Energy Policy 168 (2022) 113116

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Learning from electricity markets: How to design a resilience strategy☆

Natalia Fabra [a,*], Massimo Motta [b], Martin Peitz [c]

[a] *Universidad Carlos III de Madrid, Spain*
[b] *ICREA-Universitat Pompeu Fabra and Barcelona School of Economics, Spain*
[c] *University of Mannheim and MaCCI, Germany*

ARTICLE INFO

Keywords:
resilience
prevention
detection
mitigation
electricity capacity markets
essential goods

ABSTRACT

Security of supply concerns are at the forefront of the public debate. The pandemic and post-pandemic times have demonstrated that preparing for global shocks requires the quick availability of some essential goods and services, including energy. Private incentives are typically insufficient for an economy to be prepared for rare events with large negative impacts. Instead, governments and preferably supranational institutions should implement mechanisms that make sure that prevention, detection and mitigation measures are taken. The economics of electricity capacity mechanisms provides valuable lessons for the provision of essential goods in such events, which need to be complemented with other elements aimed at mitigating the causes and impacts of potential crises.

1. Introduction

Concerns over security of supply have come at the forefront of the public debate, during and after the COVID-19 pandemic. The health crisis caught our economies largely unprepared. Across Europe, there were shortages of products and services essential to deal with the pandemic at different points in time, ranging from face masks and hand sanitizers to vaccines, to name just a few.[1] Not only have these concerns not vanished as the pandemic eases out, but some of them have even got worse as supply chain disruptions are threatening to halt the economic recovery. From shortages of processor chips and metals to disruptions in shipping, this crisis has uncovered a global lack of resilience. The Russian invasion of Ukraine has created further shortages of goods such as wheat, rare metals, fertilisers, and energy, among others.

The increase in energy prices as economies recovered from the pandemic was another manifestation of the same phenomenon. Gas supply remained scarce due to reductions in field investments, maintenance problems, and political tensions across exporting and importing countries (notably, Russia *vs.* Europe, or Algeria *vs.* Morocco). In turn, attempts to restock lower-than-average gas inventories pushed gas demand up. Both supply and demand factors contributed to a gas price spiral that spread across other energy markets. As gas is often the price-setting technology in electricity markets, the increase in its price put additional pressure on electricity bills, while also leading to coal and oil price increases as utilities struggled to get cheaper, though more polluting, energy alternatives. These soaring energy prices did not reduce the risk of gas shortages or power blackouts during the winter, as energy demand proved to be highly inelastic. In 2021, China already experienced widespread power shortages that led numerous factories to halt production, and in Europe, Austria warned its population against the non-negligible likelihood of energy shortages. The war in Ukraine made these matters even worse, with soaring energy prices all across Europe and fears of a potential disruption in Russian gas supplies.

Countries are considering several options to mitigate the energy crisis. For instance, as first proposed by the finance ministers of seven European countries in a joint statement, there are attempts to enhance

☆ We are grateful for comments by the Editor and two anonymous referees. Natalia Fabra gratefully acknowledges funding from the European Research Council (Grant Agreement No 772331 ELECTRIC CHALLENGES). Massimo Motta gratefully acknowledges financial aid from the Spanish Agencia Estatal de Investigación (AEI) and FEDER (project ECO2016-76998-P) and from "Ayudas Fundación BBVA a Equipos de Investigación Científica 20192" (project on "Digital platforms: effects and policy implications"). Martin Peitz gratefully acknowledges financial support from the Deutsche Forschungs-gemeinschaft (DFG) through CRC TR 224 (project B05). Mateus Souza provided excellent research assistance.

* Corresponding author.
E-mail address: natalia.fabra@uc3m.es (N. Fabra).

[1] See WHO [2020]. While it is too early to make further assessment, as of October 2021, some parts of the economy have been resilient. Despite an increase in usage of certain digital services (e.g., online streaming of videos) the Internet infrastructure has proven to be resilient; the provision of utilities (electricity, water, garbage collection) has not been at risk; the food supply chain was fully operational and transport across borders did not suffer major interruptions for longer periods.

https://doi.org/10.1016/j.enpol.2022.113116
Received 4 November 2021; Received in revised form 9 April 2022; Accepted 16 June 2022
Available online 1 July 2022

Europe's strategic gas reserves. These reserves would be built up through procurement auctions run at the European Union level to strengthen its bargaining position *vis-a-vis* the big gas exporters. They would be made available to national gas Transmission System Operators to avoid unaffordable gas prices or gas supply disruptions. It has been argued that this gas buffer will also be increasingly necessary during the energy transition to cope with the intermittency of renewables, at least until other energy storage solutions are deployed. More recently, the European Commission has made it compulsory for Member States to build up gas reserves for up to 90% of the storage capacity ahead of the winter.[2] The underlying reason is that externalities "such as security of supply or sustainability" are better dealt with public policies in a coordinated fashion.

In sum, the COVID-19 pandemic and the energy crisis are showing how vulnerable our economies are to security of supply problems. What has gone wrong? Why weren't our economies sufficiently prepared? How should a resilience strategy be designed so as to prevent and mitigate the most adverse consequences of such crises and other unexpected events in the future?

In this article, we take an economist's perspective regarding security of supply issues with a focus on the COVID-19 pandemic and the energy crisis. Our starting point is the observation that severe market failures might endanger the provision of essential goods and services, particularly so at times of crisis. In Section 2, we report on the experience of electricity markets in which regulators have traditionally understood that market forces alone do not provide enough incentives to ensure security of supply at all times. This is the reason why they have put in place capacity mechanisms to reduce the likelihood of shortages. These mechanisms are often implemented through markets, but they require that regulators take a stance on how much capacity has to be procured, a decision that would otherwise be left to the market.[3] We highlight the lessons from the use and design of capacity mechanisms in electricity markets that might be applicable to the broader question of how to take adequate measures before and during crises of other sorts. At the same time, we also acknowledge the limits, i.e., not all of the necessary measures can be implemented through market solutions similar to capacity mechanisms. In Section 3, we put these insights into perspective and point to important infrastructure requirements as a prerequisite to cope with adverse shocks. We address prevention measures, measures that help early detection and mitigation, as well as measures for effective and efficient reaction. While some of our proposals are specific to the European Union, most insights are broadly applicable. Section 4 concludes with policy recommendations.

2. Lessons from electricity markets

Electricity is commonly traded through a combination of short-run wholesale markets and long-term contracting. Even though electricity market design differs across countries, they tend to have one feature in common: everyday, on a day-ahead basis, generators compete to supply their electricity through a centralized auction mechanism. The market operator selects the low bidding suppliers until total demand is met, and pays the winning firms at the market clearing price. This price becomes the reference for all transactions that are taken outside the market, i.e., through bilateral contracts, that typically have a longer duration.

