SAND2022-6719C

A Lifecycle Framework for Industrial Decarbonization

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Abstract. A lifecycle framework has been developed to categorize needs and opportunities for industrial decarbonization. The framework includes the following four categories: (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel greenhouse-gas sequestration, and (4) recycling, repurposing, and recovery. Energy efficient processes underlies each of these four areas. This paper provides a summary of gaps, challenges, and research opportunities for industrial decarbonization in each of these categories, along with a discussion of technoeconomic analyses that can be used to help prioritize activities and potential impacts.

Keywords: Industrial decarbonization, feedstocks, solar heating, hydrogen, biofuels, electrification, sequestration, recycling, repurposing, recovery.

1 Introduction and Background

The United States Environmental Protection Agency estimates that industrial processes contribute nearly a quarter of greenhouse gas emissions in the U.S. (Figure 1). Industrial processes all require energy in the form of heating and electricity. Nearly three quarters of the energy used for industry is for heating, and about a quarter is used as electricity [1]. The vast majority of this energy (~90%) is currently produced by burning fossil fuels, either in gas- or coal-fired power plants, to generate electricity or by burning coal, natural gas, or oil for heating [1].

In addition, some industrial processes, such as the production of cement and steel, produce carbon dioxide (CO_2) during high-temperature processes to decompose and purify the feedstock into useable materials. For example, in cement production, calcium carbonate (limestone) is heated to high temperatures during the calcination process to produce calcium oxide, but CO_2 is also released as a chemical byproduct during the reaction. CO_2 is also emitted when iron ore is heated and mixed with coal to produce iron for steel production. Nearly a ton of CO_2 is emitted for each ton of cement produced, and nearly two tons of CO_2 are emitted for each ton of steel produced. Conventional cement production contributes ~3 – 5% of global CO_2 emissions [2, 3] and ~8% of anthropogenic CO_2 emissions [4]. About 60% of CO_2 emissions results from the calcination of calcium carbonate, ~30% is from burning of fossil fuels to supply heat for the highly endothermic reaction, and ~10% is for indirect energy needs (e.g., electricity and transportation) [4]. Steel has a similar contribution to global CO_2 emissions. Combined, cement and steel production contribute to ~15% of global CO_2 emissions. Predictions of growth vary, but several sources expect cement and steel production to grow through 2050. Cement demand is expected to grow by a total of ~10% – 25% by 2050, and steel demand is expected to grow by 0.4 – 1.4% per year through 2035 with growth driven largely by Africa, India, and other developing countries [5]. China currently leads the world in cement and steel production.

As a result, comprehensive global decarbonization will need to include decarbonization of industrial processes, including reduction of fossil fuels for heating and reduction of carbon-intense feedstocks for material processing. This paper describes a total lifecycle framework to categorize and identify gaps, challenges, and opportunities for industrial decarbonization.

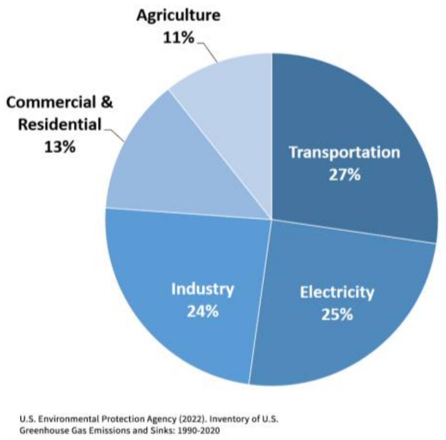

Figure 1. Total U.S. greenhouse gas emissions by economic sector in 2020 (U.S. Environmental Protection Agency [6]).

2 Framework for Industrial Decarbonization

Sandia National Laboratories has developed a lifecycle framework for industrial decarbonization as part of its new Climate Change Security Center strategy. Sandia's objective is to utilize its diverse and cross-cutting capabilities to mitigate greenhouse gas emissions in all sectors, including transportation, electricity, and industry (Figure 2). The framework for industrial decarbonization includes four major areas: (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel greenhouse-gas sequestration, and (4) recycling, repurposing, and recovery. It should be noted that energy efficiency underlies all four areas.

