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Article

Institutional implications for science and industrial capacity: policy lessons from the UK's pandemic response

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Global shortages of critical equipment and supplies induced by COVID-19 forced countries to rapidly build and ramp up their indigenous testing and production capacities. However, the many ways in which institutional and organizational change occurred has not been sufficiently captured. Building domestic capacity requires the leveraging and repurposing of existing domestic scientific and technological capabilities, coupled with intensified global outreach to new and existing partners and suppliers. Using the framework of institutional variety, this paper looks at two facets of the UK's COVID emergency industrial response: (1) building its laboratory testing capabilities and (2) for increasing production of personal protective equipment; assessing the institutional capacities and relations that were leveraged in this regard. It uses these findings together with observations of 'innovation processes under emergency conditions' and the potential uses of a 'critical equipment policy' to sharpen some of the recommendations made in the UK's post-COVID Research and Development Roadmap.

Keywords: industrial policy; institutional variety; capacity building; COVID-19; UK; science infrastructure.

1. Introduction

The COVID-19 pandemic has underscored the importance of national autonomy in responding to emergency conditions and the freedom to make complex choices about medical equipment and testing, with local health outcomes in the foreground. However, this has been done in a context of highly uneven, conflicting, global health guidelines, and inter-country information sharing about how to respond to COVID-19. Rather, with little industrial policy expertise, the WHO issued a universal guideline to 'test, test, test' with understandable interest in, but incomplete and uncertain, clinical foreground detail and very little attention to the vital industrial background and national customization needs of countries as they moved to initiate testing in a supply-constrained environment (Srinivas, Prasad, and Rao 2020). Policy needs to acknowledge that in different national and regional contexts, the co-evolution of key institutions regarding industrialization and healthcare is not one of uniformity but of institutional variety (Srinivas 2021, 2023). Understanding this variety of how institutions (customs, norms, guidelines, standards, laws) and organizational forms can change during an emergency can be critical both to crafting and implementing an effective pandemic response and aligning emergency health response with long-term economic development gains in the development of core innovation processes and critical equipment.

Equally crucial was the political economy of building such capabilities. While shades of a new economic nationalism pervade much of the political discourse in support of the domestic capacity building, such rhetoric distorts both the real policy and industrial response to COVID in most countries. Our findings point to a different process in which institutional variety (IV) is useful to explain how and why an inward focus on domestic capacity and production cannot be separated from, indeed is coupled with, intensified global outreach to new and existing suppliers worldwide. Contrary to some of the accompanying rhetoric, the actual policy and practice is one where no country could do it alone. In this perspective, the pandemic illuminates the adaptability through recombination of industrial innovation systems and the continued importance of external sources of knowledge and resources, with new emergent strategies under emergency conditions. While this industrial policy response under highly compressed timelines could be viewed as largely temporary, the details of the recombination and extent of IV matter to its post-pandemic UK industrial strategy and future emergency responses in a variety of national contexts.

As such, this paper looks at the COVID emergency industrial response of the UK, specifically its Lighthouse Lab Network, and its efforts at increasing the production and supply of personal protective equipment (PPE). Both laboratory-based diagnostic capability and PPE production demonstrate innovative repurposing capabilities under rapid change, and constitutes a crucial example of a critical equipment policy that could have long-term economic development potential if recognized as such. In the case of increasing testing capacity, we show that the UK leveraged and expanded both its existing domestic laboratory capacity and university–industry relationships, with the help of incumbent international partners and newly established global suppliers. For increasing access to PPE, the UK pursued a strategy that aimed to increase domestic production of PPE through non-traditional suppliers of PPE in the UK and through aggressive contracting with both existing and new global suppliers of PPE. In this sense, the UK epitomizes this dual track industrial strategy, where the immediacy of the pandemic forced the UK to rapidly leverage domestic scientific and business engineering capabilities while seeking secure links to global suppliers for the same types of capabilities and products.

