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Energy Supply Chains and Change

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Abstract

The energy sector's critical importance to the economy and national security on the one hand and its association with potential environmental impacts on the other subject it to competing and sometimes oscillating forces in policymaking and corporate decision-making that can affect both supply and demand. As such, energy supply chains need to be resilient in order to meet the economy's dynamic demand for energy services, adapt to policy actions, respond effectively to natural and manmade disasters, foster transitions to emergent technologies, and serve long-lived infrastructure. This paper presents a framework that guides systematic analysis of energy supply chains subject to ongoing change. While the framework is qualitative, it is strengthened by quantitative data. A case study of the utility-scale gas turbine supply chain illustrates the framework.

Keywords: critical infrastructure, energy, energy policy, supply chain, gas turbine

Introduction

Energy resource and technology supply chains (herein called "energy supply chains"[1]) directly comprise a small fraction of a nation's gross domestic product. However, they are foundational for the broader economy, societal welfare, security, and the environment. These supply chains produce energy technologies that power farm equipment for modern-day agriculture; factories producing food and goods; utilities providing drinking water, lighting, and temperature control essential to shelter and health; mobility for safety and commerce; and information tech-

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[1] Abbreviations used in this article: CT = combustion turbine; CCGT = combined-cycle gas turbine; DHS = US Department of Homeland Security; EIA = Energy Information Administration; GE = General Electric; MHI = Mitsubishi Heavy Industries; MHPS = Mitsubishi Hitachi Power Systems; NG = natural gas; OEM = original equipment manufacturer; PPIFUA = Power Plant and Industrial Fuel Use Act; R&D = research and development.

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nologies fostering communication and economic growth. As such, energy supply chains are critically important to the economies and national security postures of both developed and developing countries. Not only is energy infrastructure considered a "critical infrastructure sector," it also underlies a number of other critical infrastructure sectors, ranging from water and wastewater to transportation to communications to critical manufacturing (DHS n.d.).

The energy sector's importance to the economy and national security on the one hand and its association with potential environmental impacts on the other subject it to competing and sometimes oscillating forces in policymaking and corporate decision-making that can affect both its supply and demand (Nyman 2018, 118-145; Wirth, Gray, and Podesta 2003, 132-155). Because of their importance, energy supply chains need to be resilient in order to meet an economy's dynamic demand for energy services, adapt to policy actions, respond effectively to natural and manmade disasters, foster transitions to emergent technologies, and serve long-lived infrastructure (Araújo 2014, 112-121). The large number of forces and responses at different spatial scales over different time horizons can be difficult to untangle. Nevertheless, obtaining a deep understanding of the dynamic forces and responses is valuable because energy supply chains are so important across society and are sensitive to the broader context.

While there are many studies that address supply chains, studies focused on supply chain dynamics that comprehensively consider the conflicting forces and complexity affecting energy technology markets are sparse. Published studies of energy supply chains commonly focus on the production, processing, and delivery of fuels, such as NG, petroleum, and biofuels. Many of these studies address the important issues of energy security and resilience (Månsson, Johansson, and Nilsson 2014, 1-14; Urciuoli et al. 2014, 46-63; Winzer 2012, 26-48; Yergin 2006, 69-82). Energy supply chains, however, also include those that produce, deliver, and maintain technologies that generate and transmit electricity (e.g., nuclear reactors, wind turbines) and use energy (e.g., industrial motors, lighting, and vehicle power-trains). The concepts of industrial dynamics (Bonaccorsi and Giuri 2000, 847-870, 2001, 1053-1083; Jacobsson and Bergek 2004, 815-849; Klepper 1997, 147-182), innovation (Gravier and Swartz 2009, 87-102; Lee and Lee 2013, 415-432; Malerba 2007, 675-699), and sociotechnical transitions (Geels 2010, 495-510; Markard, Raven, and Truffer 2012, 955-067; Smith and Stirling 2010) are important for studying change in these supply chains. In fact, developing a rich understanding of the effect of change on energy supply chains requires consideration of all of these concepts.

We present a framework that guides systematic conceptual analysis of energy supply chains subject to ongoing change. While the framework is qualitative, it is strengthened by quantitative data. The framework guides the analyst in identifying and assessing change experienced by the supply chain.

Methods—Framework

In the framework, shown in Figure 1, change vectors—including industrial dynamics, policy, innovation, and resources—lead to changes in market conditions in which the energy supply chain operates. These changes include demand growth and shrinkage, technology shift, resource undersupply, and supply disruption. In turn, these market condition changes lead the supply chain to respond—in various ways and across time frames—to meet demand for its energy products. The supply chain's characteristics are likewise dynamic and affected by change vectors, changing market conditions, and how the supply chain responds to change.

