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# Reducing greenhouse gas emissions through operations and supply chain management

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ABSTRACT

The experiences of the largest corporation in the world and those of a start-up company show how companies can profitably reduce greenhouse gas emissions in their supply chains. The operations management literature suggests additional opportunities to profitably reduce emissions in existing supply chains, and provides guidance for expanding the capacity of new "zero emission" supply chains. The potential for companies to profitably reduce emissions is substantial but (without effective climate policy) likely insufficient to avert dangerous climate change.



## 1. Introduction

In December 2011, at the climate change negotiations in Durban, South Africa, representatives of 190 countries agreed upon the need to limit the increase in global average temperature to 1.5 or 2 °C above pre-industrial levels, to avert dangerous climate change. Global anthropogenic greenhouse gas emissions must fall by at least 50% below 1990 levels before 2050 to have even a 50% probability of holding the global temperature increase to 2 °C. Cutting emissions sooner rather than later will reduce temperature and associated climate change impacts (Meinshausen et al., 2009). However, emissions of the primary greenhouse gas $CO_2$ from fossil fuels are now over 50% *higher* than 1990 levels (the reference year for the Kyoto Protocol) and growing rapidly, particularly in the emerging economies of China and India (Peters et al., 2012). The production and transportation of goods causes approximately 45% of those emissions, and the energy consumed when people use those goods accounts for much of the remainder; energy use in buildings alone accounts for approximately 25% (IPCC, 2007).

Therefore, to avert dangerous climate change will require tremendous changes in the design and operation of *supply chains*, defined here as encompassing the multi-stage production, transportation, use, and eventual disposal of goods, and the energy generation and transmission that supports all of those activities. This article sheds light on how companies can profitably reduce greenhouse gas emissions in their supply chains. Section 2 below describes how the world's largest corporation and a start-up in the building industry have already profited from doing so. Those examples suggest that the potential for profitable emissions reduction is substantial but (without effective climate policy) likely insufficient to avert dangerous climate change. Section 3 reviews academic literature on operations and supply chain management that provides further insights into ways to reduce emissions, and begins to quantify the potential impacts of climate change on supply chain performance.

## 2. Profitable reductions in greenhouse gas emissions: company experiences

Companies seeking to reduce their greenhouse gas emissions often find that their direct emissions are dwarfed by the emissions in their supply chains. In fact, Matthews et al. (2008) found that across all industries, companies' direct emissions average only 14% of their supply chain emissions prior to use and disposal; accounting for the emissions in use and disposal of goods would make that percentage even lower.

Therefore, companies must take a global supply chain perspective in order to identify the most profitable means to reduce overall "Scope 3" emissions. [1] They must find ways not only to reduce emissions under their direct control but also to influence emissions caused

[1] Under the Greenhouse Gas Protocol, "direct" emissions are emissions from sources that are owned or controlled by the reporting entity. "Indirect" GHG emissions are emissions that are a consequence of the activities of the reporting entity, but occur at sources owned or controlled by another entity. Emissions are categorized into Scope 1 (direct emissions), Scope 2 (indirect emissions from consumption of purchased electricity, heat or steam), and Scope 3 (all other indirect emissions). Guidelines for accounting for Scope 3 emissions are at http://www.ghgprotocol.org/standards/scope-3-standard; though extensive, these guidelines allow flexibility that may lead to widely varying estimates of Scope 3 emissions, and they may be improved over time, as discussed in Section 3.5 below.

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by their suppliers and customers—by providing them information and incentives, and collaborating or even vertically integrating with them. The experience of two companies suggests how these steps can be taken. For contrast, we consider a well-established corporation (the largest in the world, as measured by revenue) and a start-up.

### 2.1. Walmart: increasing profits by reducing GHG emissions

Walmart is the largest corporation in the world in terms of revenues, and is widely recognized as a leader in supply chain management. In the last several years it has embraced its responsibility to protect the environment and has sought to reduce emissions in ways that improve its bottom line. In 2005, CEO Lee Scott announced that "Being a good steward of the environment and being profitable are not mutually exclusive. They are one and the same." He set sweeping environmental goals for the company: "to be supplied 100% by renewable energy; to create zero waste; and to sell products that sustain people and the environment." Since roughly 90% of Walmart's greenhouse gas emissions and other environmental impacts occur in its extended supply chain, the firm must work with suppliers and customers to achieve these goals.

In a case study I wrote in 2007 and updated in 2010 (Plambeck and Denend, 2007a, 2007b), I found that Walmart is profiting from its actions to reduce greenhouse gas emissions in its own operations and its supply chain. Emission reduction is associated with cost reduction, new sources of revenue, improved employee motivation, enhanced public relations, and increased voice with policy makers. The summary below of how Walmart has tapped each of these five sources of value provides a template for other companies seeking to do the same.

#### 2.1.1. Reducing costs

Cost reduction through energy efficiency is the most obvious source of business value associated with emissions reduction. Anderson and Newell (2004) have documented that small and medium-sized firms in the U.S. commonly overlook energy-efficiency projects that have a high net present value. Walmart, though famous for the efficiency of its operations, found "quick wins" in profitable energy efficiency as soon as it looked. In just the first year of its sustainability program, for example, Walmart improved the average fuel efficiency in its logistics network by 25%, which translates into annual savings of $75 million and 400,000 tons of $CO_2$, with relatively little investment.

Nonprofit environmental organizations, including the Rocky Mountain Institute, contributed substantially to Walmart's success in reducing emissions and costs in its logistics network, by identifying energy-efficient technologies and ambitious-but-achievable goals for emission reduction. Walmart is also relying on various other nonprofit organizations to help its suppliers identify and implement energy efficiency projects (see Sectio2.1.8.8), which will ultimately reduce Walmart's cost of goods.

Not surprisingly, cost reduction is a primary reason for seeking to measure and reduce supply chain emissions, for many of 57 multinational corporations (as various as Dell, Ford, EADS, and Vivendi) participating in the Carbon Disclosure Project (CDP) Supply Chain Program (Carbon Disclosure Project, 2011).

#### 2.1.2. Increasing revenues

Walmart's efforts to reduce emissions have opened up many sources of new revenue. For example, improved public relations stemming from its environmental stewardship initiatives may help the company to add stores in communities where they would otherwise face greater resistance, and may also help the company to attract more customers to its existing stores (see 2.1.3).

Consumers are more inclined to pay a premium for "green" products when "green" is associated with some private benefit. Walmart charges a higher price per unit for organic cotton clothing, for example. The company was surprised to see, in point-of-sale data, that customers who historically would shop only for toiletries began to "cross the aisle" to buy organic cotton clothing and other organic products. Many consumers perceive a health benefit with organic apparel and food. Walmart also informs customers of electricity-cost savings with some energy-efficient products.

Greenhouse gas emissions may decrease substantially as Walmart sells organic instead of conventional products. The first reason is that organic farmers do not use synthetic nitrogen fertilizer, which tends to reduce emissions of nitrous oxide, a potent greenhouse gas, as well as $CO_2$; fertilizer manufacturing consumes a huge amount of natural gas. The second reason is that nonprofit organizations monitor and certify each stage in the supply chain for an organic product. That gives Walmart (and other buyers) unprecedented visibility of the entire supply chain, which enables rationalization of the supply chain to reduce emissions and production costs (see Section 2.1.6). Walmart is pursuing local sourcing of organic produce, and transports local produce in the same trucks used for other goods, to avoid adding trips (Ata et al., 2012). However, out-of-season produce must be transported over long distances or grown in energy-intensive hothouses (Rosenthal, 2011), which tends to increase emissions.

