SUPPLY CHAIN DISRUPTIONS AND THEIR IMPACT ON ENERGY SECTOR DURING COVID-19

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ABSTRACT

The impact of COVID-19 on the lives of people and businesses across the globe was devastating. While governments across the world had undertaken a slew of measures to control the spread of the COVID-19 virus within their geography, many of these measures had long and unintended consequences. The restrictions imposed by the governments on the movement of people and goods across the world brought supply chains to a grinding halt. This study identifies the cascading effects of supply chain disruptions (SCDs) on the energy sector and thereby on the security of supply of energy from a European Union perspective. Since these systems are closely integrated and the impact of COVID-19 needs to be analysed at a much broader level, this study uses a systems-thinking approach to study the effect of SCDs on energy services. The study develops a causal loop model to gain further insight into how SCDs caused by COVID-19 affected the coping capabilities of society and how critical services were affected. Furthermore, the study puts forth certain policy recommendations for both businesses and governments to prepare for and protect against a similar situation in the future.

Keywords: Qualitative systems model; COVID-19; energy supply chain; supply chain disruptions; system dynamics; disaster management; group model building

INTRODUCTION

Recent trends and developments in supply chains, such as the increase in the outsourcing of manufacturing and research and development to suppliers, the

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reduction of supplier base to gain competitive advantage and reduction in inventory and lead time buffers for improving efficiency, have created lean and interconnected supply chains that are often vulnerable to disruptions (Hasani & Khosrojerdi, 2016; Ivanov et al., 2016; Rezapour et al., 2017). Furthermore, the integrated nature of supply chains indicates that it is not possible to manage the disruptions and risks associated with these disruptions within a single stage; there can often be a ripple effect across the supply chain due to disruptions (Dolgui et al., 2018). This has been the concern of businesses for a long time, and industry efforts to combat supply chain disruptions (SCDs) have focused on formulating either supply chain–wide or company-specific strategies (Ivanov et al., 2018). However, recent COVID-19-induced SCDs indicate that global supply chains are still vulnerable to disruptions and can potentially have long-lasting impacts on multiple global economies simultaneously (Moosavi et al., 2022; Pujawan & Bah, 2022).

SCD is an unexpected event that stops or slows the normal flow of material with potentially negative consequences to supply chain members (Chopra & Sodhi, 2004). At a broad level, SCDs are usually classified based on their causes, such as acts of nature (e.g. flooding, earthquakes, hurricanes and pandemics). While this cause-based classification identifies the underlying reasons for these disruptions, it is often much more useful to further classify them based on various other factors. This has led to multiple classifications of SCDs. Ivanov et al. (2017) classified SCD based on the level or echelon at which the disruption has occurred: production-based disruption, supply-based disruption and transportation disruption. Chopra and Sodhi (2014) classified SCD based on the causes of disruption. They identified that SCDs can be caused by disasters, delays in commerce systems, forecasts, intellectual property, procurement, receivables, inventory and capacity. Other classifications for SCDs are based on frequency of occurrence (Tang et al., 2014), nature and their source of origin (Christopher et al., 2011) and who they affect, from broad to specific (Dolgui & Ivanov, 2021).

The impact of SCDs has also been studied in detail in the supply chain literature. The main impacts on businesses can be broadly classified into operational, marketing and financial (Katsaliaki et al., 2021). Operational impacts may include, for example, a failure to meet the end customer demand because of product unavailability, partially fulfiled orders, late deliveries, logistic challenges, the use of alternative transportation sources for product deliveries and higher administrative costs (Jabbarzadeh et al., 2018; Wagner & Neshat, 2012). Some of the marketing impacts due to SCDs include an increase in customer complaints, damage to brand reputation, loss of customers, breach of supplier contracts, penalties associated with breach of contracts and failure to meet legal or regulatory requirements (Ponomarov & Holcomb, 2009). Financial impacts include, for example, loss of sales and revenue, reduced market share, production shutdown and reduction in asset utilisation (Ivanov, 2017).

However, what has been lacking in studies related to SCDs is their impact on the security of the supply of critical services, such as energy. The International Energy Agency (IEA) is mandated to promote energy security among 29 member countries. Member countries include European states such as Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Norway, Poland, Portugal, Spain, Sweden and Switzerland (IEA, 2014). According to the IEA, energy security means that energy sources are available uninterruptedly and at an affordable price. In the short term, the energy system must be able to react to supply and demand risks. Sources of risks can be further categorised as technical, human-made and natural. Technical risk sources include, for example, failure of transmission lines, power plants or transformers. In contrast, human-made risks include demand fluctuations, withholding of suppliers, terrorism, wars and export embargos. Natural risks include risks such as natural disasters and the depletion of fossil fuel stock. Technology advancements, shifting market trends and environmental issues all contribute to the ongoing evolution of the risk environment for the energy sector (Larsen et al., 2017).

SCDs caused by COVID-19 had far-reaching impacts on energy security. Many energy companies experienced the dual shock of the rapidly changing demand profile of consumers and the demand itself. SCDs also affected energy generation capabilities and energy generation capacity. For instance, China produces more than 60% of the world's solar panels and accounts for nearly 58% of world's wind turbine production capacity. It also supplies roughly 75% of the world's lithium-ion batteries, among many other components (Nahm & Urpelainen, 2022). With disruptions in the supply chain, clean energy projects have been on hold for several months, and many of them have been stalled indefinitely. This was primarily due to challenges in procurement, manufacturing, assembly, shipping and logistics, which were affected due to the shutdown because of COVID-19 (Henze, 2022). This had an unintended impact on sustainable energy production, and once again, fossil fuels started to gain traction as sources of energy (Henze, 2022).

To summarise the preceding discussion, COVID-19 has shed light on the intricate relationship between the security of the supply of energy and SCDs. In the modern world, products and services depend on the intricate supply chain network (SCN) connecting buyers, sellers and consumers. Any disruption in the supply chain often has far-reaching impacts. While previous studies on SCDs have primarily focused on business and commercial aspects, the societal impact of these disruptions has received much less attention. In this line of thought, the impact of SCD caused by COVID-19 on the security of the supply of energy was brought to the attention of policymakers and energy companies. Any disruption of energy services causes a severe societal impact and might even be detrimental to people's lives, as observed during the COVID-19 peaks. This study aims to address this gap in the literature by exploring the impact of SCDs due to COVID-19 on the security of the energy supply. The study further aims to identify the major impacts of SCDs on the energy supply chain. Finally, the study also aims to identify how the security of the supply of energy is connected to the coping capability of society towards a crisis such as COVID-19.