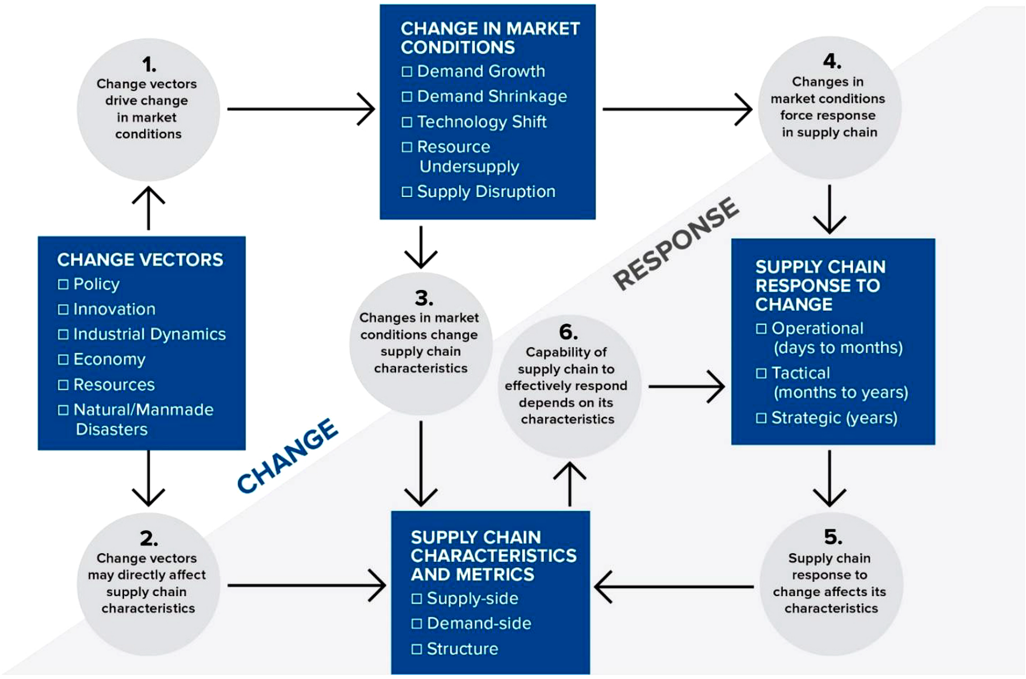


Figure 1. Framework for envisioning change in energy supply chains

The framework also describes how supply chains respond to change. Understanding how the network of companies that manufacture energy technologies can deploy their resources to respond to changes and meet demand is important. Focusing attention on the supply chains, however, can be constrained by a lack of visibility of their capacity to meet demand under changing conditions. The framework presented here is a structured conceptual approach that takes advantage of available data to assess plausible supply chain responses to forces of change, where:

1. Supply chains need to respond to change in different time frames: operational, tactical, and strategic.

2. Their capacity to respond, in turn, is dependent on their intrinsic supply-side, demand-side, and structure characteristics and associated metrics (Wagner and Neshat 2010).

The operational, tactical, and strategic time frames are related to the length of time in which an effective supply chain response can be implemented and the complexity of the required response. Regarding the latter, the strategic time frame is distinguished from the tactical time frame by the complexity and innovation required of the response. For example, adjusting inventories can be achieved in an operational time frame (days to months) to resolve a temporary shortfall in supply. If the supply shortfall extends to months or years, tactical or strategic responses are necessary: tactical if adding supply capacity is feasible, strategic if novel changes in the product design and its manufacture are required.

The "characteristics" considered in the framework describe different aspects of the supply chain, including those that pertain to the production chain (supply-side), the product technology and end-use market (demand-side), and the types and organization of firms (structure). "Metrics" are observable, measurable, and useful for quantitatively or comparatively assessing their associated characteristics. The intrinsic capability of a supply chain to respond (its robustness and resilience) can be described by these characteristics and associated metrics.

In the following section, we illustrate how the framework can inform thinking of supply chain dynamics using a case study of the gas turbine global supply chain. The next section reviews change vectors and market condition changes historically experienced by the supply chain—the "change" elements of the framework. The last section applies the framework to explore the "response" elements of the framework, namely, the supply chain's responses and capacity to respond to ongoing market changes. While the discussion presented here examines historical phenomena, the framework can be applied to explore current scenarios and future change.

Results—Case Study

Gas turbines are marketed in different sizes ranging from 50–600 MW capacity, where smaller units are deployed in mechanical drive and industrial applications and larger ones are deployed in utility-scale electricity generation (Frost and Sullivan 2014). We focus the case study analysis on the latter, including the production and sales of gas turbines for CT and CCGT power plants. In 2017, approximately 23 percent of world electricity use was generated by natural gas (International Energy Agency [IEA] 2018). This market is particularly important for climate goals, supporting the switch from coal to gas, and providing flexibility for the integration of renewables (IEA 2019).

Figure 2 shows the major components of large gas turbines. The global gas turbine supply chain includes four main production stages. It begins with (1) raw materials suppliers, followed by (2) the refining and processing of materials, (3) fabrication and subcomponent supply, and (4) final turbine assembly (Court 2008). Figure 3 shows these major production steps and the selected materials, additives, and parts manufactured in each step. Many different plants and companies source intermediate products with varying levels of market concentration. For example, the thermal barrier coatings contain yttrium, a rare-earth element of which more than 85 percent of mined supply over the past decade has originated from a single country: China (Van Gosen al. 2017). As one example of the complexity of the gas turbine supply chain, a Siemens turbine blade reportedly required as many as seven global supply chain steps, including both in-house and external production (Capgemini 2008). By another account, gas turbines contain more than 1,000 precision parts cast from a range of metal alloys (Moss et al. 2013). At the final assembly stage, only a few large OEMs remain, of which GE, Siemens, and MHI control the majority of the global market (Crooks 2018). Note that MHI's gas turbine business is currently operated through MHPS, which is a joint venture formed in 2014 between MHI and Hitachi, Ltd.