For this paper and its IV perspective, we take a preliminary look at the institutional relationships and resulting capabilities that shaped the UK's COVID emergency response; this informing potential future research on the nature, governance, and speed of such change, a crucial question for the organization of scientific efforts and industrial policy design. Finally, we look to put forward a set of broad policy recommendations that both inform and reinforce the UK's post-COVID Research and Development Roadmap. The UK is a compelling case to begin our inquiry. While the UK's COVID response was national, strategies for building domestic capabilities and securing access to PPE were, on the one hand, coordinated between the four nations of England, Scotland, Wales, and Northern Ireland. On the other hand, each of the devolved administrations exercised varying degrees of autonomy in implementing the national strategy.

This paper is structured as follows. Section 2 builds our research framework and key assumptions. Section 3 explains our methodology and the case study approach. Section 4 and 5 present our two cases, along with some initial analysis regarding key assumptions. Findings from each are further discussed (Section 6), including implications for policy and future research. Section 7 concludes.

2. IV, innovation, and emergency response

National responses to COVID-19 have generated interest among academics and policy makers as to how the institutions that govern and produce innovations have adapted and changed in meeting this necessary response, particularly in the push to develop new therapies and vaccines. For example, Sampat and Shadlen (2021), taking an innovation systems approach, argue that the US response to COVID-19 has involved a change in government funding of biomedical research, from a pre-pandemic focus on basic research funding and patent-based development incentives to a new emphasis on late-stage product development and procurement agreements. Given less attention in the literature, although not less important, are expected changes to other areas of the biomedical innovation and industrial production system as a result of COVID-19, notably in the areas of diagnostics and other medical equipment. Whereas new therapies and vaccines will initially require significant R&D, an emergency ramp-up for diagnostics and other essential medical equipment will likely involve less intensive R&D and more emphasis on rapid development and deployment of capabilities and scale-up processes. Our choice of framework and attention to PPEs emerge from an interest in industrial systems and the R&D functions and manufacturing embedded within it.

2.1 IV, emergency response, and organizational interactions

Building upon innovation systems, yet diverging in fundamental ways, IV is an approach that considers how different institutional contexts and relationships over time shape the way new knowledge is sourced and converted into productive capabilities (see Srinivas 2021). 'Institutions' means the evolving set of customs, norms, guidelines, standards, and various rules, that shape and govern innovation and related industrial policies. For example, industrial procurement, intellectual property, good manufacturing practice standards, are all examples of institutions in industry, but so too are new, more fluid, hybrid public–private partnerships, special purpose vehicles for investment, consortium bidding, and so forth. Specific organizations and agents act under such institutional frameworks, and also shape institutions in turn over time, a feature well recognized in scholarship of institutional as well as evolutionary economics. In this way, IV can demonstrate and explain how the institutions that structure, facilitate, and govern innovation and new organizations—behave rather differently in different national, regional, and sectoral contexts, and in this paper, under emergency stressors.

Moreover, the health policy response itself can be framed through the institutional emphasis on specific industrial institutions. For example, Srinivas, Prasad, and Rao (2020) highlight at least seven biological and clinical uncertainties that depended on exactly how countries industrially approached the problem of Covid-19 diagnostic kits production, making the relationship between laboratory science and clinical effectiveness highly dependent on available industrial characteristics and the organization and network ability to operate at scale, a point that WHO health policy directives did not appear to recognize. Furthermore, the several uncertainties on biological and clinical ends and their industrial dimensions are not directly equitable and are also parsed differently by professional communities well before PPE or diagnostic kits supply meets demand. In essence, countries with existing technological capabilities when faced with trade blockages and/or lock-downs had to scramble to institute customized scientific as well as engineering problem-solving, and to institute systems of incentives and norms and laws that ensured diagnostic kits and PPEs were rapidly manufactured and used to clinical specifications.