CONTEXT OF THE STUDY

Security of Supply in the European Union

Energy policy is a shared competence between the European Union and its Member States. Security of supply (of energy) is one of the five mutually reinforcing dimensions of the EU's Energy Union strategy. To a certain extent, a common energy policy has existed since the beginning of the European integration process. Concrete developments towards a single EU energy market, however, began in the 1990s (Wilson & Doberva, 2019). Fig. 1 summarises the various directives in the EU that deal with supply security.

The legislative focus on supply security came into existence in the aftermath of a series of terrorist attacks in the first part of the 21st century. In response to these attacks, the European Council asked for the preparation of an overall strategy to protect critical infrastructure. They identified that the risk of another potentially catastrophic terrorist attack that can affect critical infrastructure is high (Lazari, 2014). However, the consequences of such an attack on the industrial control systems of critical infrastructure could vary widely. The call identified that critical infrastructures consist of physical and information technology facilities, networks, services and assets that, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens and the effective functioning of governments in the Member States. Critical infrastructures extend across many sectors of the economy, including banking and finance, transport and distribution, energy, utilities, health, food supply and communications, as well as key government services. Some critical elements in these sectors are not, strictly speaking, 'infrastructure' but are, in fact, networks or supply chains that support the delivery of an essential product or service (EU, 2004).

In 2005, Justice and Home Affairs called for a final proposal for the European Programme for Critical Infrastructure Protection (EPCIP). The general objective of the EPCIP was to improve the protection of critical infrastructures in the EU by creating an EU framework concerning the protection of critical infrastructures. The framework consisted of a procedure for the identification and designation of European Critical Infrastructures (ECIs), measures designed to facilitate the implementation of EPCIP, support for Member States concerning National Critical Infrastructures (NCI), contingency plans to ensure security of supply and accompanying financial measures (EU, 2006).

While the protection of ECIs began as a counterterrorism measure, the Member States realised that an all-hazard approach would be beneficial to ensure the safety and effective functioning of ECIs (Pursiainen, 2009). Under this approach, anthropogenic technological threats and natural disasters should also be considered for the critical infrastructure protection plan, but the threat of terrorism should be given priority. As a first step, it was decided to identify and designate ECIs and assess their needs to improve their protection. The 2008 EU directive concentrated on the energy and transport sectors to ensure their security and operations (EU, 2008). The ECI directive (2008) also mentioned that each Member State should come up with operator security plans or equivalent

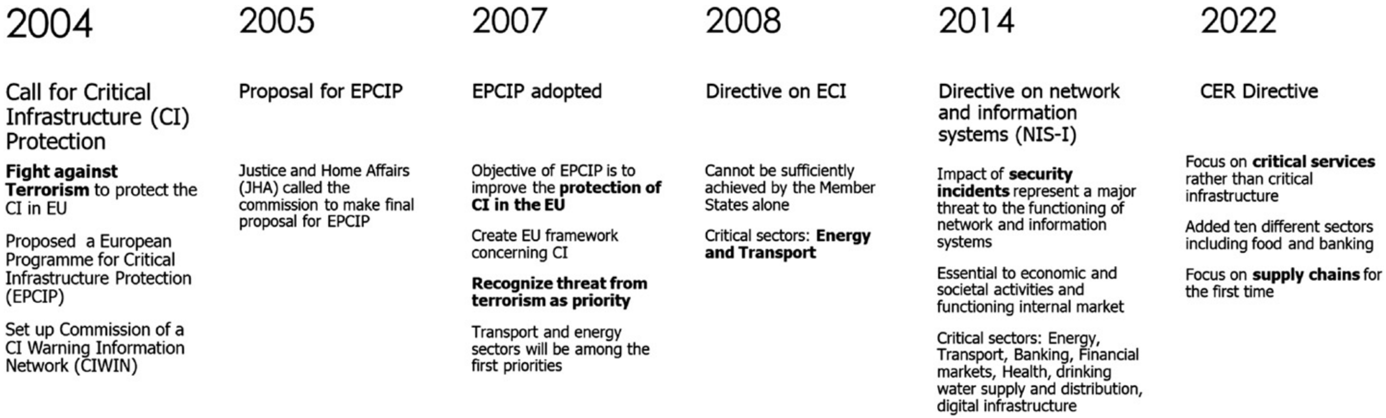

Fig. 1. Evolution of Security of Supply in the EU. *Source:* Authors.

measures comprising an identification of important assets, a risk assessment and the identification, selection and prioritisation of counter measures and procedures in all designated ECIs (EU, 2008).

In 2016, the EU passed another directive called the Directive on security of network and information systems (NIS-I). NIS-I identified that networks, information systems and services play a vital role in society. Their reliability and security are essential to economic and societal activities and the functioning of the internal market (Fantin et al., 2021). NIS-I expanded the purview from just energy and transport to other sectors, including banking, financial markets, health, drinking water supply and distribution and digital infrastructure. In addition to cross-sectoral factors, the NIS-I also discussed sector-specific factors that should be considered to determine whether an incident would have a significant disruptive effect on the provision of an essential service (EU, 2016).

In the wake of the COVID-19 pandemic, the ECI directive (2008) was revisited to evaluate standing, considering new challenges. A 2019 evaluation of the ECI directive (2008) concluded that existing European and national measures of each Member States face challenges in enabling operators to address the operational challenges they face. Furthermore, the interdependent nature of vulnerabilities often leads to a complex risk landscape within which multiple critical infrastructures operate. Some of the most pertinent reasons were, first, that operators are not fully aware of or do not fully understand the implications of the dynamic risk landscape within which they operate. Second, resilience efforts diverge significantly between Member States and sectors. Third, similar types of entities are recognised as being critical by some Member States but not by others, meaning that comparable entities receive varying degrees of official capacity-building support (in the form of, e.g. guidance, training and exercise organisation), depending on where they operate in the EU, and are subject to different requirements (EU, 2020).

The new Critical Entities Resilience (CER, 2022) framework identifies that given the increasing interconnection among infrastructures, networks and operators delivering essential services across the internal market, it is necessary to fundamentally switch the current approach from protecting specific assets towards reinforcing the resilience of the critical entities that operate them. Thus, the implication of this is clear – a disruption affecting the service provision by one operator in one sector has the potential to generate cascading effects on service provision in other sectors and potentially in other Member States or across the entire EU. Keeping this in mind, the new CER directive (2022) focuses on preventing incidents from occurring through disaster risk reduction and climate adaptation measures; ensuring adequate physical protection of sensitive areas, facilities and other infrastructure, including fencing, barriers, perimeter monitoring tools and routines, as well as detection equipment and access controls; resisting and mitigating the consequences of incidents, including the implementation of risk and crisis management procedures and protocols and alert routines; and recovering from incidents, including business continuity measures and the identification of alternative supply chains (EU, 2020).