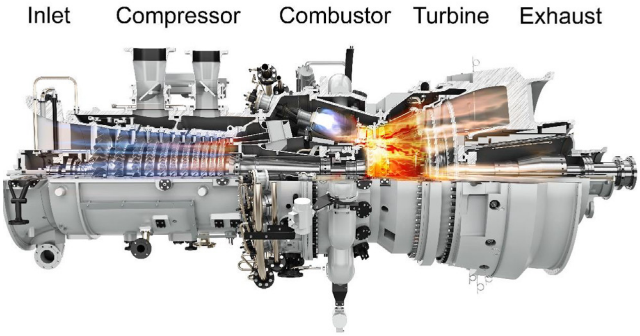
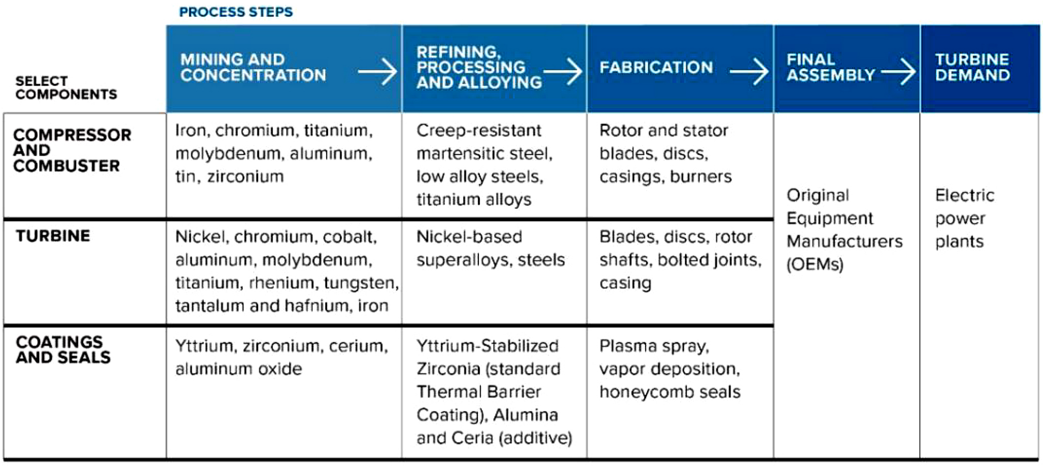


Figure 2. Diagram showing gas turbine components
(Source: Siemens 2017a, copyright Siemens AG, Munich/Berlin)



	PROCESS STEPS				
SELECT COMPONENTS	**MINING AND CONCENTRATION** →	**REFINING, PROCESSING AND ALLOYING** →	**FABRICATION** →	**FINAL ASSEMBLY** →	**TURBINE DEMAND**
COMPRESSOR AND COMBUSTER	Iron, chromium, titanium, molybdenum, aluminum, tin, zirconium	Creep-resistant martensitic steel, low alloy steels, titanium alloys	Rotor and stator blades, discs, casings, burners	Original Equipment Manufacturers (OEMs)	Electric power plants
TURBINE	Nickel, chromium, cobalt, aluminum, molybdenum, titanium, rhenium, tungsten, tantalum and hafnium, iron	Nickel-based superalloys, steels	Blades, discs, rotor shafts, bolted joints, casing		
COATINGS AND SEALS	Yttrium, zirconium, cerium, aluminum oxide	Yttrium-Stabilized Zirconia (standard Thermal Barrier Coating), Alumina and Ceria (additive)	Plasma spray, vapor deposition, honeycomb seals		

Figure 3. Major production and demand stages of the industrial gas turbine supply chain.

For our case study and with reference to the systems analysis framework shown in Figure 1, we define the gas turbine supply chain to encompass both turbine production and demand from owner/operators of electric power plants. To reflect this definition, turbine demand is included in the far right column of Figure 3. In the following sections and in the context of the gas turbine supply chain, we examine the change elements of the framework ("change vectors" and "change in market conditions") and response elements ("supply chain response to change" and "supply chain characteristics and metrics").

Systems Analysis Framework Illustration: Change

From the time that gas turbines first entered the electricity generation market in the 1950s, change vectors have affected the supply chain's market conditions. Figure 4 highlights examples of policy, innovation, resources, and industrial dynamics/economy change vectors that have created change in US market conditions over time. In the text that follows, we describe examples of US and global market changes (specifically, demand growth and shrinkage, technology shift, and resource undersupply) caused by various change vectors. Importantly, change vectors have led to market condition changes in both the production of and demand for utility-scale gas turbines. We consider both in our analysis. Further, we describe a few examples of how change vectors and market conditions have affected gas turbine supply chain characteristics (Figure 1 circles labeled 2 and 3, respectively).

Demand Growth and Shrinkage

As Figure 5 (EIA 2017) shows, US demand for gas-fueled power plants has experienced periods of both growth and shrinkage. US demand originally grew in response to the Great Northeast Blackout in 1965 and then fluctuated in response to policy and economic changes affecting natural gas prices and electricity demand (Unger and Herzog 1998). One such policy that led to demand shrinkage was the 1978 PPIFUA, which prohibited the burning of natural gas in new power plants. Rescission of this policy in 1987 fostered growth in US gas turbine demand in the 1990s. In the late 1990s, a confluence of factors led to a "dash for gas" in the United States, which by far led to the largest surge in gas turbine installations. Contributing factors to the surge included natural gas and electricity deregulations, improved gas turbine efficiency, and increasing cost competitiveness of natural gas compared to other power plant fuels.

