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Toward an infinitely reusable, recyclable, and renewable industrial ecosystem

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ABSTRACT

The industrial sector in the United States consumes one-third of the nation's energy and emits one-fifth of the nation's carbon dioxide. It also consumes virgin materials at unsustainable rates and produces substantial amounts of wastes. To reverse these trends, the United States can transition to an infinitely reusable, recyclable, and renewable industrial ecosystem (IR_3). The concept requires new classes of infinitely reusable materials based on advanced carbon technologies; increased recycling of standard materials such as glass and plastic; and substitution of renewable materials for non-renewable virgin materials. In combination with new emphases within our energy system, implementing the IR_3 ecosystem could reduce United States carbon dioxide emissions from the industrial sector by more than 80% by 2050.

"Every nation on this planet is at risk, and just as no one nation is responsible for climate change, no one nation can address it alone."

—President Barack Obama (2009) (Chipman and Morales, 2009)

"The best way to predict the future is to invent it."

—Alan Kay (1989)

1. Introduction

In 2009, the Group of Eight (G8) nations each pledged to reduce their greenhouse gas (GHG) emissions to 80% below 1990 levels by 2050 (European Climate Foundation, 2010) in order to reduce sea-level rise and global warming. Shortly thereafter, we began researching the most challenging aspect of their pledge: What will it take to reduce United States (U.S.) industrial sector carbon dioxide (CO_2) by 80% of 2010 levels by 2050? Most emissions come from a small number of large facilities (West and Pena, 2003), and most production emissions come from the manufacturing processes for key materials such as steel, aluminum, glass, and paper (U.S. Energy Information Administration, 2008), yet we depend heavily on these large facilities and key materials.

An industrial ecosystem with infinite reuse, recyclability, and renewability (IR_3) produces fewer original materials, thus reducing production and energy emissions. Based on this premise, we developed a list of materials that can be manufactured once and then be infinitely reused, recycled, and renewed: Steel, aluminum, plastic, glass, wood, nano yarns, nano self-locking building blocks, graphene, transgenic silk, concrete, paper and cardboard.

To study our concept, we developed a vision of current and future CO_2 production and energy emissions based on our IR_3 concept (the underlying datasets are available via the lead author's Dataverse Network account at the Institute for Quantitative Social Science at Harvard University (Harvard University)). The second section presents an overview of the current industrial ecosystem. The third section addresses our proposed industrial ecosystem while the fourth section details the characteristics of the individual materials. The fifth section addresses our methodology and the sixth section details the resulting material flows in the U.S. industrial sector by the year 2050. The seventh and eighth sections

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include our discussion and policy and research recommendations, respectively. The paper concludes with the limitations of this work and the related opportunities for future research.

2. The current industrial ecosystem overview

Industrial sector energy consumption and emissions are 31.5 percent (U.S. Energy Information Administration, 2010) and 22.5 percent (U.S. Energy Information Administration, 2008) of the nation's totals, respectively: The U.S. industrial sector consumed 31.3 quadrillion British thermal units (Btu) of energy in 2008 (U.S. Energy Information Administration, 2010) and simultaneously emitted 1589.1 million metric tons of carbon dioxide (CO_2) (U.S. Energy Information Administration, 2008). Additionally, in 2008 this sector consumed virgin materials such as iron and steel and aluminum at a rate of 108.1 million tons (U.S. Department of Energy, 2008a,b) and 4.29 million tons (U.S. Department of Energy, 2008a,b), respectively, while generating 7.6 billion tons of non-hazardous industrial solid waste (United Nations Environment Programme, November 7, 2012).

A substantial portion of the industrial sector's energy demand and associated emissions of greenhouse gases is the result of processing virgin materials to produce steel, glass, plastics, and aluminum; producing energy-intensive concrete; and wasting materials. Waste attributable to this sector is the result of low levels of recycling for some materials (e.g., plastics) and products (e.g., electronics) and the use of non-recyclable materials (e.g., concrete). This waste is offset by recent progress in recycling or reusing some industrial materials such as steel (58% of steel in the United States is made from recycled steel) (Steel Recycling Institute, 2010) and aluminum (75% of aluminum ever produced is still in use) (ALCOA Recycling, March 9, 2012). Even if a material is completely unused or just waiting to be discarded, it is still available for reuse or recycling, which fits with the systemic behavior we are promoting.