One of the key aspects of the new CER directive (2022) was identifying the role supply chains play in ensuring the operation of the ECI. The EU identified that major crises, such as the COVID-19 pandemic, have shown the importance of ensuring the security of the supply chain and have demonstrated how its disruption can have a negative economic and societal impact across a large number of sectors and across borders. Therefore, Member States were directed to consider the effects on the supply chain, to the extent possible, when determining the extent to which other sectors and subsectors depend on the essential service provided by a critical entity. The directive specifically stated that Member States will take adequate measures to recover from incidents, duly considering business continuity measures and the identification of alternative supply chains, in order to resume the provision of the essential service (EU, 2022).

LITERATURE REVIEW

The disruption of supply chains during the COVID-19 period is a well-documented fact. The impact of these disruptions has been phenomenal and has spread through national and international boundaries, cascading across various sectors. This section summarises the impact of COVID-19 on energy consumption and the impact of COVID-19-led SCDs on the energy industry in the EU.

Supply Chain Disruptions

The impacts of COVID-19 on supply chains were far more disruptive than any localised disaster would have. The pandemic-induced disruptions have three specific characteristics that make them distinct. First, the pandemic had a long-term disruption and was unpredictable in its scaling (Dai et al., 2021). Second, the pandemic caused simultaneous disruption propagation in the supply chain (i.e. the ripple effect) and epidemic outbreak propagation in the population (i.e. pandemic propagation) (Ivanov, 2022). Finally, the pandemic also caused disruptions in supply, demand and logistics infrastructure (Diop, 2020). These characteristics were not unique to COVID-19 but were observed previously in Severe Acute Respiratory Syndrome, Middle East Respiratory Syndrome, Ebola and swine flu outbreaks (Dasaklis et al., 2012).

In the past few decades, supply chains have moved towards efficiency and cost reduction. One way to improve the efficiency of supply chains is to leverage economies of scale, reduce safety stock and focus on the sole source of suppliers to be strategically integrated into supply chain planning (Parmigiani et al., 2011). With improvements in data-capturing mechanisms and data analytics, centralised supply chain planners get better insights into the supply chain process in real time. Armed with computational power for better visibility into the supply chain process, managers across the world were able to save billions of dollars through supply chain process optimisation. However, the major side effect of these optimisations was that the supply chains became extremely fragile and would break down even at the slightest disruption since not enough cushions were built into the process (Ivanov et al., 2016). This was most evident during the COVID-19 pandemic, when supply chains were under severe stress owing to supply and demand shocks (Atkinson et al., 2020). A report by the corporate data analytics firm Dun and Bradstreet (2020) says that 51,000 companies around the world have one or more direct suppliers in Wuhan (the epicentre of the COVID-19 outbreak) and at least 5 million companies around the world have one or more tier-two suppliers in the Wuhan region, where COVID-19 was first discovered. Moreover, 938 Fortune 1000 companies have tier-one or tier-two suppliers in the Wuhan region (Dun & Bradsteet, 2020).

SCD severity is influenced by design characteristics and mitigation capabilities, highlighting the need for resilience planning and business continuity planning (Craighead et al., 2007). Mitigating SCDs requires implementing process management, information sharing and partner and service provider relationship management, with the depth and breadth of security initiatives depending on top management mindfulness, operational complexity, product risk and coupling (Speier et al., 2011). SCD propagation is driven by disruption nature, structure, dependence and managerial decision-making (Scheibe & Blackhurst, 2018). Disruption at one point in the supply chain also has a cascading effect across the entire SCN. The propagation of a disruption across the SCN and its associated impact is called the ripple effect. A ripple effect is distinct from the well-known bullwhip effect. This manifests when the impact of an SCD cannot be localised or contained in one part of the supply chain and cascades downstream, resulting in a high-impact effect on supply chain performance (Dolgui et al., 2018). The ripple effect is initiated by a severe disruption and describes the propagation of the impact of this SCD downstream, for example, in terms of the propagation of the disruption of the demand fulfilment capabilities of the supply network because of a severe disruption. In more severe cases, the ripple effect can cause some nodes and arcs in the SCN to become temporarily dysfunctional (e.g. due to a material shortage and capacity loss) (Dolgui et al., 2018).

To understand the supply chain ripple effect, it is imperative to understand risk propagation in the SCN. In practice, a disruption to an SCN often begins locally, with a trigger event affecting any one or a group of nodes in the network usually located within the same vicinity. This impact spreads to other firms (or nodes) through their relationships. Consequently, the impact might propagate to parts of the network through a set of cascading impacts and affect nodes that are far from the origin of the impact (Scala & Lindsay, 2021). The extent to which the impact propagates in the supply network is also a testament to the resilience of the network (Li & Zobel, 2020). Dolgui et al. (2018) discussed the main reasons for the systemic vulnerabilities that make SCNs more prone to the ripple effect when presented with a disruption in any or multiple nodes within the SCN. These reasons can be broadly classified into four main categories: sourcing strategy risks, production planning risks, inventory management risk and control risk. Fig. 2 summarises the main risks.

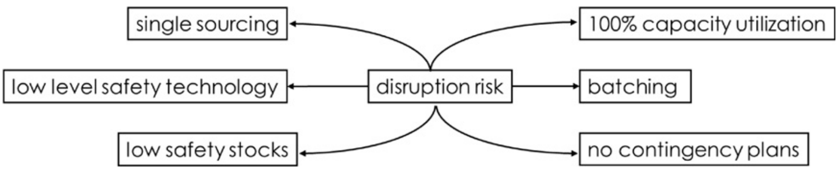

Fig. 2. Main Reasons for Ripple Effect in Supply Chain Network. *Source:* Dolgui et al. (2018).