Similarly, in looking at emergency response to communicable disease outbreaks (e.g. TB, Malaria, and Ebola), Ramalingam (2015) posits that under emergency conditions, the innovation process can look much different than it is normally described. First, because of the rapid unfolding of most emergencies, timeframes for making decisions are condensed. Second, available resources are also limited, and this difficulty can be compounded by the location of the emergency. Third, processes for innovation and processes for delivery will need to occur concurrently. Finally, these accumulated pressures often result in solutions that rely on known technology and processes rather than on new technology and new approaches to either production or delivery. Overall, the need to rapidly respond to the said emergency constrains the innovation process, forcing it to make decisions on a narrow, more familiar set of options and processes that are more likely to address the emergency in an acceptable timeframe. As such, the focus of the response is on the scaling-up of existing capabilities and the repurposing of know-how, rather than the development of an entirely new technology or product; this likely under unusually tight resource constraints.

The interlinkages but not necessarily the variety itself are recognized in the constructs of most institutional treatments of innovation (e.g. innovation systems, innovation ecosystems, etc.), the core institutional actors are (1) governments and related agencies supporting innovation through regulation, standard-setting, public–private partnerships, and funding of basic research; (2) sectors and industries comprised of firms that generate commercial innovations through experimentation, R&D, and product improvement; (3) universities which conduct basic research and train a technical and scientific workforce; and (4) other public and private organizations that engage, often in an intermediary role, in knowledge collection and diffusion activities (Patel and Pavitt 1994; Watkins et al. 2015). Key to this structure are interactions within and between institutions which Lundvall (1992) and others describe as a variety of user–producer linkages and feedback loops (Nelson and Winter 1982) that facilitate information sharing leading to cumulative knowledge and collective learning. From an IV perspective, these interactions are understood as 'relationships' that evolve over time and which shape the behaviour, customs, and governance of innovation. In some countries and industries, these relationships may have different configurations. That said, under emergency response conditions, it is expected that some similar response tendencies will be exhibited across different country contexts assuming they are able to manage these existing relationships or steer them to new goals.

Assumption 1: Under emergency response conditions, it is expected that interactions between organizational actors will be more intense, more narrowly focused, and that learning processes will speed up. It is also expected that the government will take the 'leading' role in directing and coordinating the ramp up of capabilities for innovation, production and scale-up, with the main institutional and organizational relationships emerging between government and industry.

2.2 Innovation, emergency response, and strategies for development

Although early institutional frameworks regarding innovation, most notably, the national innovation systems (NIS) approach, were derived primarily from countries in the developed 'North', these frameworks were also used to gain understanding on how some emerging countries successfully developed (see Nelson 1992, 1993). For example, the story of Japan's NIS and the subsequent rise of South Korea, Taiwan, and Singapore (see Kim 1993; Nelson 1993; Lall 1994; Freeman 1995; Mowery and Oxley 1995) is one of the effective economic 'catch-up'. Common to these countries' catch-up strategies were significant government intervention in and championing of key industries, along with carefully crafted policies to support reverse engineering of foreign technology and subsequent technological leapfrogging by latecomer firms, support for patent protection, as well as an emphasis on public education and the building of a technical workforce (Nelson 1993). Importantly, these countries supported and directed national innovation strategies that effectively balanced protectionism for key indigenous industries with a degree of system openness—allowing these industries to adopt, exploit, and improve upon technology and organizational practices from the advanced economies. This gave rise to notions that effective innovation systems required a degree of openness and receptivity to external ideas and information.

From an IV perspective, domestic capabilities of some industrialized countries, even when regarded less 'advanced' in comparison to those of other industrialized countries, will likely offer more appropriate and effective solutions to a country's innovation priorities. Also, a country's openness to external knowledge and technology is not akin to technology replacement or adoption, but rather 'absorption' in that it is normally integrated, where appropriate with domestic capabilities, often utilized in novel or unintended ways; these are based on a particular country's pre-existing innovation-related customs, standards, and norms. If IV, the many possible ways of doing things, is not constrained by existing technological capabilities, then at least in principle, all institutional combinations are possible and policy-induced institutional change merely reverts to policy-makers' priorities. On the other hand, if existing technological capabilities are in question or weakened by missing imports at a crucial time, only some institutional combinations are amenable to policy interventions in the industrial arena.