Still, more progress is needed to meet the goal agreed to by the G8 and enacted in The American Clean Energy and Security Act of 2009 (ACESA) (U.S. Energy Information Administration, 2008). Improving energy efficiency and reducing energy intensity, and therefore CO_2 emission profiles, of typical industrial processes solely by focusing on improving industrial processes (e.g., steam, motors, etc.; see Figure A in the Appendix) seems daunting, if not impossible. We propose an alternative course of action: meet the goal by minimizing the use of traditional industrial processes through a radical reconceptualization of industrial and energy production.

3. The IR_3 industrial ecosystem overview

To meet this challenge, an industrial ecological approach is needed (McDonough and Braungart, 2002). We argue that the current U.S. industrial ecosystem is still substantially a Type I system, characterized by a belief in unlimited resources and a lack of concern about wastes. At best, the current U.S. industrial ecosystem is a nascent Type II system, characterized by some attempts to conserve resources and minimize wastes (Krones). Industrial ecologists seek to develop Type III industrial ecosystems, which generate zero wastes, as waste outputs from one set of processes become inputs for other processes. The only inputs are minimal resources and solar energy (Krones).

According to Korhonen (2001), ecosystems must fulfill four principles: 1) roundput, 2) diversity, 3) locality, and 4) gradual change. Roundput is recycling or cascading energy, which we satisfy by encouraging product recycling and reusability. Diversity is diversity of actors, inputs, and outputs, which we meet by suggesting a mix of producers, raw materials, and finished products. Locality involves respecting the local natural environment, but also using local resources, which we accomplish with our mix of local and national production. Gradual change refers to the fact that you cannot change ecosystem types or even features overnight, which is why our system depends on a transitional period, addressed below.

Consistent with Korhonen, we propose an enhancement to the Type III industrial ecosystem, which we refer to as an infinitely reusable, recyclable and renewable industrial ecosystem. IR_3 will radically reduce energy consumption, wastes, and the emissions of GHG, including CO_2, by:

- Introducing into the industrial ecosystem new carbon-technology based materials that are essentially infinitely reusable to substitute for materials that are difficult-to-impossible to recycle and are energy-intensive to produce (e.g., concrete);
- Increasing recycling rates of traditional industrial materials, such as glass and plastics; and
- Substituting sustainably-produced renewable materials (e.g., bio-plastics) for materials produced from non-renewable resources that are energy-intensive to process.

Below, we present our vision of an IR_3 industrial ecosystem for the U.S. that emits 80% less carbon dioxide by 2050 than in 2010. We look at the total changes in CO_2 from changing energy and production emissions, but our focus is on the change in CO_2 from the change in production emissions. This new system relies heavily on new and novel materials. It also emphasizes local production.

The IR_3 has two main classes of materials, as depicted in Fig. 1: 1) infinitely renewable materials and 2) infinitely reusable and recyclable materials. The first class of materials is produced by trees, crops, and genetically-modified members of the biota (e.g., transgenic silkworms). These renewable resources yield materials that can be directly used in various products (e.g., lumber) and can be used as plastic and carbon feedstock to produce infinitely reusable and recyclable materials.

The components of the second class of materials include several well-known materials, such as glass, plastic, aluminum and steel. Steel, aluminum and glass are almost infinitely recyclable, in which we defined "infinitely recyclable" as being able to use the base material again and again rather than just leaving every option open for the next product. For example, to make all plastics recyclable, it is necessary to melt the same types of plastics together and minimize the use of additives like dyes and fillers that are economically-inefficient to remove. The IR_3 design also relies heavily on the development of reusable nano fibers and a new type of reusable material, which we have named *Nano Self-Locking Building Blocks*. Drawing inspiration from LEGO® building kits, we conceive of nano self-locking building blocks as indestructible, interchangeable, and interlocking carbon-based pieces that can be assembled into products and structures and then disassembled for direct reuse. Nano self-locking building blocks could take many forms, such as carbon bricks, sheets of carbon materials, large assemblies of carbon nanotubes, and carbon I-beams.

Not all metals are infinitely reusable, but the research is promising. For example, Fleury and Davies (2012) make the case that products have to be designed so that we can reclaim the metallic material at the end. This means taking into account the mix of other impurities and the shape and form of the item in design and original manufacturing so that recycling later is feasible.

Also interesting, the International Institute for Environment and Development's (Starke, 2002) report, "Breaking New Ground: Mining, Minerals and Sustainable Development," notes that infinitely recycling metals is feasible, but subject to tradeoffs in environmental factors for extraction and social factors in processing.