Walmart can earn higher revenue by selling products that are more energy-efficient, even without charging a higher price for energy-efficient products. Many of its customers have little disposable income and shop almost exclusively at Walmart. When they save money on their electricity bills, they spend that money at Walmart. The potential for emissions reduction with energy-efficient products is huge. For example, in its first year of promoting compact fluorescent (CFL) lights, Walmart achieved sales of over 100 million bulbs, which would reduce customers' electricity use and hence $CO_2$ emissions by 20 million metric tons, approximately equal to Walmart's total corporate emissions (Scope 1 and Scope 2) in 2010. (That figure presumably does not account for any increase in emissions when customers used money saved on electricity bills for additional consumption.) A second example arises in apparel, the product category wherein Walmart has the highest associated supply chain greenhouse gas emissions. Approximately half of those emissions occur in the customer use phase—i.e., washing and drying. The company is working with suppliers to change labeling on clothes to "cold water wash" instead of "hot water wash," which will substantially reduce electricity use. The company also gives prominent shelf space to detergents that are designed for cold-water washing and are triple-concentrated, which reduces cost and emissions in transport.

Even in product categories where Walmart cannot charge a premium for "green," it may gain market share by labeling products with environmental impact information. Laboratory experiments suggest that when a firm voluntarily reveals the environmental impacts associated with its product—even when those emissions are very high—it gains market share and the trust of consumers (Kalkanci et al., 2012). Indeed, of 57 prominent firms participating in the CDP's supply chain program, 73% cite brand improvement and 60% cite product differentiation as objectives for their climate strategy (Carbon Disclosure Project, 2011). Walmart took a leadership role in launching the Sustainability Consortium to develop industry standards for labeling consumer products with environmental impact information (including greenhouse gas emissions). Especially for Walmart's privately branded products, an eco-label indicating that a product performs as well or better than alternatives with prominent brands could boost sales. However, developing appropriate metrics and labels for the environmental impacts of consumer products and gathering the requisite data is difficult and contentious and will take time. Labels may eventually be used in only a limited number of product categories.

Conceivably, in future, Walmart or its suppliers or customers might be allowed to sell offset credits for emissions reductions that are measurable and additional (not profitable without the offset credit). Some critics of offset systems argue that emissions reduction and additionality are not measurable and verifiable. Conceivably, Walmart might be able to respond to those critics by holding up its promotion of CFLs as an example of a project for which emissions reduction and additionality could be measured and verified. The company has already obtained third-party verification of the emission reduction from the sale of CFLs, based on detailed sales data, the distance driven by Walmart customers, and the carbon-intensity of electricity generation in the vicinity of various Walmart stores. Perhaps Walmart's detailed sales, inventory, and cost data could also be used to verify additionality. Indeed, in promoting CFLs, Walmart gave up substantial profits on incandescent bulbs. In contrast, CFLs were more costly and difficult to source. Demand was uncertain (unlike that for incandescents) leading to stockouts. A caveat is that the determination of additionality and amount of reduction in emissions should perhaps account for customers purchasing more goods from Walmart due to their electricity-cost savings. That phenomenon is presumably difficult to measure and verify, and would tend to increase emissions and the profitability of the project for Walmart.

#### 2.1.3. Enhancing public relations

Before adopting its sustainability strategy in 2005, Walmart was entangled in controversy over employee wages, health care benefits, diversity, and working conditions in suppliers' factories. According to a study conducted by McKinsey and leaked to the public by the watchdog organization Walmart Watch, between 2% and 8% of consumers said they had stopped shopping at Walmart because of the company's practices (Plambeck and Denend, 2007a, 2007b). Moreover, the company was having difficulty gaining permission to open new stores in the U.S. According to Covalence, an organization that measures the ethical reputation of companies by quantifying their positive and negative news coverage, Walmart's reputation was negative and steadily declining; by 2007 it was in last place. In 2009, just 2 years later, Walmart's reputation was ranked third among 35 multinational retailers. The company is now the subject of more positive than negative coverage, thanks in large part to coverage about its activities to reduce greenhouse gas emissions. The positive public image may help the company to grow by weakening the resistance to its opening of new stores, and may help the company to attract more customers (or at least to avoid continuing to lose customers) at existing stores.

#### 2.1.4. Attracting and motivating employees and gaining voice with policy makers

A positive public image and the opportunity to do work that is good for the environment help Walmart and other companies motivate employees and attract talented new ones. Of the 57 prominent firms participating in the CDP's supply chain program, 47% cite improvements in employee motivation from emission reduction (Carbon Disclosure Project, 2011).

Firms recognized as leaders in environmental performance may also gain voice with policy makers. For example, Walmart executives have testified before congress on climate policy. The company has many other opportunities for emissions reduction which are not currently profitable but could become so under climate policy, as noted in Section 2.1.2 above; its leadership in environmental performance may enable it to promote climate policy that will be good for the company as well as the environment.

Walmart's own operations are now relatively efficient and, as mentioned above, account for only approximately 10% of its total supply chain greenhouse gas emissions. Therefore, to most profitably reduce greenhouse gas emissions, the company must pursue global supply chain optimization—i.e., influence its suppliers and customers to reduce their direct emissions. This is obviously more complicated than directing changes within Walmart's own operations, but the company has found ways to do this, as described below.

#### 2.1.5. Measuring emissions in the supply chain

A primary tenet of operations management (largely developed through the pioneering work of Taylor, Shewhart and Deming) is that *measurement leads to improvement*. Walmart now asks tier-1 suppliers to measure and report their corporate GHG emissions and their targets to reduce those emissions. According to Walmart executives, this simple request for information draws managerial attention and thus improves suppliers' environmental performance. It has also engaged academics to identify its product categories with highest associated emissions and the processes within the supply chain that generate most of those emissions. (Oshita (2011) and references therein show how to use input–output analysis to identify processes with highest associated emissions.)

Prior to its 2005 commitment to sustainability, Walmart interacted with tier-1 suppliers and rarely looked deeper into its supply chain. However, the company has learned that many of the highest-impact processes are far upstream in the supply chain. Indeed, approximately 85% of all industrial energy use occurs in basic material manufacturing (IPCC, 2007). To substantially reduce emissions, Walmart must engage with upstream suppliers or motivate its tier-1 suppliers to do so.

#### 2.1.6. Scrutinizing and rationalizing the supply chains

Just to identify upstream suppliers is a challenge. Walmart is working to identify the ingredients and suppliers' suppliers for all of its 6000 private brand products, and for other high-impact products. Fortuitously, for some high-impact products, third parties have developed chain-of-custody certification systems, which offer unprecedented insight into supply chain structure. For example, Walmart is obtaining detailed information about its supply chain for organic cotton apparel and organic food products from the third-party organizations that certify organic practices at each link in the supply chain, from farm to factory to store shelves. Chain-of-custody certification is intended to provide assurance to buyers that a product labeled organic is truly organic. A serendipitous benefit is that Walmart and other retailers now have unprecedented visibility into their entire supply chains for organic products.