Although the context is different, we suggest that countries responding to COVID-19 through building domestic capabilities and selective external outreach are, in some respects, following some version of the import substitution industrialization (ISI) and economic catch-up strategies of countries that have recently industrialized. Practised widely from the 1950s to the 1980s, ISI is essentially a trade and economic strategy that aims to replace foreign imports with domestic production (see Heidhues and Obare 2011; Adewale 2017). The ISI literature, at the time, was dominated by post-independence, largely national developmental contexts of analysis (see Ahmad 1978). However, ISI is still broadly conceived as a framework relevant to manufacturing industries (Lall 1994) and views the domain of production as the primary arena of building technological capabilities (Amsden 1994, 2004). One of the main differences of course, is that 'catch-up' strategies of these countries took decades to fulfil, whereas COVID-19 has forced countries to ramp up capabilities in a matter of weeks and months.

Assumption 2: Under emergency response conditions, it is expected that policy- induced institutional changes focus first on leveraging, developing, and protecting domestic capabilities while also seeking out external knowledge and resource inputs where necessary.

2.3 Innovation, location, and global linkages

Early concepts of the NIS came under increasing criticism for, among other things, missing important underlying processes through which innovations actually come about (see Miettinen 2002). As a result, several concepts were developed that considered innovation 'at other levels of the economy than the nation state' (Lundvall 2007: 100). One such approach is the regional innovation systems (RIS) concept proposed by Asheim and Isaksen (1997) and Cooke, Uranga, and Etxebarria (1997) which proposes that innovation is best understood as a local or regional phenomenon where interactions, knowledge exchange, and learning occur between geographically proximate actors and institutions which are bounded to a particular location. That said, these agents hold sector-specific knowledge and their interactions are influenced by institutions that may have both local and international dimensions, interactions that are facilitated, for example, through the research linkages of universities and the global R&D activities of multinational corporations (see Pietrobelli 1996; Pavitt 2002).

From an IV perspective, regions, and localities, even those closely proximate to one another and within the same national context, can exhibit long-standing differences in how knowledge is viewed and sourced, institutional adaptability especially within existing umbrella rules, capacities for innovation, and differing degrees of absorptive capacity, leading to variation in innovation processes of production, delivery, and governance. These differences driving a predominately 'local' response (not only planning, investment, implementation, and delivery, but also 'acceptable' risks, delays, and shifting power of actors) to emerging and more immediate innovation and production needs, and this led in large part by local and regional institutions.

Assumption 3: Under emergency response conditions, it is expected that institutional uncertainties and new organizational shifts toward developing capabilities will occur most prominently at the local and regional level. Also, it will be at the level of the region where domestic capabilities and global inputs will interface.

3. Methodology and case study approach

For exploring these assumptions, we focused on two significant components of the UK's COVID response in order to understand which institutions were changing and what organizations were coming to the forefront at any time: (1) the UK's Lighthouse Labs network, and (2) the UK's ramp-up system for PPE production. Document collection and online research were carried out from June 2020 to August 2020. Importantly, we do not directly assess the effectiveness of these two 'cases', each representing different types of institutional responses. For each case, our aim was to identify changes (by law, business strategy, new associations, and new techniques) in the main institutional frameworks and the resources and processes through which main and supporting organizations framed, developed, and deployed their capabilities. For doing so, we collected and analysed relevant journal articles, newspaper articles, learned society publications, government COVID strategy reports, as well as analysis of relevant websites, e.g. LLN facility websites. The most important reports and sources are referenced. Journal and newspaper articles were used primarily to understand the context and state of diagnostic capability and critical equipment supplies running up to the pandemic and for corroborating the implementation of the UK government's COVID strategy. Government reports and white papers were used to understand the government's rational and strategy toward increasing testing capability and PPE supplies, as well as strategy implementation and progress.