SCDs and the Energy Sector

Energy supply chains are essential assets in modern societies. A disruption in the energy supply chain can have tremendous impacts on the quality of life we have; hence, the safety and security of the production and distribution of energy products is often a major concern of all national governments. While supply chains face the risk of disruption due to endogenous and exogenous factors, energy supply chains are often affected catastrophically by exogenous risks (Urciuoli et al., 2014). These exogenous risks include, for example, terrorist attacks, natural disasters, wars and piracy. Furthermore, due to the extensive network of suppliers abroad, energy supply chains could be disrupted due to any of the exogenous risks. Managing the disruption caused by exogenous factors is a highly important activity for energy industry executives. Multiple strategies for managing energy SCDs have been discussed in the literature. These include diversification of suppliers (Tørhaug, 2008) and network re-engineering (Christopher et al., 2011) by diversifying the supplier network base and creating a global sourcing risk management culture. In contrast to diversification, Melacini et al. (2011) argued in favour of centralising supply chains to improve the lead time and reliability of supply chains. Urciuoli et al. (2014) identified that in practice, energy supply chain managers do not rely on a risk management approach to handle SCDs caused by exogenous factors but on management strategies and information sharing. These typically include safety stocks to handle emergencies and diversification of suppliers based on factors such as geography, quality of product supplied, type of country or region, transport capabilities available and price. Energy companies also focus on developing multiple long- and short-term contracts and investing in manufacturing capabilities to ensure that they have the flexibility to use different types of raw materials.

SCD in the Energy Sector Due to COVID-19

COVID-19-induced disruptions have had a major impact on companies dealing with the production and distribution of energy across the world (Zahraee et al., 2022). Although COVID-19 was an exogenous disrupter, it had an impact on the demand and supply sides of the energy supply chain. The nationwide lockdowns led to an unprecedented reduction in the demand for energy across the world, excessive supply of raw material used in the energy sector and an unexpected change in the demand profile of energy consumption (Zakeri et al., 2022). The impact on the energy sector, in turn, has had a tremendous impact on other sectors. For instance, households, industries, hospitals and transportation consume energy to upkeep their operations.

Furthermore, plummeting oil prices expanded the scope of cheap oil-based energy generation, which impeded renewable energy development. The shift to low-carbon production and renewable energy was to be halted temporarily around the world. Meanwhile, a Bloomberg study predicted that solar power would decline, as policymakers were more concerned with battling the impact of COVID-19 on their economies than building new plants and agreeing on renewable energy growth goals (Manzanedo & Manning, 2020). Green energy ventures are also facing instability as a direct result of COVID-19 after the global pandemic. Wind producers GE, Vestas and Siemens Gaemsa were preparing to close their factories. The shortage of construction components, such as inverters and modules, pushed up costs by as much as 15% in some markets (Priya et al., 2021). Payment defaults were also causing ripple effects on the entire renewable energy market. A shortage of working capital dried up funds for short-term routine operating liabilities (Priya et al., 2021).

The lockdown-led restrictions across the world had a significant effect on the energy consumption pattern, and the distribution of energy usage shifted a great deal. For instance, industrial energy usage was reduced significantly, while domestic energy consumption saw a marked increase. Due to a reduction in the energy consumption for transportation, industrial manufacturing and other economic activity, oil prices fell to a record low (Carvalhaes et al., 2020).

Many countries saw a sudden reduction in energy consumption in the commercial and industrial sectors (Table 1). In the United Kingdom, energy consumption dropped to as low as 20% of normal usage during the weekend in comparison to over weekdays at the height of the COVID-19 lockdown (Wilson et al., 2020). The sudden reduction in electricity consumption has led to a significant deviation in voltages due to the capacitive elements in the transmission line that generate reactive power (Carmon et al., 2020). This abnormally low consumption of electricity affected the management and control of the generation

Table 1. Energy Demand Development (Based on Jiang et al., 2021).

	Growth in Energy Demand (%)	
Region	2019	2020
EU	−1.9	−10.9
USA	−0.6	−9
Japan	−2.9	−7.8
Korea	−0.3	−6.8
India	0.9	−4.1
China	3.4	−4.1
South East Asia	3.4	−3.4
Africa	2.9	−3

of power units and led to high fluctuations in the voltage and frequency of the electric current. These fluctuations, in turn, affected the resilience and reliability of the entire system (Carmon et al., 2020) and required shutting down power generation units. Since electricity consumption was exceptionally low, the system operator had to shut down conventional power plants until consumption returned to normal. However, several large power plants cannot be fully reactivated in a brief time, once shut down for a few days. This means that in the case of a contingency, such as a failure in a generation unit or an unexpected load deviation, backup units with a short start-up time are used, which are usually more expensive and polluting options. Furthermore, there may be delays in the synchronisation of these units to the grid, making it difficult for the system operator to supply demand during peak requirements (Carmon et al., 2020).

The most visible impact of COVID-19 was the energy market collapse. The price of the Brent crude fell from US $69 a barrel (6 January 2020) to under US $23 (30–31 March 2020) before partially recovering to around US $32 (13 April 2020) because of deep production cuts by OPEC plus countries (Duffy & Disis, 2020). Cross-border travel limitations, supply insufficiencies, quarantines and Capex reductions had a pronounced effect on the European energy service market, which is heavily dependent on its international workforce and efficient flow of goods and services between nations. A vast majority of the European Oil Field service, in Norway and the United Kingdom, lost purchases worth around $4.5 billion within the segments of maintenance, modifications and operations, drilling rigs and well services. It is estimated that about 1,000 small- and mid-sized suppliers in the United Kingdom and Norway have become insolvent or have been acquired by companies upstream (Bajic, 2020).

Impact on Renewable Energy

Renewable energy sources can be primarily classified into solar power, wind energy, hydro energy and others. The solar energy industry was the worst affected by SCDs. China is known to be the largest solar photovoltaic cell manufacturing country in the world and accounts for almost 80% of all solar cells and modules manufactured globally. The pandemic brought the production of the components used in renewable energy systems to a halt (Kanda & Kivimaa, 2020). As a result of lockdown disruptions in supply, there was a major decrease in solar energy supplements.

Table 2 shows that there was a steady increase in the proportion of renewable energy usage during the pandemic. However, this can be, in essence, a little misleading if the entire picture is not considered. As shown in Table 2, the percentual growth of renewable energy sources has decreased in 2020 compared to 2019. Therefore, the increase in the percentage of energy used from renewable energy sources does not come directly from the actual increase of renewables but is due to the total decrease in energy consumption as a result of pandemic-induced lockdown. The reasons for this reduction in the growth of energy sources from renewable energy sources are multifold. First, the sharp economic downturn caused by the pandemic had a significant impact on

Table 2. The Projected Change Rates of Energy Types Across 2019–2020 (Based on Jiang et al., 2021).