By scrutinizing the entire supply chain, Walmart can identify opportunities to rationalize the supply chain to reduce costs and emissions. For example, in the past, cotton would be grown in Turkey, shipped to China for spinning and knitting, and then shipped to Guatemala to be cut and sewn. Seeing the cost and emissions associated with all that transport, Walmart intervened to eliminate the shipment to China and instead have all the processing done in Guatemala. That has saved both time and money, and reduced the greenhouse gas emissions associated with transportation. In supply chains for certified fish, Walmart intervened to eliminate brokers, so that fish now flow more directly from boats to Walmart stores. This has reduced emissions from transportation and energy use in freezer storage. It has improved quality and eliminated waste by avoiding the partial thawing and refreezing that commonly occurred when fish were transferred from one party to another. Eliminating margins for brokers may also have reduced the ultimate cost to Walmart.

#### 2.1.7. Making quantity and other commitments to motivate suppliers to reduce emissions

Historically, Walmart has had a reputation for squeezing its suppliers and for transacting with whoever offers the lowest price at any given time. A supplier that invests in process improvement or capital equipment to improve energy efficiency will see a reduction in variable production costs. If the supplier anticipates, however, that Walmart will negotiate a corresponding low purchase price which barely covers the production cost, the supplier is unlikely to make such investments. Similarly, a supplier has little incentive to develop innovative, energy-efficient products, without a guarantee that Walmart will purchase and promote those products. Therefore, to motivate suppliers to improve environmental performance, Walmart is beginning to make long-term purchasing commitments.

Walmart will typically commit to purchase a *larger quantity* over a longer period of time, as opposed to paying a higher price per unit. In addition to making explicit quantity commitments with some suppliers, Walmart is changing its overall procurement practices to shift quantity to suppliers with better environmental performance. For example, in its private-brands operations, the company uses information on emissions and emission–reduction efforts in allocating business among tier-1 suppliers. The company has also announced that it will, in certain product categories, seek long-term collaborative relationships with a smaller number of suppliers that pursue environmental innovation. The prospect of a winning a higher volume of business with Walmart is a strong motivator for suppliers to improve environmental performance.

Prior to 2005, Walmart would typically interact only with direct, tier-1 suppliers. However, environmental considerations have motivated the company to make quantity commitments to some high-impact suppliers further upstream. For example, after several failed attempts to purchase organic garments from tier-1 suppliers at reasonable rates by Walmart's standards, the company began in 2006 to engage directly with cotton farmers. Management verbally committed to buy cotton and co-products over a 5-year period if the farmers would pursue organic certification. (A farm must be free of non-organic pesticides and fertilizers for 3 years prior to the harvest of a certified-organic crop, and organic farmers must alternate the planting of cotton with nitrogen-fixing legumes and other crops to rejuvenate the soil. Demand for organic cotton is variable, so a farmer risks being forced to sell organic cotton at low prices, as conventional.) These quantity commitments would help to expand the supply of organic cotton to an economic scale for downstream manufacturing operations, and thus significantly reduce manufacturing costs.[2]

#### 2.1.8. Collaborating with third parties to support sound environmental practices among suppliers and customers

The success of Walmart's sustainability strategy stems largely from collaboration, not only with its suppliers but also with third parties with an interest and expertise in reducing greenhouse gas emissions. Starting in 2005, the company has invited environmental nonprofit organizations, academics, suppliers and other stakeholders to scrutinize the environmental impacts of its extended supply chain and offer suggestions for performance improvement. The Environmental Defense Fund and Business for Social Responsibility, for example, are working with 200 of Walmart's highest-impact suppliers in China to reduce their energy intensity by 20% by 2012 (relative to a 2007 baseline). These nonprofit organizations primarily provide information—helping suppliers to see how to improve energy efficiency.

A major barrier to the pursuit of profitable energy-efficiency projects is a shortage of sustainability professionals—i.e., people with the information and expertise necessary to undertake those projects—particularly in China. To address this problem, Adidas, GE, Nike, Timberland, Walmart and other multinational buyers are collaborating with the Chinese government and the Institute for Sustainable Communities, a U.S.-based nonprofit organization, to develop an academy for training 4000 sustainability professionals per year in Jiangsu and Guangdong (Plambeck et al., 2012).

Walmart is also beginning to collaborate with other multinational buyers to jointly motivate suppliers to improve performance. For example, in the apparel supply chain, substantial environmental impacts occur in the dying process, at tier 2 or tier 3 from the perspective of Walmart. Even dominant buyers such as Walmart, Nike, and Levi-Strauss typically account for only a small fraction of the business for a dye house. Therefore these firms and other multinational buyers are by necessity beginning to work together to motivate and assist their common suppliers to improve environmental performance (Plambeck et al., 2012) Walmart is also partnering with Unilever and other large multinationals to attempt to source "sustainable" palm oil and reduce the burning of peatland rainforest for conversion to palm plantations, which results in enormous $CO_2$ emissions.

Although this article focuses on climate change, humanity faces other environmental challenges that are of commensurate importance. Examples include the widespread use of toxic and persistent chemicals, water pollution and scarcity, and loss of biodiversity. Walmart is addressing many environmental challenges using the same approaches as described in this article for greenhouse gas emission reduction. More information about Walmart's environmental efforts is in Humes (2011) and Plambeck and Denend (2007a, 2007b, 2011).

Walmart's approaches to greenhouse gas emissions reduction are suited to its industry, its business model, and its size and influence. While other companies may be able to emulate some of its approaches, they are not the only ways to reduce GHG emissions, nor are they the best for all companies. Let is turn to a very different company in a very different industry and see how it has taken a different and creative approach to reduce emissions arising from the supply chain.

### 2.2. ZETA Communities: reducing emissions in the building industry by changing the product and reforming the supply chain

ZETA Communities is a start-up company in the building industry, which offers tremendous and largely untapped opportunities for profitable emissions reductions. Buildings account for half of U.S. energy use and associated $CO_2$ emissions (Randolph and Masters, 2008) and a similarly large fraction worldwide. Proven technologies could profitably eliminate 30% of $CO_2$ emissions from buildings worldwide by 2030, but are not being widely adopted (McKinsey and Company, 2009). Supply chain fragmentation and poor coordination limit the adoption of energy-efficient technologies and processes and invention of new ones. Work tends to be allocated based on low-cost competitive bidding for each functional component of a building project. As a result, a new team forms for each project—thereby interrupting the transfer to future projects the lessons learned—and each building component is designed largely in isolation (Sheffer and Levitt, 2010). In contrast, optimal energy efficiency requires integrated design. For example, using high-performance windows, doors and insulation to prevent heat loss can eliminate the need for expensive heating and cooling systems. The marginal benefit of thermal efficiency in one component of a building depends on the efficiency of all the other components (Randolph and Masters, 2008).