Electricity demand varies widely across the day and across months due to several seasonal components. This, together with changes in supply conditions (i.e., changes in input prices or in the availability of renewable resources) implies that prices and firms' quantities fluctuate over time. Due to these seasonal fluctuations in demand and supply, together with the absence of sufficient storage solutions, electricity markets provide an extreme example of the need to have excess generation capacity to meet the expected peaks in demand net of the expected changes in supply conditions. The main reason is that electricity demand and supply have to be equalized at all times as failure to do so can trigger the whole system's collapse.

The sophisticated market developments involved in electricity regulation over the last thirty years have found market solutions to provide security of supply at all times. In what follows, we will discuss whether or not such solutions can provide lessons for securing supply of essential goods and services in other contexts.

2.1. *The public good nature of security of supply*

It is widely agreed that security of supply has public good characteristics. In the context of electricity markets, security of supply has a private value (how much each consumer is willing to pay to avoid disconnection) but also a social value as an increase in generation capacity reduces the probability of a system collapse. Hence, when a firm invests in new generation capacity, it reduces the risk that the lights go off in hospitals, schools, streets, homes, and factories, thus creating positive externalities on health, education, safety, living standards, and the economy as a whole.

The parallel with the necessity to guarantee the supply of certain goods in situations of emergency is evident, as it is the fact that failing to provide such goods would have not only private, but also social costs that far exceed the private costs. The COVID-19 crisis provides a major example. All across Europe,[4] countries suffered from a shortage of products and services essential to deal with the pandemic. For all our sophisticated and technologically advanced firms, in the first wave it was difficult to obtain enough face masks (whether surgical or more protective), hand sanitizers, tests to detect the virus or the reagents needed to process those tests, protective garments for health care workers, ventilators, and so on. Stockpiling of such products was mostly inexistent,[5] also because some governments had been heavily criticized for "wasting" funds when they had accumulated stock of vaccines and protective equipment in response to the SARS pandemic or in preparation for a flu pandemic, which never materialized.[6] Presumably, the strategy (if any) or hope was that "should the need arise" a surge in demand would be met with imports, and/or with timely supply response. But neither worked. The combination of reduced production (due to their own confinement measures, which had slowed down production) and of an increase in demand (China started to import from everywhere), made it impossible to rely on imports from China, at least during the initial stages of the crisis. The dire consequences that followed this lack of preparedness are well-known. Lack of face masks increased contagion risks and lack of tests made it difficult to control the spread of the disease, forcing the authorities to adopt more severe

[2] See the European Commission's communication "REPowerEU: Joint European action for more affordable, secure and sustainable energy", March 8, 2022.

[3] Cramton et al., [2020] also derive lessons from the performance of electricity markets that could be useful to tackle health crisis. They highlight the role of electricity markets as clearing houses in which prices contribute to matching supply and demand. We instead focus on the lessons that can be obtained from the design of explicit capacity mechanisms.

[4] This article has been motivated by the European experience. Similar problems occurred in other parts of the world.

[5] An exception was Finland, where a stockpiling program has been in place since the cold war, apparently in case of an invasion. In the rest of the EU, some private firms also held stocks; e.g., some factories store face masks to protect workers in production and/or against accidental release of toxic fumes. However, such local storage is inadequate to deal with non-local shocks. In some cases, EU manufacturers exported all of their production just before the crisis hit. As the crisis took hold of Europe, some EU member states prohibited exports of some goods as a precautionary measure, thereby creating shortages in others where they were badly needed.

[6] See, e.g., Jenny [2020].

lockdown measures that led to even greater economic and social distress.

In this example, just as in the case of energy supply, the availability of essential goods and services benefits users but also creates positive externalities that make the whole economy better off. The conclusion is well documented: the public good nature of security of supply for essential goods and services implies that market forces alone cannot address it efficiently, giving rise to under-provision and, in the extreme, a lack of provision. Therefore, the first lesson is that, both in the case of electricity markets as well as for the supply of essential goods in times of crisis, some sort of public provision or government regulation that ensures private provision is needed.

2.2. Does scarcity pricing contribute to security of supply?

One might argue that price signals can achieve enough demand reductions so as to find a new equilibrium in which the market clears despite the demand or supply disruption. However, price signals alone are rarely enough, and they are often socially unacceptable.

In the context of electricity markets, demand rationing is rarely a feasible option. This is so for economic reasons - many customers do not face real-time prices and hence lack the incentives to reduce their consumption[7] – as well as for technical reasons – system blackouts can be triggered in a very short period of time, which makes it difficult for System Operators to curtail consumers in an orderly manner. Even when demand rationing can occur, the costs (in terms of forgone surplus) can be very large.[8] To provide some orders of magnitude, the so-called Value of Lost Load (which is a measure of the value of security of supply) has been estimated to be 400 times above the marginal cost of producing electricity under normal conditions.[9]

One might argue that scarcity prices provide adequate incentives to induce the optimal investments in generation capacity so that supply disruptions do not occur [Hogan, 2017].[10] Letting prices rise would allow producers to fully capture the private value of their investment, thus aligning firms and consumers' incentives. In many countries, however, regulators have introduced price caps to prevent prices from exceeding socially acceptable levels, which undermines firms' incentives to invest. According to those who advocate for scarcity pricing, if electricity markets fall short of delivering the optimal investments, it is due to price caps, not market failures. The conclusion would be to remove price caps, with no need to resort to additional mechanisms.

The analogy with the question of how to better procure essential goods in times of scarcity is straightforward. Letting prices for masks, sanitizers or vaccines increase during times of crisis could induce demand reductions until the market clears. However, since the demand for essential goods and services tends to be very price inelastic, particularly so at times of crisis, such demand reductions are rarely enough to clear the market. One could also argue that the mere prospect of price increases should a health crisis occur should encourage producers to stockpile those goods or to build capacity to flexibly provide them when needed. However, it would be misleading to assume that public authorities could credibly commit not to have price caps and to allow for scarcity pricing as a way to promote stockpiling and capacity investments. When it comes to essential goods, policy makers are rarely willing to accept that prices skyrocket in times of crises. We have seen this during the COVID-19 crisis, when most countries have regulated the price of masks, hand sanitizers, tests, and other goods considered essential. [11] We have also seen it during the current energy crisis, when the Spanish and the Portuguese governments have obtained permission from the European Council to cap gas prices in an attempt to reduce electricity prices.[12] Hence, even if under normal conditions the prices of essential goods and services may not be subject to explicit price caps, the expectation that they would eventually be regulated after a demand or supply shock, would undermine firms' incentives to invest in building up excess capacity. It is therefore unlikely that the market alone, through scarcity pricing, may be able to credibly guarantee continuity of supply of essential goods during catastrophes.