Because of a distributed innovation response in organizations and also UK policy structure, we sourced data from previous research projects on Scottish and UK innovation systems (Tait, Chataway, and Wield 2002; Mastroeni *et al.* 2017). Our primary sources of data were the UK government's COVID strategy documents; documents pertaining to both the UK's overall strategy for COVID diagnostic and PPE development, as well as separate strategy documents put forward by the Scottish government. For both the UK and Scotland, these documents described the initial respective strategies at the onset of the pandemic, roughly January/February 2020, and then its subsequent and rapid implementation in the form of strategy 'progress reports', these coming out every 4 to 6 weeks during the height of the pandemic. Websites pertaining to the LLN and PPE production were searched and analysed to understand the background and implementation of the government's strategy and to capture the background and role of participating actors.

Given the focus on the building of emergency capabilities and simultaneously cataloguing the variety of institutional responses and organization forms (including ownership), this descriptive data mainly offered, among other things, a lens to understanding strategic continuity and possible divergence as the pandemic and corresponding strategy unfolded within the structure of the two cases over those first critical months of emergency response. Again, these data were continuously corroborated with online news articles—reporting on the government's COVID strategy—and relevant websites, e.g. websites for individual LLN locations and laboratories. These articles and websites provided crucial background on the organizational and technical capabilities of individual laboratories, the extent of capability enhancement and expansion that took place, as well as the main actors involved.

Following a mainly inductive method, tracking the organizational emergence as well as policy narratives in real-time, preliminary analysis of data were carried out from September to October 2020, with more follow-on analysis completed in December 2020. Thus, looking for evidence of our main assumptions, our analysis focused on tracking (1) government–industry partnering in developing COVID diagnostic and PPE capabilities; (2) the extent of both leveraging existing domestic capabilities and seeking out external capabilities; and (3) the role that regional capabilities, e.g. the capabilities of specific laboratories and related infrastructure, play in the selection, development, and operation of diagnostic facilities and PPE manufacturing sites.

This is a preliminary contribution to understand the nature of institutional variety, the uneven nature of organizational shifts taking place, and the important role of policy design. As such, fast-moving emergency contexts offer promise for a new emphasis on improving inductive methods especially new 'tracking calendars', offering ways of capturing and separating policy rhetoric from actual organizational networks and their capabilities.

4. UK COVID testing capability at the beginning of the pandemic

As the pandemic emerged in January 2020, the UK found itself in a seemingly favourable position as it was one of the first countries to have an accurate antigen test—developed from the COVID genome which scientists in China identified and made available (La Marca et al. 2020). At this time, the UK had 40 NHS labs capable of carrying out 4,000 daily COVID tests, which appeared sufficient for the small number of initial cases (Baraniuk 2020; UK GOV 2020a). The UK also had long-established links to global suppliers for reagents and testing equipment for which they relied on exclusively, i.e. there were no domestic UK suppliers. That said, the UK did not have a working test and trace system in place, although was attempting to develop such a system. As UK and global cases rose significantly in February and March, the UK's 40 NHS labs were carrying out about 5,000 tests a day, far short of what was needed: the UK simply did not have the lab capacity for large-scale public testing. Furthermore, no reliable testing system had been developed or implemented and, most concerning, global supplies of needed reagents and swabs were limited due to the unprecedented global demand (Baraniuk 2020; Kirkpatrick and Bradley 2020). As a result, the UK had to do the following: (1) increase laboratory capacity; (2) create a testing system (3) secure future testing supplies; (3) implement an effective test and trace system; and (4) do this rapidly (1–2 months). All four challenges were pursued. However, to do this, the UK placed most of its efforts toward expanding and developing laboratory testing capacity and re-establishing global supply links to source critical testing supplies and equipment (UK DOHSC 2020).