In a case study I co-authored in 2011 (Levitt et al., 2011), I found that ZETA Communities is, in fact, radically reducing GHG emissions by pioneering a business model that integrates architecture, engineering, green material procurement expertise, and the various functional construction specialties. They do this by producing buildings in their factory in Sacramento, CA, rather than on the customer's site. While other factory builders make only simple homes with minimal variation, essentially holding the design constant, ZETA produces a wide variety of residential, commercial, and educational buildings. It is able to do so because of its innovative, flexible production line, and the presence of an in-house architect and in-house building engineers who intimately understand that production line. ZETA's co-founders targeted factory construction (as opposed to on-site construction) in order to promote integrated design for energy efficiency. Whereas on-site construction is a sequential and adaptive

[2] In late 2010, Walmart ceased to make new long-term purchasing commitments to organic cotton farmers, and instead delegated that responsibility to its tier-1 cotton apparel suppliers. However, the company continued to make long-term commitments to motivate other suppliers to improve environmental performance, notably in its private brands business.

process, factory construction requires advance planning of every aspect of a building's design.

ZETA manufactures buildings that can generate (from solar photovoltaics) as much energy as they consume (Marshall, 2012), at a cost that is roughly 15% to 20% lower than with conventional on-site construction. With its advanced design and the highly accurate equipment housed in the factory, ZETA minimizes materials requirements. The factory also shields materials from rain damage and vandalism, and enables ZETA to sort, store and reuse scrap. Thus, even though the materials required for a highly energy-efficient building may be more costly than conventional materials, ZETA keeps overall material costs low by using less. Using less materials also reduces the emissions associated with manufacturing and transport of building materials.

Factory construction also enables the company to use less labor and pay lower wages. According to CEO Naomi Porat: "ZETA is about 15% lower priced [than traditional builders] in urban markets. Part of that differentiation is that any project that has public financing (city, state, or federal) requires prevailing union wages. Offsite construction is exempt from prevailing wages, which gives us an immediate 15 to 20% discount. But in addition to that, labor hours are just less." Advanced design, ergonomically optimized equipment, and in-factory coordination of the functional specialties maximizes labor productivity.

According to Porat, ZETA's factory approach requires less than half of the vehicle travel required to transport materials and equipment to a construction site, resulting in lower transport costs and roughly 70% fewer $CO_2$ emissions from transport. The company targets projects within a 300-mile radius of the factory in order to limit the costs and emissions associated with trucking the finished modules to a site.

ZETA is growing, despite the current severe downturn in the construction industry, by offering its green buildings at prices competitive with conventional ones.

In addition, factory construction enables ZETA to offer a short lead time and minimal neighborhood disruption. Compared with the many months of work that on-site construction demands, ZETA's manufacturing process takes just weeks, and can occur while the site is being prepared. (A potential disadvantage is that design, which must occur prior to manufacturing, takes longer. ZETA is developing IT systems to better learn and reuse design elements from prior projects, in order to shorten future design costs and lead times.) ZETA utilizes a crane to stack its modules into a finished building, and can do so on urban sites with zero lot lines. ZETA has a particular competitive advantage in urban infill construction, because it eliminates the neighborhood disturbance and health issues caused by the noise, dust, and vehicle emissions of on-site construction. Indeed, ZETA's founders aim to help rejuvenate cities and pull populations in from the suburbs, which would further reduce emissions from transportation.

Perhaps ZETA and similar entrants can overturn the conventional, emission-intensive building industry. However, ZETA's buildings will truly produce as much energy as they consume only if occupants behave in a responsible manner. ZETA has developed an IT system to monitor temperature, light, and electricity use in finished buildings, which should enable the company to provide feedback to building occupants and improve its design of future buildings. Like Walmart trying to motivate its customers to wash clothes in cold water, ZETA relies on behavioral change by consumers to achieve its goals for environmental performance.

### 2.3. Conclusions from company experiences

The companies considered in this article are leaders in pursuing greenhouse gas emission reduction. Their experiences suggest that other companies can profit *now* from taking steps to reduce emissions. However, the magnitude and pace of profitable emission reduction may be insufficient to address the threat of climate change. As population and consumption continue to grow, even if firms "do everything right" (i.e., reduce the carbon-intensity and energy-intensity of their operations to the maximum extent possible without competitive disadvantage) overall emissions are likely to remain high.

For example, between 2005 and 2010, Walmart improved the fuel efficiency of its fleet by 60% (Duke, 2010) and reduced GHG emissions from new stores by 30% and from existing stores by 5%. Nevertheless, the company's overall emissions increased, due to new store openings and other growth-related factors. In 2010, under great pressure from its environmental nonprofit partners, Walmart announced a goal to eliminate 20 million metric tons of $CO_2$ (or equivalent) from its global supply chain by the end of 2015. That is equal to one and a half times the expected growth in emissions from the global supply chain over the same 5-year period. Thus Walmart may slightly reduce its global supply chain emissions by 2015, relative to 2010. However, that is far lower than the approximately 80% overall emission reduction needed soon to avert dangerous climate change, and additional emissions reductions may be more costly and difficult, insofar as the "lowest hanging fruit" have already been harvested.

In our second example, whereas ZETA designs buildings to produce as much energy as they consume *after installation*, substantial energy use and emissions occur in manufacturing and transportation prior to installation. Such "embodied energy" could account for up to 20% of the life-cycle energy requirements of a conventional building (Randolph and Masters, 2008). This suggests that ZETA's business model may eliminate roughly 80% of the emissions associated with buildings. ZETA's business model does require additional energy for construction and operation of a factory. However, most of its supply chain emissions likely occur in the manufacturing of building materials, notably cement. The cement industry accounts for approximately 6% of anthropogenic greenhouse gas emissions. Another start-up, Calera, converts $CO_2$ emissions from a power plant into a substitute for cement, with overall net negative emissions of $CO_2$ to the atmosphere. However, in the absence of effective climate policy, I think that Calera is unlikely to substantially displace conventional cement production (Plambeck, 2011).

A second concern is that ZETA operates in Northern California, where air conditioning and heating requirements are minimal, photovoltaics are highly effective, and its initial customers are eager to participate in reducing energy consumption. In other regions, even with ZETA's innovative business model, making buildings that produce as much energy as they consume (after installation) may be prohibitively costly. Thirdly, emissions from the stock of existing buildings are likely to remain high for decades. Therefore, despite the substantial emission reductions achieved with ZETA's business model, I have difficulty imagining an 80% reduction in all emissions associated with buildings worldwide in the near future—without effective climate policy.

These examples suggest that policies that cause companies to internalize the social cost of carbon are needed to avert dangerous climate change.

## 3. Other opportunities to reduce greenhouse gas emissions: lessons from the academic literature

Surveys of the academic literature on "green" operations and supply chain management can be found in Corbett and Klassen (2006); Kleindorfer et al. (2005); Srivastava (2007); and Seuring and Müller (2008). However, remarkably few of the papers they survey focus explicitly on energy or greenhouse gas emissions. Some of the most fundamental papers in operations management, on the other hand, have important implications for energy use and greenhouse gas emissions. In the following sections, I will draw out some of those implications. Then I will survey the nascent literature in operations management that explicitly addresses greenhouse gas emissions.

### 3.1. The bullwhip effect: avoiding energy inefficiencies from variability in demand

In arguably the most influential paper in the field of operations management, Lee et al. (1997) explain how small fluctuations in consumer demand translate into increasingly large fluctuations in demand for upstream manufacturers. This amplification of variability in demand throughout a supply chain, known as the "bullwhip effect," can lead to excessive greenhouse gas emissions, particularly in basic material manufacturing.