		Growth Rate (%)		
Energy Type	Change Rate	Type of Renewable	2019	2020
Renewables	0.79	Hydropower	2.4	0.7
Nuclear	−2.52	Bioenergy	7.8	2.8
Gas	−4.99	Wind	11.9	11.7
Coal	−7.73	Solar PV	22.3	16.1
Oil	−9.12	Others	7.1	2.8
Total energy	−6.05	All renewables	6.5	4.6

renewable energy. With reduced financing and government funding for market incentives, renewable energy investment has raised serious concerns among developers. In Germany, which is one of the leading renewable energy producers in the world, the decreasing overall level of energy demand negatively affects pricing schemes for renewable energy production and carbon trading. Furthermore, the sudden halt of the manufacturing process across the world led to major disruptions in the global renewable energy supply chain (Ivanov & Dolgui, 2021). SCDs and halting nonessential manufacturing activities have caused significant delays in the deployment of renewable energy projects. China, the leading supplier of solar photovoltaic cells, experienced a widespread shutdown of its factories due to the COVID-19 outbreak. Finally, the grid integration of new renewable energy projects was postponed due to a delay in distribution system operators' noncritical operations (Energy Community and Energy, 2020). Power companies adapted their operations in response to the fallouts from the pandemic by putting aside new investment projects, tightening budgets, cutting unnecessary spending and reassessing project implementation and investment priority, which collectively resulted in major impacts on global renewable energy production in the near term (Hoang et al., 2021).

The preceding discussion summarises SCDs and their impact on the energy sector in general and in particular due to COVID-19. While previous studies have investigated the impact of SCDs primarily from the perspective of a firm, studies on the impact of SCD on energy supply chains are sparse. Furthermore, very few studies have focused on SCDs in the energy sector caused by exogenous factors, such as the COVID-19 pandemic. While the exogenous risk to SCDs often affects the supply side of the energy supply chain, COVID-19 had both supply- and demand-side impacts on the energy supply chains. In addition, the impact of COVID-19 on the energy supply chain affected the strategic nature of the industry, especially with respect to its position on renewable energy and the nature of the SCN. Therefore, a deeper understanding of how COVID-19 has affected the energy supply chain and the impact of COVID-19 on the supply chain is warranted.

SYSTEMS THINKING

The fields of systems thinking bring three important patterns of thought to this study: (1) thinking dynamically, (2) thinking in feedback loops and (3) thinking endogenously (Sterman, 1994). Thinking dynamically means considering issues as they have evolved and will manifest themselves in the future. The behaviour over time (BOT) plot is one of the main tools for facilitating dynamic thinking. Drawing these BOT plots across time enables researchers and policymakers to shift their attention from a phenomenon as a discrete dramatic event to an ongoing process or phenomenon (Howick et al., 2006). The reasoning in feedback loops is centred on circular causality or the expected long-lasting ripple effects of system players' activities (Richardson & Andersen, 1995). Feedback loops are a source of visibility in policy resistance. Planners have the chance to circumvent the innate tendencies of competitive systems by discovering, reinforcing and balancing feedback loops that are active or latent in the system structure. Thinking endogenously is the most powerful part of systems thinking. Although it develops from the feedback concept, it serves as its foundation (Anderson & Johnson, 1997; Forrester, 1968). Thinking endogenously extends the border that normally surrounds our thinking about a problem to the point where underlying causes are perceived as connected in circular causal loops with internal forces over which we may have some control rather than as autonomous forces from the outside. Many disparate schools of thought are motivated by 'systems thinking', but at their foundation, they are all focused on identifying endogenous drivers of system activity.

Systems thinking has been used as a tool to study complex interactions in supply chain research. Within the supply chain context, the system is defined as 'a whole consisting of two or more parts (1) each of which can affect the performance or properties of the whole, (2) none of which can have an independent effect overall, and (3) no subgroup of which can have an independent effect on the whole. In brief, then, a system is a whole that cannot be divided into independent parts or subgroups of parts' (Ackoff, 1994, p. 175). In the same vein, Ackoff (2010) defined systems thinking as looking at relationships (rather than unrelated objects), connectedness, process (rather than structure), the whole (rather than just its parts), the patterns (rather than the contents) of a system and context (Ackoff, 2010). This view of systems thinking aligns with the supply chain function, in which various aspects of the supply chain need to relate to an established process to communicate with various parts of the supply chain to fulfil consumers' demands (Wilden et al., 2022). Given the complexities of modern-day supply chains, systems thinking has recently received much attention. Advocating for systems thinking, Jackson (2020) argued that systems thinking could have helped respond to COVID-19 in the United Kingdom, specifically the systems thinking frames of reference used to address some of the supply chain–related challenges (e.g. personal protective equipment). While not referring to systems thinking directly, Sarkis et al. (2020) took a systems view to critique the weaknesses in the supply chain and promote resilience measures, in addition to detailed lessons learnt from a post-COVID perspective. Elias et al. (2021) used systems thinking to holistically analyse the complexities involved in the adoption of a sustainable wood supply chain in Amazon and to develop strategic interventions to improve the system. However, COVID-19-led SCD has generated many important insights into supply chain resilience as a research paradigm and has been criticised for missing opportunities to learn from other fields (Wieland et al., 2023). Nikookar et al. (2021) argued that adaptations or even radical transformations may well be required in order not only to survive but also to flourish in an era characterised by factors such as geopolitical, social, epizootic, climate and biodiversity crises. According to Wieland et al. (2023), supply chains are not only complex adaptive systems but also have close connections with social, economic, ecological and political contexts within which they are embedded. Thus, supply chains are much more fluid in nature and cannot be expected to operate as engineering systems.

This study aims to understand the impact of COVID-19 on SCDs. The subsequent impact on the energy sector has all the characteristics that make it ideal for the use of systems thinking and qualitative system models using causal loop modelling. These characteristics are as follows:

- The problems are dynamic (developing over time).
- The root causes of the dynamics are not clear.
- Different stakeholders have different perceptions.
- Past solutions have not worked; solutions that fail to consider how the system will respond will fail to produce desirable long-term results.
- Implementing change will require aligning powerful stakeholders around policies that they agree have the highest likelihood of long-term success (Senge, 1997).

The next section summarises the overall methodological approach employed in this study.

METHODOLOGICAL FRAMEWORK

System dynamics, a research approach based on systems thinking, often uses group model building (GMB) to identify complex relationships between various entities and subsystems (Vennix, 1999). GMB helps guide problem definition, system conceptualisation, model building and refinement and model use. GMB has been the favoured approach for the system dynamist for three main reasons: first, to capture the required knowledge in the mental models through the various stakeholders; second, to increase the chances of implementation of model results; third, to enhance the stakeholder learning process (Vennix et al., 1997). GMB exercises allow stakeholders to voice their individual perceptions of reality and help them develop a shared mental model of their perceptions as a group (Elias, 2016).