Other nations experienced their own versions of a dash for gas with similar timing. Kern (2012) identifies several change vectors enabling rapid adoption of CCGTs in the United Kingdom in the 1990s, including the economy, favorable policy, innovation, and industrial dynamics. The economy driver was the availability of inexpensive gas to fuel new power plants. Influential policies included those that fostered electricity sector competition and environmental regulations that increased the costs of coal-fired electricity.

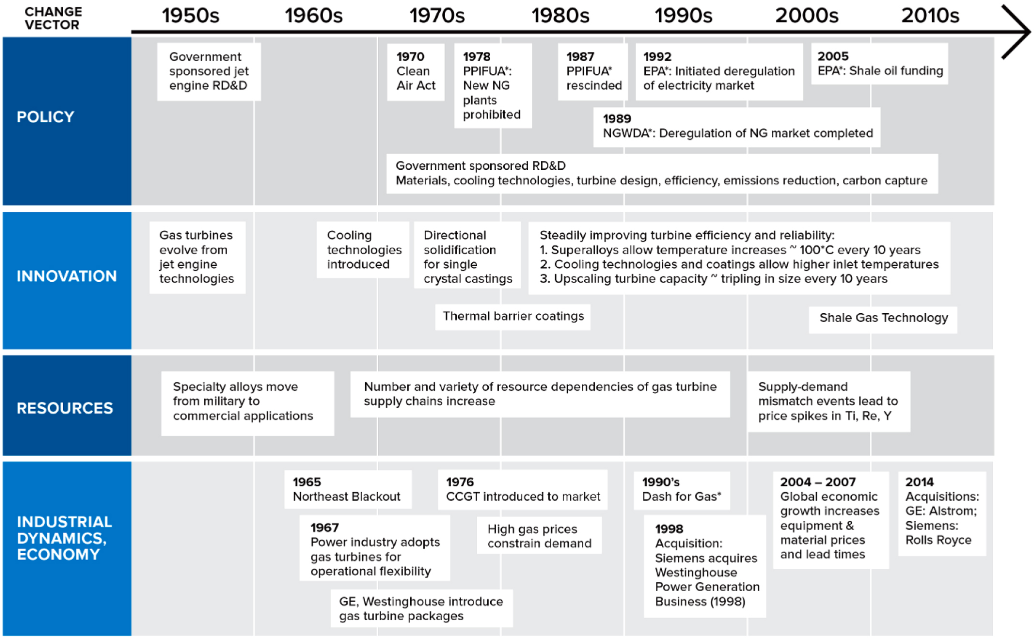


Figure 4. Change vectors affecting U.S. demand for utility-scale gas turbines since their introduction to the market. * Change fostering the U.S. "Dash for Gas" included electricity market restructuring (policy), technology improvements (innovation), and cost competitiveness of natural gas compared to other energy sources (economy). Abbreviations: EPA = Energy Policy Act; NGWDA = Natural Gas Wellhead Decontrol Act; PPIFUA = Power Plant and Industrial Fuel Use Act; RD&D = research, development, and demonstration.

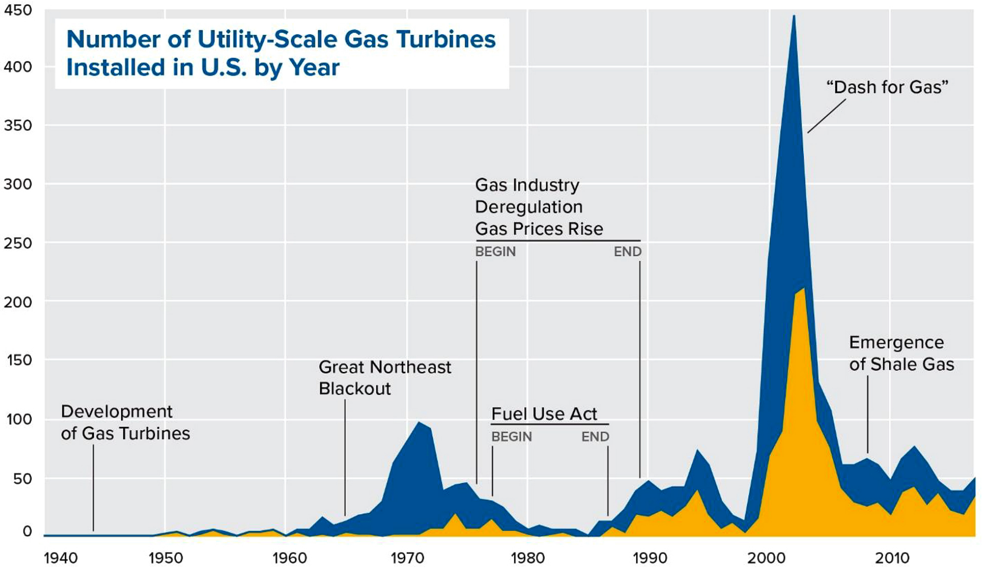


Figure 5. Number of utility-scale gas turbines installed in the United States by year of first operation (Source: EIA 2017). Key: blue = combustion turbine (CT), yellow = combine cycle gas turbine (CCGT).