The bullwhip effect arises when a retailer interprets a surge in consumer demand as a signal of high future demand, which in turn causes the retailer to increase its order to the manufacturer by more than the surge in consumer demand. Similarly, a drop in consumer demand may cause the retailer not to order at all. Thus, variation in consumer demand is amplified in the retailer's orders to the manufacturer. The amplification is greater to the extent that consumer demand is positively correlated over time, when transportation and other fixed costs associated with placing an order are high, or when the order-fulfillment lead time is long.

For similar reasons, Lee et al. argue that the manufacturer's orders to a component supplier will be even more variable than its demand from the retailer, and the component supplier's orders to its material supplier will be yet more variable. Thus, variability in demand will be maximized upstream, at the level of raw material extraction and fabrication.

On the contrary, manufacturers typically have limited capacity and incur fixed costs associated with starting and stopping production, so they should ideally smooth production over time (i.e., produce at a constant rate). To meet variable demand while maintaining a constant (or nearly so) production rate, a firm must hold inventory. Production smoothing would tend to make a firm's orders to suppliers less variable than its own demand, in opposition to the bullwhip effect.

Empirically, economists have observed that production and orders are more variable than demand in most industries (see the survey in Blinder and Maccini (1991)). Most of those early studies relied on seasonally adjusted data, and therefore failed to account for the production smoothing that optimally occurs in response to predictable, seasonal variation in demand (Cachon et al., 2007; Chen and Lee, 2011; Ghali, 1987). Nevertheless, even with data *not* adjusted for seasonality, Cachon et al. (2007) find that in wholesale industries and many manufacturing industries (though not retail industries), aggregate orders and production are more variable than aggregate sales. In particular, wholesalers of chemicals, petroleum products, and construction materials including cement, as well as manufacturers of primary metals, fabricated metals, petroleum products, and paper, exhibit greater industry-level variance in orders and production than variance in demand.

Using firm-level data for 4689 public U.S. companies in a variety of industries, Bray and Mendelson (2012) find that a majority of the firms have greater variance in production and orders than in demand. The mean percentage increase in the variance of production relative to the variance of demand is remarkably high in the energy-intensive chemicals (15%), pulp and paper (11%), primary metal (30%) and fabricated metal (17%) manufacturing industries. Bray and Mendelson separate the variation into a seasonal, predictable component and uncertain component, and observe that firms tend to smooth production in response to seasonal variations but that they amplify uncertainty. Last-minute shocks in demand, in particular, are amplified in the corresponding variation in production and orders, in 97% of their sample. In related theoretical work, Chen and Lee (2011) show how demand information is distorted through supply chains, amplifying uncertainty and causing inefficiency and excess costs in upstream production.

The bullwhip effect has dramatic implications for energy use and greenhouse gas emissions because over a quarter of global energy use, and approximately 85% of all energy use in manufacturing, occurs in the manufacturing of basic materials: metals, chemicals, fertilizers, paper, minerals, cement and petroleum products (IPCC, 2007). Basic material manufacturing is farthest upstream in the supply chain and presumably therefore subjected to the maximum bullwhip amplification of variability and uncertainty in demand. Basic material manufacturers would ideally have a smooth and predictable production schedule to minimize energy use. Demand variability and uncertainty drives variability and inefficiency in production, and hence will tend to increase greenhouse gas emissions, though empirical research is needed to quantify the magnitude of the increase in emissions associated with an increase in variability in production, particularly in energy-intensive basic material industries.

The bullwhip effect likely also exacerbates emissions from freight transport, which accounts for approximately 8% of energy-related $CO_2$ emissions (IPCC, 2007; McKinnon, 2008; Schipper et al., 2011). The reason is that an unanticipated spike in demand often causes a manufacturer to expedite shipment of input materials from suppliers, using a more rapid, emission-intensive form of transportation (e.g., air rather than container shipping) and/or a partially loaded vehicle.

Lee et al. (1997) suggest several remedies for the bullwhip effect. Some will reduce emissions, but others might increase them. The first remedy is to share real-time information about inventory levels and end consumer demand data throughout the supply chain. The second is to reduce transportation lead times. A third is to order in smaller quantities, more frequently.

Having detailed, real-time information about downstream inventory levels and consumer demand, as recommended by Lee et al. (1997), would enable manufacturers to better forecast demand for their intermediate products, and thus better smooth their production and orders to suppliers. Reducing the uncertainty and variability in demand throughout the supply chain would increase efficiency and reduce emissions in production. It would also enable firms to plan transportation in advance and therefore use slower, less emission-intensive modes of transport (Caro et al., 2011). Unfortunately, despite the potential to increase profitability and reduce emissions throughout the supply chain, many retailers do not yet share point-of-sale data with their suppliers (Cooke, 2011).

Some of Lee et al.'s (1997) other remedies for the bullwhip effect—reducing transportation lead times and ordering in smaller quantities, more frequently—might *backfire* by increasing greenhouse gas emissions from transport. Increasing the speed of a container ship by 25%, for example, increases energy intensity and hence emissions by approximately 40% (IEA, 2011, Table 8.7). Transporting goods by airplane rather than container ship increases energy intensity by a factor of 10 to 100, depending on physical and operational characteristics of the airplane and ship (Gucwa and Schafer, 2011).

In an empirical analysis of the energy intensity of major freight transportation modes, Gucwa and Schafer (2011) find that most of the variation in energy intensity within a transportation mode is explained by load carried per vehicle and vehicle size. The key variable affecting energy efficiency for ships, trucks, and rail (and the second most important factor for air, behind stage length) is the amount of cargo transported per vehicle: energy efficiency increases as that load increases. It also increases with the size of a truck, ship, or airplane, or the number of cars per train (holding the carried load, as a percentage of vehicle capacity, constant). This suggests that just-in-time operations management (narrowly defined as ordering more frequently, in smaller quantities) will increase emissions, unless firms can batch multiple types of products or components for transport to achieve large shipment sizes and full vehicles.

Third-party logistics providers, highlighted by (Lee et al., 1997), achieve fuller loads and can potentially use larger vehicles, by pooling shipments from multiple firms. Hence by using third-party logistics providers, firms may be able order more frequently in smaller quantities (to mitigate the bullwhip effect) while reducing the costs and emissions associated with transport.

In the famous Toyota production system, just-in-time operations management is facilitated by having suppliers located nearby a production facility. Workers strive to immediately identify quality problems and eliminate waste, which is synergistic with the just-in-time operations and supplier proximity. Eliminating waste and designing products to require less material (exemplified by ZETA as well as Toyota) can reduce emissions from material manufacturing and transport; effective practices for eliminating waste are described in Lapre et al. (2000); Lee (forthcoming) and references therein. A caveat is that when a firm converts waste into product, it is motivated to increase production, which tends to increase its emissions (Lee, forthcoming).

### *3.2. Global optimization of supply chains: incorporating the cost of emissions*

As discussed in the case of Walmart in Section 2, reducing global emissions from supply chains in the most cost-effective manner requires a global optimization perspective. Graves and Willems (2005) provide a method for designing a multi-stage supply chain which optimizes transport modes, production facilities, processes, and materials to minimize the total cost of meeting demand from multiple regions within a target maximum service time. The method could easily incorporate a cost associated with greenhouse gas emissions to suggest how best to reconfigure global supply chains to account for climate concerns.