For this study, an exploratory approach using the GMB method was adopted to gain an understanding of the complex nature of SCDs due to COVID-19 and its impact on the energy sector (Rouwette et al., 2002). Due to the exploratory nature of the research, the discussions were semi-structured to enable the researchers to discover the varying causal influences that the participants perceived to occur in practice (Graham et al., 1992). The subsequent sections broadly explain the main parts of the research process. The research process was divided into four main steps as described below (Hovmand et al., 2012).

(1) The first step included an initial literature review and identification of the main impact on the energy sector due to SCDs caused by COVID-19. The main findings of this stage are summarised in the Literature Review section of this study.
(2) The second stage involved initial data collection based on a questionnaire developed by the gatekeepers, which was shared with the sCience and human factOr for Resilient sociEty (CORE) consortium members to gather insights into the impacts of SCD on the energy sector due to COVID-19. The data collection for this stage was carried out during an annual conference among CORE partners in Vienna in September 2022. The structure of the questionnaire, with open-ended questions, was first introduced to the attendees and then subsequently shared with them. The questionnaire captured the direct and indirect impacts of lockdown, beginning of unlocking (with certain restrictions) and beginning of back to normalcy on energy sectors. Subsequently, after the annual conference, the questionnaire was shared with the rest of the consortium members who were not present at the annual meeting.
(3) The third stage involved a GMB workshop in Helsinki, in which the participants developed an initial set of relationships between the variables and helped identify an initial set of relationships. As part of initiating GMB, experts in HUMLOG were contacted and invited to be part of GMB. The HUMLOG Institute was established in 2008, after 2 years of close collaboration and exchanges between several schools, universities and institutes within the Nordic countries. It is a joint institute between the Hanken School of Economics and the National Defence University in Finland and is hosted at the Hanken School of Economics in Helsinki. Subsequently, the variables and relationships were evaluated, and the final model was developed after multiple rounds, as suggested by Andersen and Richardson (1997).
(4) The fourth stage involved final model building and validation, where the model was shared with members of the CORE consortium project. The causal loop model developed in GMB was shared with the consortium members to seek their input in validating and further refining the model. The feedback received was incorporated into the final model.

RESULTS AND DISCUSSION

Based on the discussion in the GMB session, the impact of COVID-19 on supply chains and how SCDs have affected the energy sector are discussed. The first part of this section summarises the general impact of COVID-19 and SCD caused by lockdowns as preventive measures for societal coping capabilities. The second part of this section specifically delves into the impact of SCD on the energy sector.

Impact of SCD on the Overall Well-Being of Society

The impact of COVID-19 on supply chains was critical, owing to the disruptions. As COVID-19 cases across the world increased, almost all governments responded by cutting down the interactions among their populace, and as a result, various forms of lockdowns or restrictions were put in place (Coccia, 2021). Some of them included extreme levels of lockdowns, where no one could move within or across the boundaries of the nation, and in some other cases, conditional restrictions were imposed on the movement of people. However, the general impact of the increase in the number of COVID-19 cases was the surge of restrictions limiting the movement of people and goods. The direct impact of these restrictions was, thus, not just the disruption in the flow of the people but also on that of the goods and services and thereby on the level of economic activity. This had a profound impact on supply chains across the globe and led to massive disruptions (Vo & Tran, 2021).

While the governments recognised this as a potential impact of rapid lockdowns, the impact of SCDs was far-reaching, especially on critical services. For instance, the lockdowns led to the sudden drop in the shipments of various goods, including raw materials, semi-finished parts and finished goods across industries (Arunmozhi et al., 2021; Raj et al., 2022). This was further aggravated by the fact that the lockdown-induced fall in economic activities led to either job loss or a reduction in the average wage across multiple sectors (Deshpande & Ramachandran, 2020). Combined with higher inflation and supply disruptions, the overall coping capacity of many individuals and households was significantly affected (Erokhin & Gao, 2020).

While the conditions during the lockdown were similar for everyone (in most countries), the impact was not uniform. Multiple studies (see Burlina & Rodrigues-Pose (2023), for detailed exposition) have identified that the impact of pandemics and income inequality are closely related, and this was the same for COVID-19. Households' decrease in access to work and education are two of the most important drivers of the reduction in well-being, both in the short and medium terms (Mahmud & Riley, 2021; Zoch et al., 2022). Having said that, the impact was not the same across the EU. It was observed that the countries with the greatest degree of deprivation are a group of Eastern European countries: Bulgaria, Latvia, Serbia, Lithuania and Cyprus. On the other hand, some Nordic countries, such as Norway and Finland – together with Croatia – are those with the lowest degree of deprivation (Ayala et al., 2022). This disproportionality within social groups had further adverse effects on vulnerabilities across society, where the already disadvantaged were further and disproportionately affected by lockdowns and subsequent SCDs and their impact on critical services (Jesus et al., 2021; Moore et al., 2021). With an increase in cases across the geographies, many administrations resorted to further clamping down and extending the restrictions. This further tightening of the restrictions added to the already existing conditions that had led to the disproportionate impact of COVID-19.

Causal Model of SCD and the Energy Sector

Total energy consumption in any economy is the sum of industrial energy consumption and household energy consumption. Energy generation and transmission processes are also based on consumption patterns. The sudden reduction in economic activities had a significant impact on the energy sector, especially on the profitability and energy generation capabilities of energy companies. This reduction in total energy consumption combined with SCDs has also affected the revenue of energy companies, which in turn has affected the profitability of the companies and thereby any investments in both maintenance and green energy transitions. Fig. 3, given below, captures the essence of the discussion.

Total energy consumption within an economy depends on both domestic and industrial consumption (Zhong et al., 2021). Usually, peak industrial loads and domestic loads are different. Residential customers usually have moderate energy consumption during daytime hours, with a minor increase in the morning and a peak demand around dinnertime. On weekends, the energy consumption of residential customers is generally higher, while the afternoon peak is substantially lower (Ayón et al., 2017). On the other hand, peak load in commercial buildings tends to occur during the late afternoon or early evening hours when businesses are operating at full capacity and people are using more electricity (Darwazeh et al., 2022). The highest peak load in industries typically occurs during the daytime, specifically during late morning and early afternoon hours. This is when