As a second lesson, it follows that, while price signals can partially contribute to reaching a new equilibrium in which the market clears, scarcity pricing alone is rarely enough to find a socially acceptable solution.

2.3. Can market solutions address security of supply concerns?

The public good nature of security of supply and the fact that prices alone cannot help find an adequate equilibrium does not necessarily imply that markets cannot provide efficient and acceptable social solutions in some cases.

Indeed, in the context of electricity markets, several countries in Europe and elsewhere have introduced regulatory mechanisms to promote adequate investments in generation capacity (the so-called "capacity mechanisms"). [13] The capacity mechanisms that have been introduced in the various countries differ in various dimensions, as we describe further below. However, they all have one common characteristic: the choice of capacity is not left to the market.[14] Rather, the regulator decides how much capacity needs to be made available to guarantee security of supply, and a capacity mechanism is put in place to determine which firms will provide such capacity and the rewards for doing so (the so-called "capacity payments").

When thinking of the sort of for catastrophic events discussed in this paper, one might be tempted to conclude that markets cannot provide an acceptable social solution. While this might be true in some cases, it is not true in others, as the use of capacity mechanisms in electricity markets illustrates. For instance, auctions could be used to procure goods and services that might eventually be needed during a crisis, just as capacity mechanisms are used to make sure that there will be enough available generation capacity in case of need. Whether such market solutions can provide adequate solutions in other contexts beyond electricity might depend on the specificities of each sector; for instance, on the intensity of competition among capacity providers; on the nature of uncertainty and the degree of firms' risk aversion; on the possibility to

[7] Even when they do, as in the Spanish case, their demand elasticity to short-run price changes tends to be very small. See Fabra et al., [2021].

[8] During the hot summer of 2020, millions of Californians have faced rolling blackouts as there was not enough capacity to satisfy the state's high electricity demand due to the increase in temperatures and the use of ACs. This avoided a system collapse, but did not stop prices from rising to USD 400 MWh (well above the USD 30 MWh average). See Financial Times, "Californians face dark, hot summer as green energy is sapped", 19 August 2010.

[9] For instance, as reported by Newbery [2016], the National Grid Company deduced the 2018 Value of Lost Load to be EUR 21,250 MWh, more than twice the direct estimates of the willingness to pay to avoid disconnections [London Economics, 2013].

[10] This view has been quite influential in the policy arena. Notably, the EU Target Electricity Model relies on scarcity pricing as a way to promote investments. For instance, the European Commission (2016, p. 210) advocates them under the premise that *"there will be more and more occasions when prices could reach very high levels (in times of scarcity) but for very short periods of time. It is these peaking prices that can provide the signals and stimulate the investment needed in flexible capacity so long as investors have the confidence that they will be able to recoup their money based on such prices."*

[11] See Motta [2020].

[12] See the "European Council conclusions, 24–25 March 2022".

[13] Fabra [2018] provides a formal analysis for the rationale of capacity mechanisms.

[14] Some capacity mechanisms rely instead on price regulation, i.e., the regulator sets a capacity price and lets investors choose how much capacity they want to make available at such a price. However, the European Commission has declared that this approach is not compatible with state aid rules.

define the goods and services that will eventually be needed; and on the willingness of policy-makers and society as a whole to pay for goods and services that might eventually not be needed, among others.

Beyond illustrating the usefulness of markets, the debate surrounding the use of capacity mechanisms in electricity markets provides other valuable lessons. We devote the reminder of this section to derive lessons from the design of capacity mechanisms in electricity markets that can be useful in other contexts.

2.4. Which products should receive capacity payments?

Once established the general principle that capacity payments might be justified, one still has to decide whether they are justified in all or only some cases for certain goods and services. For instance, whereas the common view is that there is a rationale for capacity payments in electricity markets, this does not mean that capacity payments should be granted in all cases, particularly so in cases in which enough capacity already exists or in which energy market prices already provide enough incentives for firms to invest. In the sector inquiry launched by the European Commission in 2015, which was based on the analysis of 35 mechanisms in 11 Member States, it was found that most Member States had introduced capacity mechanisms without properly assessing the need for them.

Beyond electricity markets, the difficulties for defining the set of goods that should be subject to capacity mechanisms might be even more acute. How do we know whether there is going to be a shortage of a specific good under future circumstances that we cannot even predict?

After the COVID-19 crisis, it might seem natural to conclude that we need to secure supply in *"crucial markets for e-mobility, batteries, renewable energies, pharmaceuticals, aerospace, defence and digital applications"*, as put forward by the European Commission during the presentation of its Recovery Fund.[15] But, which are the critical raw materials and intermediate and final products in these "markets"? Is it all of them, or only a subset, and at which layer of the supply chain? And what about other goods and services such as food, transport, utilities and so on?[16]

However, while shortages due to the pandemic are now in our mind, there are other types of shocks that can lead to major disruptions of the economy and society. A non-exhaustive list of "unforeseen" circumstances that may create shortage of essential goods in the future is the following[17]: other pandemics [18]; disasters triggered by natural hazards and severe weather conditions such as earthquakes, tsunamis, supervolcanoes eruption, heat waves with widespread impact and associated food shortages; food and water poisoning; nuclear accidents; disruption of internet and communication networks (including due to cyber-attacks from state and non-state actors); biological terrorism; and war (as has become apparent in 2022). And, depending on the type of shock, several goods and services may turn out to be essential. They include: medical equipment; pharmaceuticals; Intensive Care Units; makeshift hospitals; strategic oil and natural gas reserves (and in the future: hydrogen), emergency power supply, internet and mobile telephony infrastructure, food (in particular, staple food); emergency drinking water provision; human capital (doctors & nurses; rescue and civil protection teams; fire fighters) and equipment (e.g., air transport capacities), among many others.

Which of these goods and services should be procured through capacity mechanisms? There is clearly not a simple answer. The exercise of defining the set of goods and services to be procured in advance requires a high degree of fine-tuning, which calls for input from experts in different fields. It also requires an overall assessment of risks and a system of societal objectives that prioritize some outcomes over others. Here, the calculation of consumer willingness-to-pay (see Section 2.1) is likely to be a poor guide to determine the domain of security of supply considerations.