Graves and Willems (2005) observe that the benefits from applying their method to optimize the supply chain increase with longer transportation lead times and with variability in demands. Hence their method could be highly valuable as climate concerns motivate a change from rapid, emission-intensive modes of transport (air or truck) to ones that are slower and less emission-intensive (ship or rail). It could also be highly valuable for designing new supply chains for “zero”-emission[3] sources of energy, such as photovoltaics or wind. Variability and uncertainty in demand are particularly high in supply chains for renewables due in large part to uncertainty and lack of continuity in government policy and incentives. For example, a lapse in the U.S. federal production tax credit caused wind power installations to drop by more than 70%, relative to prior years, in 2000, 2002, and again in 2004 (Wiser et al., 2007).

According to Porter and Rivkin (2012), firms may off-shore production because they overlook complex, dynamic factors that are difficult to model (e.g. corruption, lack of intellectual property protection, and rising labor costs in emerging economies, shortening product life cycles, and rising transport costs). One could add the bullwhip effect to their list of factors. Careful consideration of those factors would favor local production and reduce emissions associated with transport.

### *3.3. Demand pooling: debunking conventional wisdom about the environmental friendliness of local production*

Conventional wisdom suggests that local production is best for the environment, but this conventional wisdom is not always correct. Building many local production facilities tends to increase the aggregate emissions from construction. Moreover, to meet variable local demand, local facilities need to have excess production capacity and/or hold substantial inventories of finished goods. Facilities incur fixed emissions (e.g., to keep the lights on) even when underutilized. Emissions also occur in warehousing inventory, especially at a controlled temperature.

A fundamental concept in operations and supply chain management is that *demand pooling*—for example, by having a single production facility serve multiple geographical regions—helps smooth production and reduce inventory requirements. Negative correlation in demands from various locales reduces the variance in aggregate demand and makes pooling more beneficial. When a spike in demand in one region is balanced by a drop in demand elsewhere, pooling allows the firm to meet aggregate demand with a constant rate of production. Hence it need not build excess production capacity or a “safety stock” of inventory. Van Mieghem (2007) provides an entry point to the extensive literature on pooling.

Advocates might counter that local production reduces the emissions associated with transportation. However, even that might be false. Transport by light commercial truck could increase energy intensity in MJ/tkm by a factor of 100 compared to transport by container ship, and by a factor of 50 compared to transport by rail (Gucwa and Schafer, 2011). Hence transport by truck from local production facilities to consumers might result in higher aggregate transport emissions than transport by ship and/or rail from a single production facility, even if trucks must be used for the “last mile” of distribution.

Production at a single facility might facilitate large shipments, particularly if that facility is located in an industrial center, so that multiple products from that center can be transported together to the regions of demand. As shown by Gucwa and Schafer (2011) and discussed above, such large shipments can dramatically reduce energy-intensity.

Finally, pooling production at a single facility may increase energy efficiency through scale. Energy efficiency commonly improves with scale in basic material manufacturing industries. As mentioned above, basic material manufacturing industries account for 85% of all industrial energy use.

### *3.4. Motivating suppliers to build capacity: creating supply chains for “zero”-emission energy sources and other products*

A fundamental issue in supply chain management is to ensure that suppliers have adequate capacity. This is particularly difficult in nascent supply chains for “zero”-emission sources of energy and other “cleantech” products, because demand is potentially large but uncertain; reputations, relationships, and sources of capital are not yet established; and contracts may be difficult to enter and even more difficult to enforce.

Successful new entrants in “cleantech” manufacturing often rely for material supply on the waste, by-products or excess capacity of existing industries. For example, as described in Plambeck (2011), Calera uses industrial waste streams of $CO_2$ and CaCl to make cement. Tesla Motors builds the batteries for electric vehicles out of the tiny, form factor 18650 lithium ion batteries commonly used in the electronics industry. Solar photovoltaic manufacturers have historically relied on the scrap and excess production of crystalline silicon in the supply chain for semiconductors and electronics.

To grow, however, cleantech manufacturers eventually need to motivate suppliers to build new capacity. One approach is to contract for minimum purchase quantities, at specified prices, over a long period of time. Solar photovoltaic manufacturer First Solar used this sort of contract to motivate its supplier to build a new facility to recycle its critical semiconductor material, adjacent to First Solar's own production facility in Germany. The contract also stipulated that First Solar could buy the supplier's new facility at a specified price if the supplier were to default on the specified timing, minimum quantity, or quality. First Solar is continuing to make the contractually-specified purchases, even though the company has closed its own German production facility due to drastic cuts in government subsidies for solar in the EU (Plambeck, 2011). In general, however, unforeseen contingencies may result in costly disputes and difficulties with contract enforcement, especially in a new sourcing relationship or as a supplier is developing an innovative or complex process (Tirole, 1999).

[3] Although wind turbines and photovoltaics generate electricity without producing greenhouse gas emissions, significant emissions occur in their manufacturing, notably in the production of steel and of polycrystalline silicon.

These impediments to contracting are exacerbated in jurisdictions with weak court systems— e.g., China as opposed to Germany (Master and Tung, 2010; Peerenboom, 2002).

Rather than rely on the courts to enforce a contract, firms may adopt a *relational contract*—an informal agreement regarding actions and payments, enforced by reputational concerns between parties that interact repeatedly (Baker et al., 2002). The optimal structure of a relational contract is different from that of a court-enforced contract. For example, when demand for the manufacturer's product is uncertain and the supplier's capacity is costly, a court-enforced contract would specify a minimum quantity and the unit price, whereas a relational contract would specify only the unit price; the reason is that the manufacturer would renege on a relational quantity commitment when realized demand is low (Taylor and Plambeck, 2007b).

In order to sustain effective relational contracts, firms may need sophisticated information systems or to consolidate business with a single supplier. Information systems that allow both manufacturer and supplier to commonly observe detailed process data play a critical role in sustaining relational contracts, by enabling the firms to determine which party is at fault when quality problems arise. For example, in fermentation of biomass into pharmaceuticals, fuels, or specialty chemicals, detailed information about the maintenance schedule and process variables like temperature, Ph, and feed rate may help to determine whether the manufacturer or feedstock supplier is responsible for a microbial contamination problem that reduces the process yield (Plambeck and Taylor, 2006). Consolidating business with a single supplier also helps to sustain a relational contract. As in the example of Walmart discussed in Section 2, consolidating business with a single supplier is a form of quantity commitment that helps to motivate a supplier to make investments to better serve the buyer. It increases the future value of the relationship to the buyer and to the supplier, which increases the motivation to adhere to the terms of the relational contract.

