turbines) of 450 MW each. The surplus 300 MW is being sold to the grid. Hence, investment for only 900 MW gas turbine (simple cycle) plant will be required with an estimated cost of Rupees million 4536. Hence, the savings in investment are estimated to be (7371-4536), that is, Rs million 2835.

### 4.5 | Investment analysis for mode II

The power generation required for mode II (1800 MW) is double of that required in existing mode. This is proposed to be obtained through repowering of three of the existing steam turbines (150 MW × 3) by three gas turbine (simple cycle) topping units of 450 MW each.

Hence, the investment required in mode II will be Rs million 6804. For a completely new 1800 MW combined cycle plant, the investment is estimated as Rs million 14742. Hence, the investment saving in mode II is estimated as (14742-6804), that is, Rs million 7938.

From the above analysis, it is observed that in both the modes, that is, mode I and mode II, the investment required in “repowering” of existing steam turbines is less than the investment for a completely new combined cycle (NGCC) plant.

### 5 | CONCLUSIONS

In view of the sustainability concerns due to energy-intensive nature of aluminum production, a case study in India’s context was examined for exploring opportunities of carbon mitigation with productivity improvement for an existing aluminum plant. A system’s approach was used for this study for carbon reduction through fuel substitution (coal by natural gas) along with more efficient combined cycle power generation. The results obtained in terms of ISI improvement are summarized in Table 9.

It is observed that significant improvement in sustainability is feasible for the existing coal power based aluminum industry in India. The natural gas based combined cycle power generation through for such plants can lead to 5 to 6 times improvement in the ISI along with enhanced aluminum production. In addition, the investment required for such a sustainability improvement through “repowering” of existing steam turbines is estimated to be less than that required in setting up a new gas fueled combined cycle plant.

Further opportunities for carbon reduction may also be explored in future. For the aluminum industry examined, the direct carbon emissions were found to be 6.4% of the total carbon emissions. Even these direct carbon emissions can be reduced or eliminated by adopting newly developed smelting technology, thus helping in further improvement of ISI. Recycling of scrap aluminum can lead to a significant reduction in energy required. As reported by Koulton, if aluminum is produced as a mix of 70% primary aluminum and 30% scrap (secondary aluminum), the energy requirement is reduced by 40%. Hence, opportunities for aluminum recycling in Indian context need to be exploited.
With solar power growth in India, the carbon emissions from a hybrid grid (coal/solar) electricity will undoubtedly be reduced. However, for aluminum production, there is a need for a steady and reliable power supply which may not be possible with fluctuations in solar electricity. Hence, in the present case, a more reliable option of natural gas based power generation has been considered with advantages of higher energy conversion efficiency (~50%) and reduced carbon emissions by substitution of coal with natural gas. The gas/solar hybrid power generation is still not prevalent in India, though it may provide reliable, steady power with significantly reduced carbon emissions. Such a scenario may be examined in future to assess improvement in industrial sustainability.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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