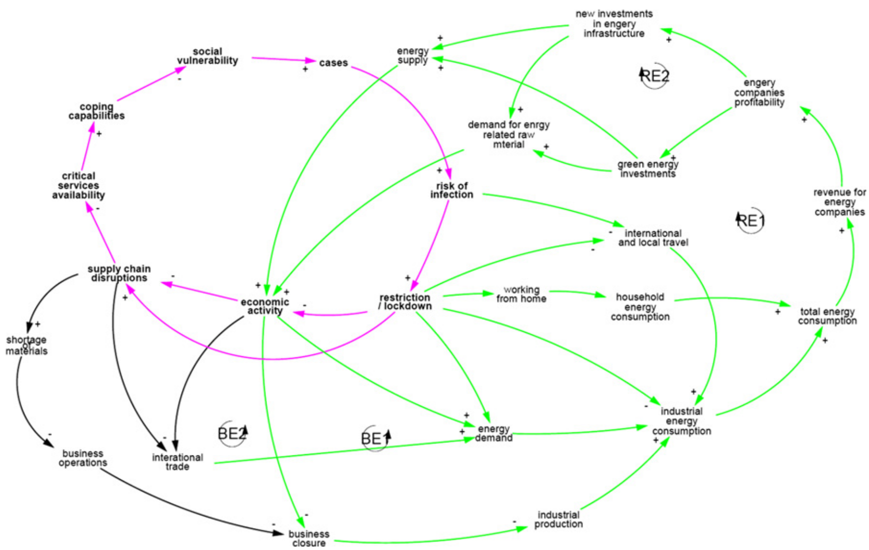

Fig. 3. Effect of Supply Chain Disruption on the Energy Sector.

industrial activities are at their peak and demand for electricity and other resources is typically highest (Ashok & Banerjee, 2000). However, due to the lockdown, the peak industrial and commercial building load was significantly reduced in the morning hours, and the domestic load was distributed across the day (Krarti & Aldubyan, 2021). Furthermore, while there was some increase in the domestic load due to remote working, which was popular during the lockdown, it was not significant enough to match industrial demand (Krarti & Aldubyan, 2021). This change in energy consumption pattern had two significant impacts. First, the total revenue generated by the energy companies had significantly reduced, while maintenance expenses had gone up (Pilloni et al., 2022). The second impact of the change in consumption patterns was the need to depend more on non-renewable sources of energy (He & Zhang, 2022).

Since majority of the revenue for energy companies come directly from industrial consumption, a significant drop in industrial consumption led to a loss of revenues for many energy companies (Zhong et al., 2020). This was a particularly difficult time for smaller energy companies, especially those that did not have their own generational capabilities but acted mostly as intermediaries between large energy companies and consumers (Busch & Hansen, 2021). During this time, there was a significant consolidation of the energy providers since many companies could not manage their revenue deficit and had to be merged with other energy companies. With reduced electricity demand from the commercial and industrial sectors, utilities have experienced a decline in revenue. This has made it difficult for them to cover fixed costs and investments in infrastructure upgrades. Some utilities have had to implement cost-cutting measures or seek financial assistance to maintain operations (Zhong et al., 2020). This contributed to redundancies in these companies, adding to unemployment (Poyner, 2020).

Another significant impact on the bottom line of energy companies was the increase in maintenance expenses for grid reliability and resilience. Companies have had to ensure that the electricity supply remains stable and uninterrupted, especially with the increased reliance on digital technologies for remote work and education. The industry has also had to adapt to the challenges posed by remote operations and maintenance, emphasising the need for a robust and flexible grid infrastructure (Zhong et al., 2020). Since transmission and generation capabilities are tuned to consumption patterns, any sudden change in this consumption pattern requires load balancing across transmission lines (Lopes et al., 2007). Load balancing exercises are extremely time consuming as well as intense processes that cannot be conducted without any planning. It was observed that energy companies had to restructure their load balancing across transmission lines, which affected their maintenance schedule and created stress on the lines, thereby requiring more maintenance than expected (Handfield et al., 2020).

The SCDs and non-availability of spare parts affected maintenance schedules and caused many companies to be unable to operate at 100% capacity. Energy companies faced challenges in obtaining replacement parts and equipment, leading to longer downtime for repairs and maintenance activities. This put additional strain on grid reliability and resilience, especially during a time when the electricity supply was crucial for supporting remote work, education and healthcare (Elavarasan et al., 2020). In Fig. 3, RE1 represents the reinforcing loop under pre-COVID conditions, while BE1 represents the balancing loop capturing the impact of restrictions and a slowdown in economic activities due to COVID.

Since the profitability of the energy companies had reduced significantly, almost all energy companies and governments reduced or stopped funding for green energy transitions. There were two primary reasons for this. First, COVID-19 affected the renewable energy sector in various ways. Construction delays and SCDs slowed down the development of renewable energy projects (Olabi et al., 2022). Additionally, the economic downturn caused by the pandemic led to reduced investments in renewables (Zhong et al., 2020). Second, the pandemic prompted discussions about the future of the energy industry and the need for a more sustainable and resilient energy system. Many governments and policymakers started considering the role of overall change in the usage of energy in economic recovery plans. This led to policy changes and initiatives aimed at accelerating the energy transition and supporting renewable energy projects (Hoang et al., 2021).

The multiple components required for solar power generation, including solar panels, are primarily manufactured in China. For renewable energy projects, SCDs have resulted in delays in the construction and commissioning of wind farms, solar power plants and other renewable energy installations (Deshwal et al., 2021). The closure of factories and restrictions on international trade have led to shortages of key components such as solar panels, wind turbines and batteries. This has slowed the expansion of renewable energy capacity and hindered the achievement of renewable energy targets. Combined with SCDs and a lack of funding for the green energy transition, the energy generated through green energy sources was significantly reduced during COVID times (Zhong et al., 2020). Furthermore, many governments and energy companies decided to freeze any major investments in the energy sector until the situation stabilised (Hoang et al., 2021). This is captured by the reinforcing loop RE2 and the balancing loop BE2 in Fig. 3. Loop RE2 is a positively reinforcing loop without being affected by COVID-19, while loop BE2 is the balancing loop, which captures the impact of COVID-19 and the associated disruption in the supply chain and international trade.

POLICY IMPLICATIONS

The impact of COVID-19 on the lives of people and businesses across the world has been devastating. While COVID-19 itself had direct effects on people's health and lives, much of the damage across the globe was indirectly due to lockdowns and restrictions, which in turn led to SCDs simultaneously causing both demand and supply shocks (Guan et al., 2020). This section discusses some of the policy implications that both businesses and governments could take into consideration to protect themselves against similar SCDs in the future.