Sociologists and organizational scholars point out that trust and collaboration between a manufacturer and supplier take time to develop, and they emphasize the importance of personal relationships, social sanctions (Granovetter, 1985; Powell;, 1990; Uzzi, 1996, 1997), and institutional routines for reciprocity in sustaining agreements between trading partners (Powell et al., 1996; Zaheer et al., 1998). Locating a new production facility in proximity to a material supplier may help to build a constructive relationship. For example, First Solar chose to site its first commercial production facility adjacent to glass manufacturers in Perrysburg, Ohio. Despite its initially small purchase volume and uncertain potential for growth, First Solar was thus able to motivate those glass manufacturers to design and produce highly transparent glass for photovoltaics, instead of focusing on their large existing business with automotive and building glass customers. An innovative firm that transforms sugar into fuels, fragrances, and specialty chemicals, Amyris built its first commercial production facility adjacent to a sugar cane mill in Brazil, in a joint venture with the mill operator, which provides capital and a reliable supply of sugar (Plambeck, 2011).

An alternative or complement to a relational contract is *capacity leadership*, in which a manufacturer expands its own capacity earlier than needed and thus motivates suppliers to build more complementary capacity. Capacity expansion by a manufacturer is a credible signal of rising demand and will enable a supplier to negotiate a higher price for its future output, both of which tend to motivate a supplier to build more capacity (Islegen and Plambeck, 2009). Having already built its own capacity, a manufacturer will have less incentive to renege on a relational contract that promises a high price and/or minimum order quantity from the supplier. Thus, capacity leadership may enable the manufacturer to offer a credible relational contract with more generous terms for the supplier, and thus induce higher capacity investment. Anecdotal evidence of capacity leadership by solar photovoltaic and wind turbine manufacturers is in Islegen and Plambeck (2009).

An impediment to using capacity leadership or a relational contract to spur capacity expansion by a supplier is the threat of bankruptcy. Indeed, for a manufacturing firm to survive, its suppliers, capital providers and customers must all believe that it will do so. A manufacturer's risk of bankruptcy reduces the future expected value of a collaborative relationship between a manufacturer and supplier, which reduces the amount of complementary capacity that a supplier will build under a relational contract (Taylor and Plambeck, 2007a). Risk of bankruptcy increases the cost of capital for capacity expansion (Boyabatli and Toktay, 2011). Risk of bankruptcy reduces customers' willingness to pay for products because in bankruptcy, a manufacturer may fail to meet its warrantee, service, and recycling commitments to customers (Hortacsu et al., 2011). In a positive equilibrium, capital providers give money, suppliers build capacity, and customers buy the product. In exactly the same business environment, however, a negative equilibrium could arise in which those parties doubt the viability of the manufacturing firm, and bankruptcy becomes a self-fulfilling prophecy (Hortacsu et al., 2011).

Hortascu et al. suggest that the existence of multiple equilibria justifies government intervention to improve social welfare by stepping in and guaranteeing warrantees or providing capital to promote a favorable equilibrium. However, a government loan (or private debt financing) for capacity expansion may cause a firm to under-invest in process improvement, which increases the risk of bankruptcy (Plambeck and Taylor, 2012).

### *3.5. Literature on operations and supply chain management that explicitly addresses climate change*

This section reviews the nascent academic literature from the field of operations and supply chain management that explicitly addresses climate change. The number of papers is small—much research remains to be done. A few begin to quantify the potential for climate change to disrupt manufacturing and supply chain operations management. Most address the extent to which a tax (or alternative mechanism that causes firms to internalize some of the social costs of their greenhouse gas emissions) will reduce emissions by motivating changes in manufacturing and supply chain operations management. Their results are mixed, suggesting that firms will change some aspects of their operations in response to even a small carbon tax, but will not change others that seem to be obvious candidates for emission reduction.

According to Chen et al. (2011), imposing even a small tax on greenhouse gas emissions will motivate changes in procurement, inventory management, and the size and location of production facilities that significantly reduce emissions. They consider three classic models of operations management. First, in the "economic order quantity" model, a firm has a constant rate of demand and chooses an order quantity and frequency. Its objective is to minimize the average cost rate, including a fixed cost per order, a cost per unit ordered, and a holding cost per unit inventory per unit time. In the second, "newsvendor" model, a firm chooses a quantity (which may represent manufacturing capacity or an inventory level) to meet uncertain demand. The objective is to minimize expected cost, assuming a constant per unit cost for both overage (when the chosen quantity exceeds demand) and underage (when demand exceeds the chosen quantity). In the third, "facility location" model, the firm chooses the number of production facilities to serve demands that are uniformly distributed over some geographical region. The firm incurs a fixed cost to open a production facility, and a transport cost per unit of product per unit distance from the nearest facility to the demand. In all three models, the objective function (cost) is remarkably flat for a wide range of the decision variables around the optimal solution. However, emissions are sensitive to the decision variable, which implies that emissions can be substantially reduced at little cost. Hence even a small carbon tax should substantially reduce emissions associated with such operations.

One might think that imposing a high carbon tax would motivate a retailer to have many small stores, rather than a few large outlets, to enable people to shop without driving a long distance. However, according to Cachon (2011), the optimal number of stores in a given area is insensitive to a carbon tax. In Cachon's model, a retailer chooses the number of stores in a given area to minimize its cost of trucking items to the stores (which increases with the number of stores) plus the cost to consumers of driving to the nearest store (which decreases with the number of stores). Cachon proves that if the retailer assigns zero cost to emissions, the resulting social cost (all the costs associated with the retailer's trucking, the consumers driving, and the climate change impacts caused by their emissions) will be less than 0.1% above the socially optimal level, assuming U.S. average fuel efficiencies. Furthermore, a carbon tax could motivate the retailer to reduce emissions by improving the fuel efficiency of its trucks, but that would have surprisingly little effect on the retailer's optimal number of stores. A caveat is that Cachon (2011) does not consider the potential for online retailing. The impact of online retailing on emissions depends on details of implementation, such as management of returns (Matthews et al., 2001).

Hoen et al. (2011a) argue that a small tax on emissions will fail to motivate most firms to shift to a slower, more energy-efficient mode of freight transport. The drawback is that using a slower mode of transport forces firms to carry more inventory and degrades their service to customers. Hoen et al. use the emission-intensity estimates of the European Network for Transport and the Environment for various modes of transport and assume that emissions from storage are negligible. For a variety of different products, they find that a tax above 30 Euros/tonne $CO_{2e}$ would be necessary to motivate a shift to a more efficient mode of transport. Some firms might, however, shift at a lower tax level. Hoen et al. (2011b) provide one example of a major European manufacturing firm that could, by switching modes, reduce its emissions from transportation by 10% with only an 0.7% increase in transportation and inventory costs.

A carbon tax might have the counterintuitive effect of reducing energy-efficiency in manufacturing. In a stylized model of a manufacturer of a commodity basic material, Plambeck and Taylor (2012) show that when the manufacturer has thin margins, the expected increase in expected profit from an improvement in energy efficiency *decreases* with the carbon tax. The intuition is that as the tax increases, the manufacturer becomes more likely to idle its facility (because the contribution margin is negative) so any investment and effort sunk into improving energy efficiency becomes worthless. Variability in the cost of emissions (as in a cap-and-trade system) further reduces the incentive to improve energy efficiency. This suggests that to substantially improve the emission-intensity of basic material manufacturing, a carbon tax must be set sufficiently high to spur investment in new “cleantech” facilities that rely on renewable energy or carbon-capture-and-sequestration (as in the example of Calera given in Section 2.3) to produce basic materials with minimal emissions.