There could be Type I as well as Type II errors; that is, failing to secure the production capacity for goods that will turn out to be essential, as well as securing the supply of goods that turn out to be not needed, or needed in lower quantities than initially expected as the crisis unfolds. In this sense, there are parallels with insurance: a payment is made for having available capacity, while ex post it may well be that capacity is not needed, just as an insurer pays a premium to protect herself from events which might not realise. However, while an insurance compensates the insurer for the damage when it occurs, capacity mechanisms avoid the damage as those producers receiving capacity payments, commit to making the physical capacity available at times of system stress. Unlike insurance, capacity markets are not about compensation, but about capacity provision.

As it has sometimes been the case in electricity markets, a hidden rationale for introducing capacity mechanisms might be to grant state aid for firms going through rough financial conditions, or for those that are close to the ears of politicians. Justifying the need to introduce capacity mechanisms should be a cornerstone of any policy aimed at securing supply that the market would not necessarily provide at lower cost. Seeking the advice of independent experts may at least partly address the political economy worries.

2.5. Which amounts should be secured?

Once established that the supply of a certain good or service needs to be secured, another critical issue is what amount is needed. In electricity markets, the choice of how much capacity should be secured has also been a cause of concern. The standard approach is to delegate this task to the System Operator, as it is best placed to forecast the future electricity needs and the future supply of intermittent resources. However, since its duty is to avoid supply interruptions in order to keep the system in balance, the System Operator is typically biased towards excess procurement. [19]

Instead, in other sectors, there might be a bias towards too little procurement, but for a fairly similar reason: a principal-agent problem. Public institutions might not be willing to pay for the costs of securing supplies that will only be used in the future, with some small probability, to the benefit of their successors. For instance, we would all have been better off if the authorities had decided to stock masks and other medical equipment before the COVID-19 outburst. However, authorities in the past overlooked the probability of this event (despite warnings from the scientific community), and gave priority to other expenditures that might have looked more urgent or expedient to them at the time. Past experiences could be an underlying cause. For instance, as mentioned above, some governments had been heavily criticized because they had bought enormous quantities of the H1N1 vaccine, which were later not used.[20]

Needless to say, electricity Transmission System Operators might find it easier to forecast future electricity demand and supply than authorities to assess the likelihood of future crises (including infectious diseases, cyber-attacks, nuclear accidents, disasters triggered by natural hazards such as droughts, earthquakes, volcano eruptions, and others that we might not be able to even name), making this issue even more difficult to address in sectors other than energy. While the former can be

[15] See the European Commission's website on "Recovery Plan for Europe".

[16] See the European Commission's document "RescEU: Helping Protect Citizens in Times of Need".

[17] See The Economist, "The next catastrophe", 27 June 2020.

[18] Tirole [2020] writes: *"We are trembling with fear at the melting of permafrost which, in addition to emitting large volumes of greenhouse gases, will also release old viruses and bacteria, with unpredictable consequences."* See also BBC Earth, "There are diseases hidden in ice, and they are waking up", 4 May 2017.

[19] See Newbery [2016].

[20] See Financial Times, "Sarkozy under fire on flu vaccine fiasco", 5 January 2010.

considered as "known unknowns", some of the others may be labelled "unknown unknowns".

2.6. Centralized or decentralized capacity mechanisms?

The experience with electricity capacity markets might also provide lessons regarding the design of such mechanisms. The first design dimension is whether capacity markets should be centralized or decentralized. Under *centralized mechanisms*, the regulator sets up a central auction that serves to determine the plants that will commit to provide security of supply, and the price at which they will do so. Under *decentralized mechanisms*, the regulator imposes a capacity obligation on the electricity retailers, who need to buy capacity credits from capacity providers, either bilaterally or through exchanges. Failure to do so is penalized through fines.

How could this choice be reflected in other set-ups? Think for instance of flu vaccines. A centralized mechanism would have the government procuring all the vaccines needed for the whole population, while a decentralized mechanism would have the regulator imposing this obligation on the hospitals according to the share of the population in their catchment areas. Depending on the good or service that is being considered, each option has its pros and cons. Typically, buying power and risk sharing considerations would recommend centralized mechanisms. To the contrary, information issues might favor the more decentralized approach. A drawback of decentralized systems is the need to put in place a system of penalties and monitoring (in cases in which violations may be detected ex ante) to avoid non-compliance. Yet, penalties might not always be credible given the nature of the agents involved (e.g., would it be credible to penalize a hospital that fails to provide essential supplies during a pandemic?) and given the scale of the penalties that in some cases might be needed to make the incentive system work. Furthermore, if violations are only detected ex-post, the costs of non-compliance may be so large that the risk that incentives do not work may largely exceed any potential benefits of decentralization. Under such circumstances, a centralized system is likely to work better. Still, centralized systems are not immune to implementation problems. Providing incentives to capacity owners is particularly challenging given that they are paid for the obligation to supply something with some probability in the distant future. We will return to this issue when we refer to reliability options below.

2.7. Market-wide or targeted capacity mechanisms?

Another design dimension is whether capacity mechanisms should be market-wide (i.e., all existing firms should be entitled to receive capacity payments) or whether they should be targeted to a subset of firms (e.g., only to new plants, only to plants located in a certain region, only to certain technologies, etc.).

Electricity markets provide examples of these two systems. Both the UK and France rely on market-wide capacity mechanisms: the former is run through a centralized auction mechanism; the latter is organized through bilateral exchanges. One alleged benefit of market-wide mechanisms is that they are better at selecting the firms that are more efficient in providing capacity. However, their main drawback is that they might give rise to infra-marginal rents, as some plants might be willing to make their capacity available even without capacity payments (e.g., a plant that is already in place, which makes enough profits by selling its energy). This is particularly the case if there are strong technology differences. Hence, even if the most efficient capacity providers are selected, market-wide capacity mechanisms need not provide the least costly way of securing capacity from consumers' perspective.

Targeted mechanisms are meant to avoid this problem by only granting payments to existing plants that would otherwise shut down, or to new investments that would not otherwise be carried out.[21] This is the case of the *strategic capacity reserves* in Germany, Belgium, Poland and Sweden, under which some plants are paid to stay on standby. They are only used in case of output shortfalls, according to criteria that are determined ex-ante. A reserve auction is used to determine the compensations and also serves to achieve an ordered closure of plants. The auctions for *reliability options* used in Italy or Ireland are also an example of targeted mechanisms. The regulator (or the System Operator) enters into an option contract that gives the right to buy electricity at a predetermined strike price. Hence, reliability contracts provide a secure source of payments for the new investments (i.e., the option price that is set through the auction process) in exchange of making them subject to price caps (i.e., the strike price). Reduced uncertainty over cost recovery reduces investment costs, while consumers are protected against excessive prices at times of scarcity.[22] Furthermore, a producer subject to a reliability option has strong incentives to be available when it is most needed (which typically coincides with periods of high prices). Otherwise, if the producer were unavailable, it would have to buy the energy that it does not produce at a high price to sell it back to the regulator at a lower strike price.