After the dash for gas, US demand shrank dramatically in the mid-2000s as a result of market saturation. Escalating costs for materials (e.g., steel, concrete), heavy equipment manufacturing, and labor in the 2004–2007 period may also have deterred new construction (Pauschert 2009). After the precipitous decline, US demand steadied due to low-cost shale gas, enabled by the innovations of horizontal drilling and hydraulic fracturing, which vastly increased US gas reserves. In the mid-2010s, the gas turbine market faced headwinds from change vectors including climate change policies and innovation, which increase the cost competitiveness of renewable energy and energy storage technology. These change vectors are leading to demand shrinkage in both the domestic and global markets for utility-scale gas turbines, as the overall energy supply chain is facing fierce competition introduced by renewable energy sources, energy storage, and demand response.

Technology Shift

Technology shifts are often spawned by the innovation change vector. A first technology shift in the gas turbine supply chain occurred after World War II with a public-private partnership that translated jet engine technology to industrial gas turbines (Unger and Herzog 1998). Another major shift was the introduction of larger and more efficient gas turbines designed specifically for CCGT power plants in the 1990s (Chase 2001). Since the 1990s, decades of public R&D investment in jet engine technology and sustained R&D investment by equipment manufacturers have improved the cost competitiveness of gas relative to coal power plants (Kern 2012). Elements of this technology shift include advances in turbine blade coatings and methods for coating application, blade metallurgy, blade designs for enhanced cooling, and combustion systems (Willis 2002). One formative innovation was directionally solidified and single-crystal superalloys for blades and vanes, allowing higher operating temperatures and associated higher efficiencies (Seth 2000, 3-12).

Resource Undersupply

Innovation in specialized superalloys and thermal barrier coatings fostered the capacity of gas turbines to operate at increasingly higher firing temperatures and thereby achieve higher efficiencies (Sims 1984). These coatings and alloys, however, contain specialized materials, introducing the possibility of resource undersupply, beginning in the 2000s. These materials include titanium alloys used in the compressor, rhenium used in superalloys (John et al. 2017), and yttrium used in thermal barrier coatings (Van Gosen et al. 2017). These metals have experienced volatile price periods indicative of resource supply shortages—titanium in the early 2000s (Seong, Younossi, and Goldsmith 2009), rhenium in 2005–2009 (Desai 2007), and yttrium in 2010–2011 (Humphries 2012). Reviews of production, markets, and approaches to mitigating the undersupply of rhenium can be found in Kesieme, Chrysanthou, and Catulli (2019, 150-158) and for yttrium in Zhang, Kleit, and Nieto (2017, 899-015).

Change Vectors Directly Affecting Supply Chain Characteristics (Figure 1, Circle 2)

Kern (2012) identifies change vectors during the British "dash for gas" that directly affected supply chain characteristics. For example, the production capacity increased, unit cost decreased, and the supply chain structure changed when the four mature OEMs (GE, Westinghouse, Siemens, and ABB) pursued takeovers and new licensing deals with other manufacturers. The industrial dynamic vector in this case imparted change in the supply chain's supply-side (production capacity and costs) and structure (supply network) characteristics.

Market Conditions Directly Affecting Supply Chain Characteristics (Figure 1, Circle 3)

The gas turbine supply chain's technology shifts caused changes in supply chain characteristics; for example, increasing turbine performance efficacy with larger capacities and increased thermal efficiency from 5MW and less than 20 percent efficiency in the 1950s to greater than 570MW and nearly 65 percent efficiency in 2018. One consequence of these efficacy advances is the increased technological complexity of gas turbines; for example, intricate air-cooled turbine blade designs have been developed using high performance computing.

Whereas this section has focused on historical changes affecting the gas turbine supply chain, the next section shifts focus to supply chain responses to a recent change in the gas turbine market: namely, demand shrinkage.

Systems Analysis Framework Illustration: Response

We use the systems analysis framework to explore how the utility-scale gas turbine supply chain's supply-side (production chain), demand-side (product technology and end-use market), and structure (types and organization of firms) characteristics affect its capacity to respond to recent demand shrinkage in the operational (days-months), tactical (months-years), and strategic (years) time frames. As noted previously, the strategic responses are distinguished from tactical responses by their complexity and degree of innovation. Table 1 lists example supply chain characteristics and associated metrics that may affect a supply chain's responses in these three time frames.

For the analysis, we rely heavily on OEMs' annual reports (GE, Siemens, and MHI), corporate press releases, market reports, journal articles, and government reports, websites, and datasets. The majority of publicly available data applies to the final assembly and demand supply chain stages as shown in Figure 3. The

OEMs' outlooks for the large gas turbine market reported in their 2013 annual reports were relatively bullish. Starting in 2014, annual reports noted a downturn in demand and a shift in demand to smaller, more flexible power generation for decentralized energy supply and supplementary power for renewable energy. In the text that follows, information pulled directly from annual reports does not include a separate citation.

Table 1. Example supply chain characteristics and associated metrics that affect supply chain's responses to change.