The industrial decarbonization framework enables an intuitive and integrated categorization of key stages in a product's lifecycle. Examples of gaps, challenges, and research opportunities to reduce greenhouse gas emissions in each of these areas are presented in the following sections.

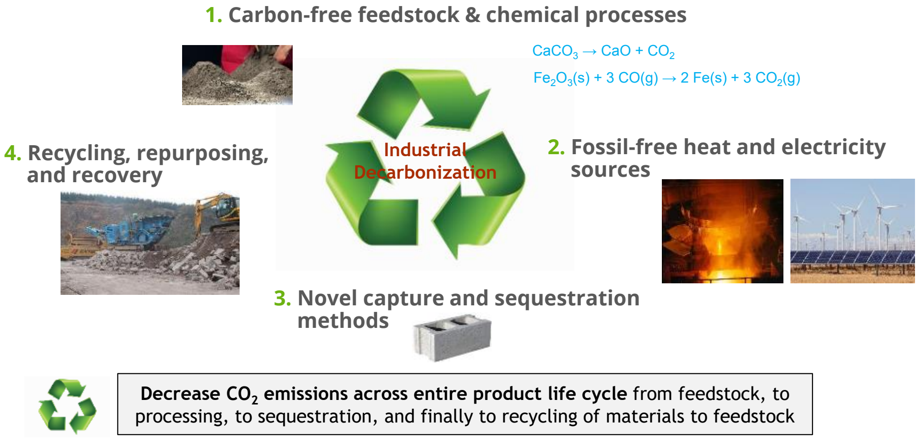

Figure 2. Lifecycle framework for industrial decarbonization.

2.1 Carbon-Free Feedstocks and Chemical Processes

As discussed above, common feedstocks for cement and steel production emit significant amounts of CO_2 during processing. Low- or non-carbon-emitting binders have been proposed for cement (e.g., phosphate-based cements [7] or belite binders [8]), but research is needed to understand aging properties, processing temperatures, and optimal compositions. Carbon-free reduction of iron ore to produce steel using hydrogen instead of coke is also being investigated [5].

Carbon-free chemical processes, such as photoelectrochemical, electrolysis, and solar thermochemistry, to produce H_2 and/or CO (for syn gas) via H_2O or CO_2 splitting, respectively, have also been studied [9-15]. For example, in one type of solar thermochemical hydrogen production, metal oxides are heated using concentrated sunlight and reduced, liberating oxygen. When cooled, the reduced particles re-oxidize by stripping oxygen from either steam or CO_2 to yield H_2 or CO, key ingredients for synfuels. Energy-intense chemicals such as ammonia, which consumes 1 – 2% of global energy, can also be made sustainably using green electrolysis or solar thermochemistry [16]. Additional research is required to increase the efficiency and scalability of these processes.

2.2 Fossil-Free Heating and Electrification

High-temperature processing can be enabled by carbon-free sources (e.g., electric arc-furnaces powered by renewable energy, combustion of clean hydrogen or biofuels, concentrating solar thermal). Development of economical methods for energy conversion, conveyance, and storage is needed, and demonstrations using local renewable resources, showing regional value, should be prioritized.

Griffiths et al. provides a review of socio-technical challenges and opportunities for industrial decarbonization using hydrogen, which has high energy density and can enable long-duration storage. However, hydrogen combustion for industrial applications faces challenges relative to carbon-based fuels: high combustion velocity, non-luminous flame, low radiation heat transfer, corrosion and embrittlement of metals, and explosive properties. Clean hydrogen utilization for industrial decarbonization will require additional socio-technical advancement, ranging from basic research and development to market stimulation.

Concentrating solar technologies use a large array of mirrors to focus and concentrate sunlight onto a receiver, which can heat a fluid or media to very high temperatures (> ~1000 °C). This high-temperature heat can be used for various industrial processes [17, 18]. Studies have been performed that show concentrated sunlight can heat a gas to ~1500 °C for use in clinker formation [19]. Challenges include storage and conveyance of high-temperature heat from the point of generation to the point of use.