Reliability options are appealing in the context of electricity markets, but their actual implementation may not be straightforward in other sectors in which there do not exist liquid markets to which these options could be indexed. Furthermore, just like insurance, reliability options essentially serve to hedge price risks, but do not necessarily secure physical availability. Last, market-wide mechanisms make sense only in sectors in which technology is fairly homogeneous, as otherwise infra-marginal rents may be too costly. Despite these caveats, capacity mechanisms for electricity are, as far as we are aware of, one of the few examples that can provide us with hints for this new endeavor of securing the supply of a wide array of essential goods and services.

As an overall conclusion of the above discussion, we believe that a centralized and targeted mechanism, such as a system of strategic reserves to be procured trough competitive mechanisms, might help guarantee the supply of several products and services which would be essential in case of crises or catastrophic events.

3. A broad resilience strategy

In the previous section we discussed the use and design of capacity mechanisms for electricity as these provide an example of how to secure the supply of other essential goods and services during times of crisis. We now turn our attention to a broader question. Namely, beyond the possibility of relying on market mechanisms to procure essential goods and services, which other elements should be taken into account to better prepare our economies for future crises or catastrophic events?

Preparation for future crises or catastrophic events calls for an articulated resilience strategy that addresses their causes (mitigation) as well as their impacts (adaptation). This might involve having an adequate research infrastructure and human capital, investing in prevention and early detection, and building the ability to react should such events materialize, among others. Climate change policies provide an

[21] A targeted mechanism need not necessarily be technology-specific. "Targeted" means that capacity payments are paid only to a subset of plants (e.g., those who win the auction; or only the ones that come online after an indicated date), not to all plants in the market. This is in contrast to market-wide mechanisms in which all plants in the market receive capacity payments. The latter tend to be unnecessarily costly.

[22] See Cramton et al., [2013] for a description of reliability options.

example of the need to address its causes and impacts. Whereas mitigation measures address the *causes* of climate change (through decarbonization, which involves investments in renewables and energy efficiency, among others), adaptation measures address the *impacts* (for instance, changing building codes taking into account future weather conditions, or building flood defenses or dams against rising sea levels). There is a clear parallel with pandemics. For instance, as the National Academy of Medicine (2016, p. 27) recommends, *"countries should work to develop real-time detection and response systems, prioritizing elements that reinforce prevention, provide early detection, and enable effective response."*

In this section, we shall briefly explain why neither market institutions (for example, through insurance markets) nor an individual country's initiatives may suffice to achieve mitigation and adaptation to the sort of crises discussed in this paper.[23] For this reason, we explore key dimensions of a broad resilience strategy that includes the build-up of a general research infrastructure and human capital (Section 3.1), prevention, early detection and mitigation measures (Section 3.2) including specific measures implemented ex ante to cope with the consequences, and which prominently include capacity mechanisms (Section 3.3) following our previous discussion (Sections 2.3 to 2.7).

3.1. General research infrastructure and human capital

Having an appropriate physical infrastructure to address health issues and a highly prepared labor force will generally help in all stages of a resilience strategy. Arguably, during COVID-19 pandemic in the first half of 2020, Germany's success rested on its dense network of healthcare facilities and chemical and bio-chemical labs,[24] together with its large number of Intensive Care Units (ICU).

Likewise, the pandemic has made manifest the importance of having genetic research centers and pharmaceutical laboratories, so as to be able to sequence the virus, monitor its evolution, develop a vaccine and find an appropriate medication (and of course, the capacity to mass-produce the vaccine, once developed, is equally fundamental). Similar arguments could also be made with respect to possible natural catastrophes. For instance, geologists and centers monitoring seismic activities would be fundamental in detecting the danger of earthquakes. Not to mention the energy transition: it is widely understood that decarbonizing our economies will require innovation breakthroughs capable of finding cheaper and more effective ways to produce and store low carbon energy, particularly so, in the transportation and industrial sectors.

With respect to research, and research infrastructure, we would like to emphasize two points. First, knowledge generated by basic research (and more generally, by research which is sufficiently far from the commercialization stage) can often be considered a public good.[25] As such, it might suffer from under-provision, that is, markets would give rise to too little of it relative to what would be socially optimal, making public support needed. Although this is certainly well known, it is still surprising to see on average low R&D investment levels in the EU[26] – even though the EU is performing well in terms of public R&D spending in percentage of GDP, as compared with other countries.

Second, some coordination at the EU level is important to make sure that there is enough research capacity in each area. Since we believe in the benefits from competition, we are not proposing the design and implementation of a centralized plan, according to which only some labs (perhaps distributed with a quota system across member stats) would be funded. Rather, we propose that the European Research Council, or a similar body, identifies the areas where research on possible catastrophic events is most needed and funds labs on the basis of merit. The analogy with energy regulators is clear: if market forces alone are not capable of incentivizing the needed investments (research-related, or energy capacity-related), the role of a social planner is justified in order to internalize the externalities created by such investments.

3.2. Prevention, early detection, and mitigation measures

Some catastrophic events (earthquakes, fall of asteroids, etc.) cannot be avoided. The only option is to be sufficiently prepared so as to identify the occurrence of such events and mitigate their impact, as we shall discuss in the next section. In other cases, however, prevention might play an important role, even if we often fail to recognize it. Global warming is a case in point, and one that unfortunately shows the inability or unwillingness to prevent a man-made tragedy and its consequences. The COVID-19 pandemic is another example. The spread of infectious diseases is linked to the introduction of invasive species, the destruction of animal habitats, and the loss of biodiversity (e.g., Sehgal, 2010; United Nations Environment Programme and International Livestock Research Institute, 2020). Landslides are another example: they are often the product of environmental neglect, deforestation and construction on unsafe grounds (due to inappropriate regulations or the lack of enforcement).

3.2.1. Private precautionary actions and the need of regulation

For prevention purposes, one may be tempted to believe that reliance on private precautionary actions may be enough. For example, one may think that an individual may not want to live in a high seismic-risk area and that if she does, she would have an interest in being able to anticipate an earthquake. However, asymmetric information and behavioral biases contribute to risky conduct and absence of precautionary measures by individuals. The behavioral economics literature has stressed the short-sightedness, over-optimism, and tendencies to procrastination of individuals.[27] As a consequence, people do not wear helmets and protective gear when working in dangerous plants; they typically do not invest as much as they should in earthquake-proof materials when building their houses; they live too close to volcanoes; and so on.

Likewise, an individual's willingness to invest in an early warning system, if any, is lower than the social optimum; similarly for environmental goods. Thus, there are obvious externalities, which will lead to the well-known "tragedy of the commons".