Response Time Frame	**Characteristics and Metrics**		
	Supply-Side	***Demand-Side***	***Structure Side***
Operational	*Supply responsiveness* • Lead time • Capacity utilization • Manufacturing flexibility	*Inventory management performance* • Working inventory • Storage costs *Market attractiveness* • Profit margins	*Network architecture* • Sourcing flexibility
Tactical	*Barrier to entry* • Entry cost and time • Technology complexity *Efficiency of supply* • Unit production cost • Materials and energy efficiency	*Demand predictability* • Demand stability • Demand visibility	*Network architecture* • Supplier diversity • Vertical integration
Strategic	*Resource supply* • Resource basic availability	*Technology attractiveness* • Performance efficacy • Product customization *Market attractiveness* • R&D expenditures	*Market structure* • Market size

Operational Time Frame (Days to Months)

Operational responses focus on meeting existing demand and managing supply chain logistics. Supply and demand may be volatile, and supply chains must be able to dampen this volatility in such a way that they are still able to meet demand profitably. Operational responses to demand shrinkage may include decreasing capacity utilization, reducing inventories, adjusting profit margins, or deploying alternative suppliers. In the operational time frame, the effectiveness of a supply chain's response to change will depend on its readily available resources and capacities. As detailed in this section, the gas turbine OEMs responded to demand shrinkage by decreasing capacity utilization and reducing profit margins. These responses, in turn, affect these supply chain characteristics, challenging future operational responses. The capability of the OEMs to deploy alternative suppliers, however, was constrained.

Supply-Side Responses

Capacity utilization among the major OEMs has been on a decline since 2014. In 2017, Siemens reported expected future demand of 110 turbines per year, while its global manufacturing capacity could produce about 400 turbines annually (Heller 2017).

Long lead times limit operational responses to demand shrinkage. Pauschert (2009) finds that gas turbine lead times increased from about 12 months to 16–18 months when global economic growth and competition for manufacturing capacity escalated after 2004 and remained high until the global recession in 2008. Lead times for the commissioning of gas power plants are even longer and include allowing for engineering, procuring, constructing, and the actual commissioning. Overton (2015) reported such lead times of 28–30 months with aggressive scheduling. MHI Group provided contract announcement dates and delivery months for a few major projects in their annual reports; see Table 2. These data indicate that lead times for delivery of gas turbines exceed the operational time frame.

Table 2. Lead times between contract announcement and delivery for individual gas turbine plants as reported in MHI Annual Reports 2014, 2015, and 2016. (Lead time ranges are estimated from the month of the reported contract announcement and the delivery year.)

Contract Announcement	Delivery	Lead Time Range (derived)
January 2016	2020	48–59 months
October 2015	2018	27–39 months
January 2015	2018	36–47 months
May 2014	2016	19–31 months
March 2014	2016	21–33 months

Demand-Side Responses

Evidence exists that OEMs have been responding to shrinking demand and overcapacity by reducing prices, hence lowering profit margins. Since 2015, Siemens has reportedly reduced large turbine prices by 40 percent (Goodall 2018).

Structure Responses

In general, OEMs facing demand shrinkage may seek to reduce costs by switching suppliers. Structure metrics that indicate the capability for such operational responses include sourcing flexibility, import reliance, and geographic concentration. However, in the manufacture of gas turbines, engaging available alternative suppliers may not be feasible for highly specialized parts and components or for parts that require certification.

Tactical Time Frame (Months to Years)

Tactical responses rely on the supply chain's capacity to respond to emerging market conditions and signals without certainty of future markets. In the tactical time frame, the effectiveness of a supply chain's response to change will depend on its alignment with current trends and its capacity to improve its operational and marketing performance. OEMs' tactical responses to demand shrinkage may include reducing capacity, minimizing production costs, expanding revenue sources, and restructuring their supply chains. We find that while high barriers to entry limit tactical responses, the OEMs responded to recent demand shrinkage by decreasing production costs, improving manufacturing efficiency and cost-effectiveness, differentiating product offerings to retain or capture greater market share, and restructuring operations and supply chains.

Supply-Side Responses

Barrier to entry is a key supply-side characteristic that is relevant to the tactical time frame. While perhaps obvious for periods of growing demand, this characteristic has relevance to periods of shrinking demand as well. The barrier to entry of companies as OEMs to the utility-scale gas turbine market is significant due to high capital and operating costs, the complexity of gas turbine technologies, existing patents, and the regulatory framework. Given these barriers, decisions to temporarily or permanently curtail or shut down capacity carry significant financial and opportunity risks should demand rebound.

In 2014, GE reported a focus on reducing production costs, with a goal to reduce its H-Class gas turbine costs by 25 percent. Among its proposed responses were increasing automation, using new manufacturing tools, insourcing, and accelerating its suppliers' learning curves. MHI reported a goal to increase the profitability of ongoing projects by increasing power plant construction efficiency.

In tactical response to demand shrinkage, OEMs have been restructuring their businesses, shutting down capacity, and reducing staff to reduce unit production costs. GE took actions to reduce costs by $3.5 billion in 2017 and 2018, including a layoff of 12,000 employees, or 20 percent of its turbine business staff (GE 2017). In November 2017, Siemens announced the elimination of 6,900 jobs

(Larson 2018), although it reduced the cuts after reconciliation (Siemens 2017b). The company has reportedly floated the idea of selling its gas turbine business in the face of declining demand (Sachgau and Henning 2018).

Demand-Side Responses

OEMs manage their markets through contracts to make demand more predictable, services to expand business revenue areas, and expansion of their global marketing. Gas turbine demand predictability and visibility are relatively high since orders involve major cost input and contracts. In response to expected shrinkage in gas turbine demand, OEMs have increased revenue through a focus on maintenance and digitalization services to expand their markets. To improve profitability, MHI is pursuing funded opportunities to increase efficiency and reduce carbon emissions of existing power generation facilities, among other initiatives. MHI also notes opportunity space in demand from emerging countries.