A tax might also fail to spur investments in energy efficiency if firms lack information about the potential for energy efficiency, lack capital, or face agency problems of the sort described in Section 2.1.5. Anderson and Newell (2004) find empirically that U.S. manufacturers commonly fail to make investments in energy efficiency that would have a positive net present value at market interest rates. The authors draw upon data from the U.S. Department of Energy's Industrial Assessment Center (IAC) program, which provides energy-efficiency assessments and recommendations to small and medium-sized manufacturing firms, primarily regarding operational process improvements. Roughly half of the projects are adopted, which suggests that providing information spurs energy-efficiency. (This mirrors the case, described in Section 2.1.7, of Walmart engaging environmental nonprofit organizations to help its suppliers in China to identify and implement energy-saving process improvements.) However, as the manufacturers tend not to adopt projects with a payback period greater than a year or in some cases 2 years (implying a hurdle rate of 50%–100%), the primary barrier to adoption might be capital constraints, agency problems of the sort described in Section 2.1.5 or managerial error. Using the same IAC data, Muthulingam et al. (forthcoming) observe that adoption rates are higher for the energy-saving projects that appear early in the list of recommendations, regardless of their financial characteristics.

Fortunately, small manufacturers often have supply chain partners with a lower cost of capital and motivation to reduce their supply chain carbon footprint. Those partners can design long-term contracts and provide capital or technical assistance to spur the small manufacturers to invest in energy-efficiency projects, and then share in the resulting long-term increase in profitability. A carbon tax would lead to more of such engagement. Even without climate policy, as seen in Section 2.1.6, the recent experience of Walmart suggests that even simply asking suppliers to share information about their greenhouse gas emissions and efforts to reduce those emissions draws managerial attention and thus improves performance. Empirically, suppliers are more likely to agree to share such information when more of their buyers request such information and when those buyers appear committed to using the information (Jira and Toffel, 2011).

As an example of using the information, in Walmart's private brands operations, the scorecard for suppliers gives points for transparency and management of greenhouse gas emissions, in addition to traditional considerations like financial performance, quality, and on-time delivery; the scorecard is used to allocate business, as well as to determine which suppliers could benefit from assistance (Plambeck and Denend, 2011). Jira and Toffel (2011) survey the literature on how firms motivate their suppliers to adopt specific practices intended to improve labor conditions or environmental performance. Firms should proceed gradually and cautiously, however, because increasing auditing and payments for labor and environmental performance can backfire by motivating suppliers to practice deception rather than improve performance (Jiang, 2009; Plambeck et al., 2012; Plambeck et al., 2011).

If one country or region unilaterally adopts climate policy, the corresponding increase in production costs may cause manufacturers to relocate to a region without such policy. Hence, perversely, the climate policy might increase overall greenhouse gas emissions, due to increased freight transport and higher emission-intensity of production in the region with no climate policy. Drake (2011) finds that a border adjustment—taxing imports in proportion to the greenhouse gas emissions that occur in their production to “level the playing field” for domestic and foreign manufacturers—will reduce overall emissions. Furthermore, the volume of imports may increase with the level of the tax because foreign firms adopt the low-emission technology at a lower tax level than do domestic firms.

To implement a border adjustment will require the development of rules for accounting for the supply chain emissions associated with a product. One issue is how to allocate emissions from a production facility among the various products (or industrial buyers of products) of that facility. Current accounting schemes allow buyers the flexibility to choose from among several allocation rules. Emissions may be allocated in proportion to the economic value of the products or in proportion to their masses, for example. This has some surprising effects on emissions. Keskin and Plambeck (2011) show that value-based allocation provides an incentive for a supplier to cut its price on products that are subject to a border adjustment, in order to reduce the effective tax on those products and sell more units. As a result, production and hence total emissions may *increase* with the level of the tax per unit $CO_{2e}$. For similar reasons, eliminating a buyer's flexibility to choose an allocation rule also may strictly increase imports and total emissions—unless policymakers specify the allocation rule correctly. Requiring firms to use the rule that allocates the most emissions to the subset of products that are exported into a region with a border adjustment may, counterintuitively, fail to minimize total emissions. Keskin and Plambeck advocate specifying an allocation rule for each industry, and suggest how to choose it. In the example of the energy-intensive mining and separation of rare earth oxides (which yields iron ore as a co-product), correct specification of the allocation rule may reduce total emissions by over a third, even at plausibly low levels of a carbon tax.

To date, schemes proposed to account for supply chain emissions have the axiomatic property that the sum of emissions allocated to the firms in a supply chain must equal the total emissions from the supply chain. Instead, Caro et al. (2011) advocate double-counting. For a seemingly ideal scenario in which a supply chain bears the full social cost associated with its greenhouse gas emissions, Caro et al. prove that the firms in the supply chain invest strictly less in emissions reduction than would be socially optimal (assuming the firms cannot contract to make payments contingent on emissions reduction). The reason for underinvestment is that optimal emissions reduction requires cooperative actions by multiple members of the supply chain (as in the example of retailers sharing point-of-sales data, to enable suppliers to better forecast demand and therefore use slower modes of transport with lower emission-intensity, described in Section 3.1) and therefore suffers from the classic problem of moral hazard in teams (Holmstrom, 1982). Currently, the underinvestment is worse because supply chains do not bear the full social cost associated with their greenhouse gas emissions. Caro et al. point out that this makes double-counting of emissions, to increase the incentive for emissions reduction, even more important.

Adverse weather disrupts supply chains. In a survey of supply chain managers in 559 companies, 14 different industries and 62 countries, weather was the most commonly cited reason for a supply chain disruption in 2011 (CSCMP, 2011). Based on a decade of production data for 64 U.S. automobile plants, Cachon et al. (2011) find that extreme weather is associated with substantial losses in productivity. Climate change is likely to worsen losses in manufacturing productivity due to extreme heat and heavy precipitation, at least in some regions. Inland, climate change might reduce wind speeds (Pryor et al., 2009) and thus benefit manufacturing. In vulnerable coastal areas, climate change might increase the frequency of the severe tropical cyclones, which would disrupt production and freight transport through airports and seaports, and/or require substantial adaptation. For example, Esteban et al. (2010) estimate a cost of between Y 31 billion and Y 128 billion to increase the capacity of Japanese sea ports to make up for the downtime (days on which the ports cannot operate) caused by the increases in tropical cyclone intensities by 2085 under plausible climate change scenarios. Even with such expansion of transportation infrastructure, the potential for disruption associated with climate change may cause companies to require more manufacturing capacity and inventory. Expanding inventories and the capacity of manufacturing facilities, sea ports and other transportation infrastructure will increase emissions unless, perhaps, it provides an opportunity for carbon sequestration in cement.

## 4. Conclusion

This article has provided examples of how companies can profitably reduce greenhouse gas emissions under their direct and indirect control. It also directs readers to operations and supply chain management literature that provides insights on additional means for companies to reduce greenhouse gas emissions and to establish new supply chains for renewable energy and other "zero"-emission products, and potential impacts of climate change on supply chains. By acting immediately to reduce greenhouse gas emissions, companies can lessen the impacts of climate change. However, the magnitude of profitable emissions reduction seems likely to be insufficient. I conclude that effective climate policy is needed to spur transformative supply chain coordination and innovation.

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