3.2.2. Public actors, institutions, and coordination

Unfortunately, there are good reasons to believe that governments would act in a similar way as individuals. For instance, absent externalities, myopic actions may be taken by politicians due to agency problems and political economy arguments: they would often oppose an investment which helps the country in the long-run (when they may not be in a position to get credit from that investment) and privilege instead actions which provide short-run benefits (and which may increase their chance of getting re-elected). We also observe that e.g., short-termism and behavioral biases in the population may the mimicked by some politicians who want to appeal to the prevailing mood despite knowing better.

And when cross-country externalities exist or the provision of a public good is at stake, for instance when several countries are likely to be affected by some event (think of environmental disasters, but also

[23] A similar viewed is expressed by the National Academy of Medicine (2016).

[24] The initial shortage of tests in some countries has been attributed not only to the lack of the tests themselves and of reagents, but also of laboratories and trained staff able to process those tests. See also National Academy of Medicine (2016).

[25] See, e.g., Stiglitz [1977]. However, Callon [1994] argues that it depends on the specific context whether knowledge is a public good. In particular, the absorption of knowledge may be rather costly.

[26] According to European Commission (2020, p. 263), R&D in the EU were around 2.2% of GDP in 2018, less than in China, Japan, South Korea, and the U.S.

[27] See e.g., Loewenstein and Prelec [1992] and Loewenstein et al., [2003].

tsunamis and pandemics), no individual government will generally want to refrain from pursuing an individual interest simply because it may harm neighbors, or foot the bill for measures which may benefit others.

Whether at the level of individuals or of countries, therefore, it is unlikely that uncoordinated solutions will arise. When it comes to individuals, it is crucial that government regulation is in place so as to prevent risk-taking behavior (which will generally have consequences beyond the individual taking the action). And when it comes to countries, two types of institutions seem to be needed: (i) independent authorities that are entrusted with the task of investing in preventive measures, possibly endowed with a budget which is not conditioned to political changes (thereby avoiding the political economy problems indicated above as much as possible); and (ii) well-functioning supra- or multi- or international bodies which may be relied upon to coordinate actions. Precautionary measures may then be publicly procured (and privately provided) or carried out by the different states, but in a coordinated manner.

3.2.3. Early detection tools

Resilience also includes early detection tools. This applies, for example, to the threat of earthquakes, volcano eruptions or tsunamis. There is a network of sensors throughout the oceans aimed at foreseeing the likely occurrence of tsunamis in real time, while seismology sensors and laboratories help identify the risks of earthquakes, thus helping to alleviate their effects. It also applies to health crises, with special reporting tools for unusual symptoms (in particular, detecting clusters) because they provide indications of dangerous infectious diseases or mass poisoning. Related considerations also apply to livestock and staple foods. In the power sector, Transmission System Operators launch public signals whenever expected peak demand is close to expected production.[28]

3.2.4. Stress tests

As part of prevention measures, the government may want to carry out stress tests for critical sectors, such as pharmaceuticals, medical supplies, utilities (water, electricity, internet), and other essential goods that address their provision in scenarios involving demand and supply shocks. Government actions can then aim at tackling detected inadequacies. Lessons can be drawn from the European experience in the banking sector, where stress tests performed by the relevant banking authorities have permitted the identification of problems within particular banks and appropriate remedies. Similarly, nuclear safety regulators regularly run stress tests on the performance of the nuclear power plants to prevent major accidents.

Civil protection drills or training measures may also help. (If the population is trained in how to respond to a problem, its consequences are reduced. Think for instance of civil drills aimed at preparing citizens in case of terrorist attacks, fire, bombs.)

3.2.5. Mitigation of the impact

Insurance can be seen as an instrument to react to events and reduce the negative impact to those directly and most severely affected (e.g., by covering the health care costs and by partly compensating for lost labor income).

If people buy insurance, the insuring party is required to cover costs associated with certain treatment. However, due to adverse selection, the purely private solution may be highly inefficient (in the extreme, no private insurance market will develop). One answer has been to require mandatory insurance. This makes sure that everybody has to buy insurance with some minimum coverage. Such insurances even exist for disaster relief (e.g., fires and inundation). Another reason why some insurance markets do not work properly are uniform pricing restrictions: for example, if insurance companies are not allowed to charge a higher premium for insuring houses located in areas that are particularly prone to floods, people are not discouraged from constructing in such high-risk areas. After addressing these concerns properly, private insurance may work well if individual risks are not highly correlated.

The problem with large-scale catastrophes is that risks are highly correlated. Furthermore, not only those directly affected need some of the essential goods and have to bear the economic cost (think of COVID-19: the whole population was hit by its consequences, whereas only relatively few suffered the contagion). Private insurance, even if mandatory, does not seem an appropriate instrument to address the need of adequate supplies in case of non-localized catastrophic events.

In some cases, proper insurance or other means to provide support in case of health issues or income losses can also mitigate the impact of catastrophes. The COVID-19 pandemic is a case in point. Reducing the spread of the virus requires proper testing and isolation of those tested positive. People who lose their income if tested positive clearly have less incentive to be tested (when they show symptoms or are likely to have been infected) than those whose income is not at risk. Thus, insurance against an income drop can reduce the spread of the virus.

As already discussed above, one might be tempted to view capacity markets as a sort of (compulsory) insurance mechanism. However, there is a clear distinction between the two: capacity mechanisms avoid the damage (i.e., the occurrence of a blackout) by making sure that generators commit enough physical capacity, while an insurance compensates the policy-holder for the damage when it occurs.

3.3. Preparing for an effective reaction

When a disaster hits, people need products or services that they would not need in normal times. Furthermore, they continue to need essential goods whose supplies may have dried up. This is the same problem that arises for any individual who is hit by an unexpected event. For example, if someone suffers an accident, one may need emergency care and the ability to deal with the aftermath (e.g., repair of the car in case of damage, foregone earnings etc.). Ex ante measures that allow for the provision of such essential good and play an important part of a broad resilience strategy.

3.3.1. Procurement of essential goods

Just as we described in the context of electricity markets (Section 2), as part of a resilience strategy, public authorities have to make sure that essential goods will be available in sufficient quantity and quality. A strategy to guarantee provision of goods and services in exceptional circumstances should consist in (i) the precautionary accumulation of essential goods, (ii) measures to guarantee that "when the catastrophic events occur" supply will be ramped up (if, as is likely, the stock of goods is insufficient), and (iii) clear rationing protocols for those goods and periods in which production is not sufficient to meet demand. Capacity mechanisms can be used to address (i) and (ii). Recently, the war in Ukraine has led some member states to design rationing protocols designed to help them cope with any disruption in supplies from Russia.[29]

3.3.2. Storage and spare capacity

Storage facilities where to stock necessary products, and

[28] For instance, in early April 2022, the French System Operator sent an orange alert to signal a tense situation in which electricity production in France was falling below demand due to a combination of increased heating needs and reduced supply availability given outages in half of its nuclear reactors. Households were encouraged to shift the use of their electric appliances and to reduce their in-house temperature.