Structure Responses

Over the past several years, OEMs have restructured their global supply chains and addressed market competition through a variety of acquisitions. In 2014, GE initiated acquisition of Alstom with expected benefits to include $5 billion in revenues from replacing external with internal suppliers, improved project management capability, and increased global market access. According to Frost & Sullivan (2014), Alstom held the fourth-largest share of gas turbine sales (by MW) in 2013, with 3.6 percent of the market. As a condition of their approval, European Union regulators required GE to sell some of Alstom's heavy-duty gas turbine assets to Ansaldo Energia. In 2016, GE acquired Metem Corporation, a turbine superalloy component manufacturer, with the objective of insourcing cooling hole drilling and other advanced manufacturing technologies.

Siemens has also actively acquired gas turbine capabilities, including the aero-derivative gas turbine business from Rolls-Royce Energy in 2014. One product that has emerged from this acquisition is a mobile, aero-derivative gas turbine designed for the fast power market, which is reportedly capable of reaching full power from a cold start in nine minutes (Siemens 2017c). With this acquisition, Siemens' intent is to become more competitive in the emerging market for flexible power production.

Strategic Time Frame (Years)

Strategic responses require foresight, planning, and resources that foster sustainability and innovation. In the strategic time frame, companies envision and pursue their future markets. Supply chains need the ability to respond to forecasted market changes by transforming production processes, technologies, resource use, and supply chain structure. Other strategies include diversifying product lines and customers. In the strategic time frame, we see evidence that OEMs have responded to demand shrinkage by investing in novel manufacturing technologies and adapting products to meet evolving customer needs.

Supply-Side Responses

Strategic responses focused on the supply side may include developing alternative resources for scarce materials or novel manufacturing technologies to sustain or improve products and business performance. Such responses are intended to retain market competitiveness in the long term. GE and Siemens have invested in the additive manufacturing of turbine components, capitalizing on the capacity for innovative designs and rapid prototyping. As reported by Prandi (2018), Siemens has been using additive manufacturing for more than ten different gas turbine parts, including a gas burner. In 2016, it acquired Materials Solutions, a leading additive manufacturing company. GE has improved fuel and air premixing with more efficient geometries enabled by additive manufacturing (Proctor 2018).

Demand-Side Responses

Strategic responses focused on demand include adapting energy technologies to changing customer expectations and investing in R&D to create new technologies and new markets. R&D expenditure is a key supply chain metric enabling strategic response. While OEMs do not report R&D investment by product line, Table 3 shows their reported R&D expenditures relative to revenues or net sales. For comparison, Table 3 includes data on 2015 global R&D expenditures as a percentage of global sales for US companies in select industries related to the gas turbine supply chain.

The gas turbine market demands high efficiency, reliability, and flexibility. In response, OEMs and governments have invested in R&D to achieve aggressive performance goals. For example, the US Department of Energy (DOE) sponsors R&D on advanced turbines with the expressed goal to "achieve greater than 65 percent combined cycle efficiency" and "support load following capabilities to meet the demand of a modern grid" (National Energy Technology Laboratory 2016). Over time, gas turbine efficiencies have steadily improved from increased firing temperatures enabled by specialty materials and coatings, advanced cooling technologies and blade designs, and other design improvements.

Larson (2018) reports OEMs' progress in reaching 65 percent combined cycle efficiency:

- MHPS: M501JAC gas turbine = 575 MW, 64% efficiency, 99.5% reliability
- GE: 9HA.02 gas turbine = 826 MW, exceeded 64% efficiency
- Siemens: HL-class turbine = 63% efficiency

Table 3. Gas turbine OEMs' R&D expenditures as a percentage of annual revenues (MHI = percent of net sales) and R&D expenditures for US companies by select industrial sectors reported as a percentage of global sales in 2015 (Source: NSF 2018).

Year	GE (%)	Siemens (%)	MHI (%)	
2018		6.7		
2017	4.6	6.2	4.3	
2016	4.4	5.9	4.1	
2015	4.5	5.9	3.7	
2014	4.5	5.7	3.4	
2013	4.8	5.7	4.1	
2015 R&D Expenditures for U.S. Companies by Sector				**(% of Global Sales)**
Engines, turbines, and power transmission equipment				3.5
Aircraft, aircraft engines, and aircraft parts				9.8
Semiconductors and other electronic components				12.5
Fabricated metal parts				1.3
Primary metals				0.7
Paints, coatings, adhesive, and other chemicals				3.54

Keywords: energy supply chain, change, resilience

GE's innovations include advances in cooling and sealing, emissions reductions via fuel staging, improved aerodynamics, and high-temperature materials and coatings (Vandervort, Leach, and Scholz 2016, 121-129). In the race to 65 percent efficiency, MHI is using supercomputers to design turbine blade castings and internal passageways for cooling them while in service (Browning 2017).

With the objective to increase their market size, all three major gas turbine OEMs invest in digital solutions to improve gas turbine design and performance and in the flexibility, control, and maintenance of operating gas power plants. The GE 2015 Annual Report, titled "Digital Industry," announced the formation of "GE Digital." The Siemens 2014 Annual Report introduced the Digital Factory Division (reorganized to the Smart Infrastructure and Digital Industries Division in 2018) and a new mission statement: "We make real what matters by setting the benchmark in the way we electrify, automate and digitalize the world around us." In 2017, MHPS began providing internet-of-things and artificial intelligence technologies for thermal power generation facilities.