The challenge businesses face is to make their supply chains more resilient without damaging their competitiveness (Chopra & Sodhi, 2004). Multiple studies have focused on finding the balance between making a supply chain resilient towards risks while ensuring that profitability is not compromised (see Pettit et al., 2013, for a detailed discussion). To meet this challenge, managers should first understand the sources of their vulnerabilities and then consider a series of steps that can be taken to ensure that these vulnerabilities do not cause future disruptions. The business-level policy implications are as follows:

Identify hidden risks: Modern products often incorporate critical and sophisticated components sourced from various suppliers across the globe. This makes it extremely difficult for a single firm to have both the technological and manufacturing capabilities to produce complex products entirely alone (Pescaroli & Alexander, 2018). To gain a competitive advantage, companies depend on suppliers that specialise in specific components. While this may be beneficial in terms of having a competitive advantage, it creates vulnerabilities within the system. Hence, firms are vulnerable because of a single supplier's dependence on a critical component. This can be seen in BE2 in Fig. 3, where a shortage of raw material can be avoided by building a larger and more diverse supplier base. The businesses must do complete risk mapping of their supply chain, identify where the risks lie, build redundancies within the supply chain, ensure that risk is distributed over a set of players and is concentrated neither horizontally nor vertically within the supply chain.

Managing net working capital: One of the main reasons for the bankruptcy of many small businesses was the lack of working capital since small businesses operate on small amounts of working capital. This is often due to long periods of cash receivables and relatively smaller periods of cash payables. As the financial function works on accounts payable and receivable, supply chain leaders should focus on freeing up cash that is locked in other parts of the value chain. This could include reducing the finished goods inventory and unlocking value within processes through strong governance. Furthermore, firms should focus on improving logistics through smarter fleet management. Most importantly, firms should test their financial situation and evaluate their level of resilience in terms of how much pressure they can handle in the case of an SCD. This is evident in both RE1 and BE1. Previous studies have shown that in the energy industry, a firm's growth rate causes a decrease in the level of working capital management measures. This may imply that although growing firms invest primarily in fixed assets, working capital is not their priority (Jaworski & Czerwonka, 2022). Furthermore, it can also be seen that the growing cash flow in the energy industry has often been prioritised to be invested in capital assets rather than working capital management. Thus, during revenue drops in the COVID-19 lockdowns, the energy companies had large amounts of capital assets that needed both maintenance and debt servicing, with little revenue to manage their operations. This led to major retracting in the energy sector. Thus, because the energy industry comes under critical resources within a society, public policies and the government can play an important role in setting guidelines, especially in working capital management, to ensure that such challenges are not faced in the future.

Keeping markets open for international trade: One of the main challenges during the peak COVID-19 was the unpredictable changes in the rules and regulations as well as the scope of their application by every government, which led to confusion and created difficulties for companies to adapt to the changes (Curran et al., 2021). This also contributed to the SCD, as shown in Fig. 3, in loops BE2 and RE2. For companies to be able to manage their operations and build resilience into the supply chain, they need policies and regulations to be stable, transparent and predictable in nature (Tomalska, 2022). While the majority of measures are probably justifiable, there were nevertheless many whose coverage or nature was such that a justification under Articles XX or XXI of World Trade Organization law was debatable. The banning of exports is an extreme measure, which is a relatively rare global trading system unless there is a global embargo. However, COVID-19 seems to have changed this. During peak lockdowns, we saw widespread recourse to export bans, sometimes with no published end date (ECIPE, 2020). Governments should focus on creating both predictability and transparency with rules and regulations and on ensuring that information is made available in a timely and transparent manner. Towards this, governments should reinforce confidence and commitment to rule-based trading to address gaps that might have led to trade tensions. Finally, governments should focus on creating coordinated efforts between various national and international governments and firms to develop common approaches for the simplified procurement and supply of essential commodities (OECD, 2021).

Governments should also establish policies for putting guardrails in the form of a risk-reduction framework within which businesses operate. This helps in stability and continuity for business operations, boosts investor confidence, helps in streamlining regulatory compliance, fosters innovations and growth and finally helps make the business resilient to global changes. Some of the policy steps governments should undertake are as follows:

Develop national-level risk assessment tools to identify risk: Governments should develop risk management frameworks at both national and local governance levels that include a supply chain perspective. Governments should focus on identifying different types of risks, especially supply chain risks pertaining to essential goods and services (Patrucco & Kähkönen, 2021). Risk identification should not be limited to the supply chains but should comprise the entire value chains. Governments should focus on creating efficient regulations through international cooperation to ensure the free movement of goods. Mechanisms should be put in place to detect and anticipate crises by monitoring vulnerabilities and risks in supply chains, including an international exchange of information and early warning signals.

Develop policies to minimise exposure to shocks: The focus of government should be to minimise shocks by ensuring the availability and accessibility of critical services to their citizens. This entails an efficient operation of infrastructures through trade, procurement and regulatory flexibility. Ensuring the resilience of critical infrastructures during shocks underpins the flow of goods, services and people (Meehan et al., 2016). Keeping in line with the recent CER 2022 directive by the EU, the focus should shift from asset protection to ensuring systemic resilience, owing to the increased interconnectedness and interdependence between infrastructure assets and various critical sectors. This should be ensured through a long-term strategic vision for infrastructure and the implementation of a government approach to managing threats. The focus should be on promoting evidence-informed decision-making to ensure that infrastructure is regularly maintained and strengthened for resilience.

CONCLUSIONS

We live in an extensively interconnected world with the ability to source, manufacture and consume products from different parts of the world. This is possible because of the interconnected network of supply chains that operate continuously throughout the year. In the past, the impact of SCDs on businesses has been studied in detail. However, their impact on the lives of common people and thereby societal vulnerability has not received much attention. The recent COVID-19-led SCDs across the world have brought this to the attention of both business owners and policymakers. The importance of supply chains in the modern world cannot be overstated.

Previous studies, while having studied exogenous risks from SCDs, usually do not consider both supply- and demand-side risks caused by SCDs. This study offers a novel outlook into the role of exogenous risks from SCDs, especially in the energy sector, which can have both supply and demand implications. Furthermore, the study uses a systems thinking approach to develop a holistic view of how SCDs produce ripple effects on the energy industry. The study also offers practical suggestions in the form of policy implications, which can be used by both practitioners and policymakers to develop policies to prevent the effects of SCDs caused by events such as COVID-19 on the energy sector in the future. While this study offers a holistic perspective using systems thinking, more empirical research needs to be conducted to quantify the real impact of SCDs across the energy value chain.

This study was carried out as part of Work Package 4, Task 4.3, under the CORE project, to study the impact of SCDs due to COVID-19 on creating social vulnerabilities. This was explored through the impact of SCDs on the energy sector. Since this sector is critical to the functioning of society, it is imperative to ensure that it functions without disruption. The study also explores how SCDs affected the operational capabilities of the energy sector and how they influenced both short-term and long-term operational capabilities. The study also suggests policy recommendations for both businesses and governments to protect themselves against system-wide SCDs in the future.

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