[29] For instance, "Germany and Austria plan for gas rationing over payment stand-off with Russia", Finantial Times, March 30, 2022.

replenishment, may be publicly provided or privately provided through public procurement. [30] The accompanying monitoring activities are aimed at ensuring that stockpiling volumes and qualities are maintained. For products that are used at some lower volume, a well-managed first-in-first-out system can avoid or, at least, reduce wasteful disposal, as stored products can still be used before the expiration date. To state the obvious, storage facilities should be selected based not only on maintenance costs but also taking into account the logistics of an eventual distribution of the stored products. The provision of such storage can be achieved through capacity mechanisms as discussed in Section 2.

A related consideration that applies to human capital is that there must exist a set of people (with particular skills and functions) who receive continuous training in order to be prepared in case of need (similarly to what is done in several countries with army reserve soldiers). The EU should extend its civil protection mechanism training program, and similar initiatives should be done to prepare, for instance, healthcare workers (in many countries, the lack of protocols on how to deal with the pandemic implied that hospitals, emergency rooms and residences for elders became major vehicles of contagion).

3.3.3. Ramping up production

When a shock hits and creates a situation of excess demand, the market should normally react to match demand and supply. Higher prices will push firms already active in the market to increase their production; other firms may convert their production facilities or enter the sector; privately stored supplies may be put on the market; (international) trade with goods and services will move from less affected to more affected areas. However, as we have explained above in the context of energy markets, there is no guarantee that market forces alone will be able to deliver, or at least not sufficiently rapidly. This may have huge social costs in cases of prolonged crises such as the COVID-19 one. Therefore, a resilience strategy calls for some sort of mechanisms able to guarantee that the availability of essential goods and inputs goes beyond storage. It is important to think of lead times to activate these goods and inputs.

For storable goods and inputs, the question is which fraction should be stored and which fraction could be provided through ramped up production capabilities. Regarding the part of essential goods that is to be stored, the government has the option to do this itself or it can procure this service from private parties. Since this service is provided continuously, standard procurement practices can be used, accompanied by appropriate monitoring to make sure that the contracting parties comply with the requirements laid out in the contract. The contracting party may purely offer storage facilities (with the government holding ownership over the stored goods) or the procurement contract may specify that certain goods have to be kept in stock; payments can then be a mix of payments for storage and for activating the delivery of the stored goods.

The part of the essential goods and inputs that are not stored, but have to be produced at the onset or during a crisis, requires maintaining capacity to provide the essential good up to some quantity within a certain time window. This can be unused capacity or capacity that can be quickly converted from its use in normal times to the production of the specified essential good. This issue links with our previous discussion regarding capacity mechanisms for electricity.

There is also the risk that the disruption in the supply chain prevents a firm from providing the committed production. Imagine that a firm has a valid procurement contract with another company to obtain inputs at short notice. If the shocks are correlated across countries, and the input provider is forbidden from exporting, the contractor will not be able to supply the product. Is there a good answer to this problem? We would argue that the monitoring mechanism has to make sure that the contractor will continue to be able to supply over time at short notice. Possibly, one may introduce a certification instrument for all critical parts of the supply chain to consider the supply chains as resilient.[31] It is possible to think of territorial restrictions because of the difficulty to enforce certain agreements in some parts of the world.

One may think that European ramp-up possibilities are preferred over such possibilities in other parts of the world. In general, however, multiple sources offer diversification and better prospects to expand production significantly. To the extent that ramp-up possibilities are strongly positively correlated in case of geographical proximity, contracting ramp-up capacities in other parts of the world may be the preferred European strategy. Since the essential products thus produced require long-distance transport, port and airport infrastructures have to be capable of accommodating such transports. For example, regional agricultural crises require the transport of food by ship or aircraft.

3.3.4. Rationing criteria

Ahead of a crisis, it is important to set out clear criteria on how to ration demand and avoid hoarding and panic buying so as to reduce the gap between demand and supply. In most countries and for most products, the food supply chain has worked remarkably well, but there is no guarantee that a crisis of different nature (say, one which affects agricultural production, or transportation networks) may not create scarcity of food or other products. During the COVID-19 crisis we have also witnessed something similar to bank runs for some (fortunately less important and certainly well-stocked) goods, such as flour, yeast, toilet paper: as soon as word of their scarcity was spreading, people rushed to buy more of them. In some places, retailers introduced caps to the number of units a single customer could buy, but this improvised rationing is certainly inferior to public protocols of priority purchases, which were absent. The absence of such protocols implied, much more importantly and with crucial consequences, that in many countries the few face masks available did not end up in the hands of those more exposed to the risk of contagion, such as doctors and nurses. As the last example shows, not having a well-thought rationing protocol may be highly undesirable from a society's perspective.[32]

In addition, under severe scarcity of supply, faulty, fraudulent, and sometimes even dangerous versions of the product in need may appear on the market. This requires well-functioning institutions of consumer protection and rigorous quality controls. This may issue may also appear in some energy markets; for instance, regarding the quality of imported coal.

4. Conclusion and policy implications

One of the key roles of the state is to respond to crises, given its *"universalistic duty to protect its inhabitants (and not only its citizens) in times of disaster and to bring relief to its victims …. This duty includes the assessment of risks and the calculation of chance … and investment in preventive measures of all kinds"* [Ophir, 2006]. The state plays a key role by its very nature, but also because private incentives are often insufficient to prepare for rare events with large negative externalities. In this paper we have tried to shed light on the question as to how the state can satisfy this "universalistic duty".

That market forces alone are in general not enough to allow the state to satisfy this universalistic duty is something which we have learnt from

[30] There is a rich literature on procurement that addresses the incentive problems that may arise in such contexts. See, e.g., Dimitri et al., [2011].

[31] The management literature on supply chain resilience addresses the issue how to make the supply chain resilient in case of the risk of disruption from a managerial perspective. For a survey, see, e.g., Mandal [2014].