Structure Responses

The OEMs' physical and digital innovations impart consequent changes to the structure characteristics of their supply chains. While we do not have visibility into their external supply chains, we note that the OEMs are acquiring hardware and software companies, thereby insourcing supply and strengthening their digital product offerings. Examples include Siemens's acquisition of Mendix in 2018 and GE's acquisition of ServiceMax in 2016.

Discussion

Understanding energy supply chains is essential because of how fundamental energy resources and technologies are to the US economy, national security, social welfare, and the environment. Nevertheless, untangling the forces and factors that affect and are affected by change can be difficult. To that end, the framework we have developed for envisioning change in energy supply chains provides a systems perspective and structure to guide conceptual analysis informed by quantitative data. The framework features broad change vectors, including policy, innovation, industrial dynamics, and resources. These change vectors drive change in market conditions, such as demand growth and shrinkage, technology shift, and resource undersupply. OEMs and other actors in the supply chain must interpret, anticipate, and respond operationally, tactically, and strategically to such changes in market conditions. Their capacity to adapt to change, in turn, depends on their supply chain characteristics as measured through metrics. In addition, change vectors, market conditions, and OEM actions directly affect supply chain characteristics. The framework provides a tool for exploring the possible effects of future change, whether they are planned (as in the case of policy actions), anticipated (such as technology maturity or demand shrinkage), or uncertain (such as economic downturns).

Our case study illustrates how the framework can be used, exploring the dynamics of gas turbine supply chains, with a focus on OEMs. The dominant change vectors evolved over time, shifting among industrial dynamics, policy, innovation, and resources. Historical change in market conditions was dramatically shown by annual installations of utility-scale gas turbines in the United States: there was a spike in installation demand in the early 2000s that was primarily caused by policy-driven natural gas and electricity market restructuring, with technical innovations also playing a role.

The framework also guided our analysis of OEM responses to changes in the gas turbine supply chain from 2013 through the present. Resilient supply chains are poised to respond operationally to market dynamics in the short term, while interpreting market signals to inform longer-term tactics and strategies. Although there has been some volatility in the market, including some resource constraints, the dominant recent signal has been of shrinking demand. OEMs have been responding to this shrinking demand in a variety of ways, including by reducing costs through improving efficiency of production, by delivering more flexible and efficient turbines, and by restructuring their supply chains.

Use of the framework also informs systematic thinking on the interactions of various supply chain characteristics across multiple time horizons. For example, actions in the tactical time horizon (e.g., reduction of production capacity in response to demand shrinkage) can affect the ability of the supply chain to respond to changes in the operational time horizon (e.g., by increasing the capacity utilization). In general, for the supply chain characteristics, there is a tension between supply chain characteristics that enable flexible response in the operational time horizon, those that underlie efficiency in the tactical time horizon, and innovation in the strategic horizon.

The framework supports systematic thinking with limited data, yet also helps to prioritize the gathering of additional data to deepen insight. For example, to further explore current strategic responses to demand shrinkage, additional quantitative data could be assembled on supply chain characteristics in operational, tactical, and strategic time frames (e.g., vertical integration, performance efficacy, market size, demand predictability) and how they have changed over the past decade.

The authors recognize the difficulty in collecting data on energy supply chains, particularly for intermediate manufacturing stages. OEMs' annual reports, corporate press releases, online industry journals, and government reports, websites, and datasets, which are accessible via the internet, provide information primarily for the final product: gas turbines in our case study. Government websites with particularly relevant data include: (1) the US EIA (https://www.eia.gov/) and (2) the US Census Bureau (https://www.census.gov/data.html). Other supply chain information can be found in market reports and the scientific literature, both of which may need to be purchased. Although outside the scope of this study, discussions with or surveys of subject matter experts and practitioners within the supply chain would strengthen the analysis.

Conclusions

Overall, the case study illustrates how this framework can be applied to evaluate the potential consequences and effects of change (including policy change) on energy supply chains over different time scales. The framework can be used with existing data to deliver insights on change in supply chains while also highlighting important data gaps that, if filled, would help in understanding additional dynamic phenomena.

Application of the framework can inform structured thinking of how a policy option might affect the associated energy supply chains in the context of ongoing change and responsiveness. Policy (including R&D investment, electricity market restructuring, natural gas market regulation, and environmental policy) is explicitly considered as a change vector that acts on energy supply chains in a variety of ways and elicits responses necessary for the supply chains to meet demand. The process of mapping change can illuminate the vulnerabilities of the supply chains in achieving these responses and meeting demand on various time scales associated with specific supply chain characteristics. In turn, certain supply chain characteristics and associated metrics are directly affected by existing or proposed policy. Moreover, the framework enables systematic thinking of interactions among different types of policies as experienced by supply chains that could inform conceptual policy design.

The framework can also guide analysts in identifying energy supply chain metrics to consider as focal points in policy development. By focusing on influential metrics, costly data collection and analysis could be minimized. In summary, the framework provides a systematic approach for considering the implications of policy over time in the context of energy supply chains that are continually evolving. This approach may be particularly useful in determining how a policy action directed at an emerging energy technology could be adapted over time to ensure its effectiveness as the technology and supply chain mature.

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