2.3 Novel Sequestration of Greenhouse Gases

Carbon sequestration can occur in a wide variety of different systems including terrestrial, biological, oceanic, geological, and engineered materials. There has been growing interest in terrestrial and biological options of carbon sequestration, but traditionally, the US Department of Energy (DOE) has focused on geologic sequestration as part of the Office of Fossil Energy and Carbon Management portfolio.

Carbon sequestration in building materials connects with the recent focus on the creation of carbon neutral, or even carbon negative, building materials in support of industrial decarbonation. Carbon sequestration within the building material, such as cement or concrete, supports decarbonization of the cement life-cycle, without requiring injection of CO_2 into geologic repositories. Conversely, geologic sequestration has the ability to sequester carbon captured from any source (such as from post-combustion gas streams) and is considered to be one of the most promising avenues for large scale CO_2 sequestration, with the USGS estimating that the US has a potential CO_2 sequestration capacity between 2400-3700 metric gigatons of storage.

Key challenges include demonstration of long-term sequestration, scale-up, and potential impacts on materials of long-term aging.

2.4 Recycling, Repurposing, and Recovery

The final stage in the industrial decarbonization lifecycle framework is recycling, repurposing, and recovery. Materials recycling is commonly performed in industry, though most commonly for purposes of reducing material waste or recapturing valuable materials/commodities. Recycling as a strategy for industrial decarbonization, though, is relatively nascent. An exception is steel recycling, which is already a widespread practice. An estimated 1.5 kg of CO_2 emissions can be eliminated for every kg of steel recycled, and steel recycling is expected to double by 2050 [20, 21]. Recycling of other building materials, such as concrete, is possible, but uncertainty exists regarding performance and aging properties of recycled concrete aggregates [22]. Hopewell et al. [23] provide a comprehensive study of challenges and opportunities associated with plastics recycling, and studies are emerging that show potential for wide-spread carbon benefit of post-consumer polymer recycling [24].

As an alternative to explicit material recycling, repurposing of CO_2 emitted during industrial processes such as cement and steelmaking has also been studied. As described in Section 2.1, CO_2 can be combined with H_2 to produce hydrocarbon fuels, and there are additional studies about reintroducing CO_2 to recycled cement as a means to improve its properties [20]. In addition, recovery and reuse of waste heat from high-temperature industrial processes can also be performed to reduce CO_2-generating fossil-fuel consumption for heating. Recuperation of heat for use in low-temperature district heating is possible [25], and studies are looking at use of industrial waste heat for electricity generation [26]. Tools and methods for industry to identify cost-effective waste-heat recovery efforts have been developed [27] and may lead to significant gains in carbon reduction.

2.5 Discussion

The previous sections provide key challenges and opportunities to decarbonize industrial processes. A method that can be used to help prioritize which activities and opportunities should be pursued is probabilistic technoeconomic analyses (TEA) [28, 29].

Probabilistic TEA honors the inherent uncertainties in a system by sampling uncertainty distributions for input parameters that describe the features, events, and processes of a given system. Numerous runs (realizations) are modeled to evaluate the desired metric (e.g., cost, greenhouse gas emission, energy yield, social equity). The results provide a probabilistic evaluation of potential outcomes, and statistical regression analyses can be performed to determine the most significant input parameters or processes that impacted the simulated metric. This enables prioritization for future research to yield the most impact for a given investment (“best bang for the buck”).

Energy efficiency is another opportunity that underlies all four areas in the industrial decarbonization lifecycle. Andrei et al. [30] report that energy efficiency is viewed as Europe’s “first fuel” in various 2030 decarbonization scenarios, and that it should be treated as an energy source because it represents value in saved energy. In the U.S., Whitlock [31] reports that 15% of industrial emissions can be cut through efficiency measures, energy management, and smart manufacturing.

3 Conclusions

This paper has described a lifecycle framework for identification of key gaps, challenges, and opportunities to decarbonize industry. The four major categories in the framework include: (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel greenhouse-gas sequestration, and (4) recycling, repurposing, and recovery. Significant reduction of greenhouse gas emissions can be achieved in each of these four areas, but challenges and research opportunities remain and have been highlighted in this paper.

Acknowledgments. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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