[32] Allocating goods based on willingness-to-pay often constitutes a socially undesirable allocation mechanism for essential goods in limited supply, as poorer and particularly vulnerable people would be deprived of these essential goods.

the performance of electricity markets. The fear with electricity markets is two-fold: first, that private incentives might not be enough to induce firms to invest in sufficient generation capacity; and second, that price signals might not lead to timely and sizeable demand reductions in response to sudden changes in overall supply or demand conditions. These fears have prompted energy regulators worldwide to put in place capacity mechanisms aimed at reducing the likelihood of energy shortages. By promoting investments in back-up generation capacity, storage capacity or demand response, these mechanisms have become a key instrument to ensure security of supply in electricity markets. Electricity capacity mechanisms therefore illustrate the possibility to address a market failure linked to the public good nature of security of supply with a combination of regulatory decisions (i.e., how much capacity to procure in advance) and market mechanisms allowing to select those firms that are willing to provide security of supply at a lower cost.

The experience with capacity mechanisms in electricity markets provides lessons to cope with security of supply problems in response to other sort of adverse effects (including "black swan" events), despite the obvious limits to which some of these lessons can be applied in practice. In energy markets, different designs of capacity mechanisms have been put in place, but not all of them are equally suited to prevent crises of other sorts, including those that cannot be even expected. As a general principle, we have argued that a centralized and targeted mechanism (such as a system of strategic reserves to be procured through auctions) may perform well in most cases.

Beyond this design question, we have also discussed broader issues when designing a resilience strategy that is based on prevention, early detection and mitigation. While one size need not fit all, certain solutions are valuable to respond to all sorts of events (be it a disaster triggered by natural hazards, another pandemic, or a nuclear accident, to name just a few). These include a robust primary health care system; a strong logistics network; emergency decision-making bodies that combine legitimacy (elected politicians) with expertise (expert advice); and institutions that promote cooperation among countries or regions. It is also worth emphasizing the relevance of "social capital" for facing disasters, a broad term in which we can include the trust in public institutions; the well-functioning of the administration; the society's willingness to follow public recommendations; trust in science against conspiracy theories, and so on.

A resilience strategy would rely on public authorities securing the provision of essential goods in sufficient quantity and quality.[33] In line with the use of capacity mechanisms in electricity markets, this requires putting in place competitive mechanisms to accumulate essential goods, establishing rationing protocols, and facilitating the ramping up of production when the crisis hits. Our analysis also provides an important lesson to energy markets. Resilience against major shocks in energy supply requires a broad resilience strategy – for an effective response, the use of capacity markets would be an important part of a broad resilience strategy, but rationing protocols are also needed in case those mechanisms are not enough to guarantee security of supply at all times – as the recent likelihood of a disruption in Russian gas supplies has demonstrated.

[33] We have argued that a strategy based on private (even if mandatory) insurance is likely insufficient, difficult to implement, and inefficient. What is more, in the best case, insurance hedges against the cost but does not necessarily reduce the incidence of the crisis, nor would it guarantee the physical availability of the essential goods when they are most needed.

CRediT authorship contribution statement

Natalia Fabra: Writing – review & editing. **Massimo Motta:** Writing – review & editing. **Martin Peitz:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Natalia Fabra is a board member of the Spanish gas TSO, ENAGAS.

References

Callon, Michel, 1994. Is science a public good? Fifth Mullins lecture, Virginia polytechnic Institute, 23 March 1993. Sci. Technol. Hum. Val. 19 (4), 395–424.
Cramton, Peter, Ockenfels, Axel, Stoft, Steven, 2013. Capacity market fundamentals. Econ. Energy Environ. Pol. 2, 27–46.
Cramton, Peter, Ockenfels, Axel, Roth, Alvin E., Wilson, Robert B., 2020. Borrow crisis tactics to get covid-19 supplies to where they are needed. Nature 582 (7812), 316–319.
Dimitri, Nicola, Piga, Gustavo, Spagnolo, Giancarlo, 2011. Handbook of Procurement. Cambridge University Press.
European Commission, 2020. Science, Research and Innovation Performance of the EU 2020 – A Fair, Green and Digital Europe. Publications Office of the European Union.
Fabra, Natalia, 2018. A primer on capacity mechanisms. Energy Econ. 75, 323–335.
Fabra, Natalia, Rapson, David, Reguant, Mar, Wang, Jingyuan, May 2021. Estimating the elasticity to real-time pricing: evidence from the Spanish electricity market. AEA Pap. Proc. 111, 425–429. https://doi.org/10.1257/pandp.20211007. URL. https://www.aeaweb.org/articles?id=10.1257/pandp.20211007.
Hogan, Michael, 2017. Follow the missing money: ensuring reliability at least cost to consumers in the transition to a low-carbon power system. Electr. J. 30 (1), 55–61.
Jenny, Frédéric, 2020. Resilience and governance. COVID Econ. 1, 64–78.
Loewenstein, George, Prelec, Drazen, 1992. Anomalies in intertemporal choice: evidence and an interpretation. Q. J. Econ. 107, 573–597.
Loewenstein, George, O'Donoghue, Ted, Rabin, Matthew, 2003. Projection bias in predicting future utility. Q. J. Econ. 118, 1209–1248.
London Economics, 2013. The Value of Lost Load (Voll) for Electricity in Great Britain. https://londoneconomics.co.uk/blog/publication/the-value-of-lost-load-voll-for-electricity-in-great-britain/.
Mandal, Santanu, 2014. Supply chain resilience: a state-of-the-art review and research directions. Int. J. Disaster Resilience Built Environ. 5, 427–453.
Motta, Massimo, 2020. Price regulation in times of crisis can be tricky. Daily Maverick, 20 April.
National Academy of Medicine, 2016. The Neglected Dimension of Global Security: A Framework to Counter Infectious Disease Crises. The National Academies Press., Washington, DC.
Newbery, David, 2016. Missing money and missing markets: reliability, capacity auctions and interconnectors. Energy Pol. 94, 401–410.
Ophir, Adi, 2006. The two-state solution: providence and catastrophe. Theor. Inq. Law 8, 117–160.
Sehgal, R.N.M., 2010. Deforestation and avian infectious diseases. J. Exp. Biol. 213, 955–960.
Stiglitz, Joseph E., 1977. The theory of local public goods. In: Feldstein, M.S., Inman, R.P. (Eds.), The Economics of Public Services, International Economic Association Conference Volumes. Palgrave Macmillan, London.
Tirole, Jean, 2020. Facing the coronavirus, "are we finally going to learn our lesson?". TSE Blog. https://www.tse-fr.eu/facing-coronavirus-are-we-finally-going-learn-our-lesson.
United Nations Environment Programme and International Livestock Research Institute, 2020. Preventing the Next Pandemic: Zoonotic Diseases and How to Break the Chain of Transmission. Nairobi, Kenya.
WHO, 2020. Global Preparedness Monitoring Board Annual Report 2020. World in disorder.