4.1 Building laboratory testing capacity: the Lighthouse Lab network

For building its laboratory testing capacity, the UK initiated plans to increase the capacity of existing NHS labs (NHS and Public Health England)—from 5,000 to 25,000 tests per day and to create 3 Mega-labs (Lighthouse labs) designed to boost mass testing to 100,000+ per day, along with tests at drive-through centres and at homes. For its choice of sites, the UK took advantage of a range of life science investments over the last decades (UK DOHSC 2020). The three lighthouse mega labs are:

(1) Lab in Milton Keynes (opened on 9 April 2020) at the offices of the UK Biocentre, a not-for-profit business established in 2011, established and funded by the UK National Institute of Health Research;

(2) Alderley Park in Cheshire (opened on 20 April 2020), run by Medicines Discovery Catapult Ltd, and funded by Innovate UK. It is located on what was once the laboratories of Imperial Chemical Industries (ICI) (see below) and what is now a science park;

(3) University of Glasgow lab (opened 24 April) located in its Clinical Innovation Zone at the city's Queen Elizabeth University Hospital campus, funded as a Scottish Catapult by the Scottish government (UK GOV 2020a).

The Lighthouse Lab Network (LLN) also includes the establishment of three smaller labs for regional and complementary capacities: a lab in Northern Ireland run by Randox, a Cambridge-based lab run by AstraZeneca and GSK, and a lab in Newport, Wales, brought online by PerkinElmer. Both AstraZeneca and GSK provide support and expertise to the entire network, with supplies and equipment provided by ThermoFisher Scientific, TECAN and Brooks Laboratories (UK DOHSC 2020). The labs are supported and governed by NHS England, Public Health England, and the UK Department of Health & Social Care, with governance of the Glasgow lab led by the Scottish government (LLN 2020).

Looking at the LLN overall, there is significant diversity among the various labs in terms of each site's origins and pre-COVID use, the extent of industry collaboration, and local actor involvement (the latter to be discussed later in the paper). The lab at Alderley Park is a good example. A historically important site for pharma research in the UK, Alderley Park was the site of the pharmaceuticals R&D laboratory of the UK national champion CI). ICI was originally set up after the First World War, an early state investment towards a private company to help catch-up to German chemical giants. This became Astra-Zeneca during the Thatcher industrial 'reforms' which led to ICIs division. When Astra-Zeneca closed Alderley Edge and moved to Cambridge, it became a science park for spin-off and new companies (Pharmaceutical-technology.com 2021).

The origins of the Milton Keynes lab are of more recent history in that it is built as an expansion to the laboratory facilities of the UK Biocentre, a non-profit organization established in 2014 (UK Biocentre 2021a). As another example, the Glasgow lab is located in the newly developed University of Glasgow's Clinical Innovation Zone, close to the Queen Elizabeth University Hospital. In this way, the Lighthouse labs, for the most part, are all built upon and/or are expansions of existing pharma and innovation-based sites, aligning with aspects of our assumptions (2) and (3), positing that the time urgency of emergency situations will force nations and localities to build on existing capabilities rather than develop inherently new capabilities.

Despite the organization diversity mentioned earlier, there are a number of additional institutional commonalities among the labs. First, the UK government and devolved administrations play the lead role, as expected in assumption (1), both in terms of funding and coordination, with Public Health England, NHS England, Department of Health and Social Care, and their Scottish equivalents all taking the respective leads. Second, the three mega-labs are managed by governmental or non-commercial entities. For example, the labs at Alderley Park and Glasgow are governed by Innovate UK and government-funded Catapults. Furthermore, the Glasgow and Cambridge labs in particular, have strong university linkages and support, including the use of university faculty, support staff, lab space, and equipment. Also, the three main labs are all housed either in public or non-commercial sites and facilities. Additionally, all main LLN sites became operational within 4 months of the pandemic's emergence in the UK. Again, government and public involvement in these sites is significant, this includes government and publicly owned facilities and capabilities, lending support to assumption (1) pertaining to the essential and leading role that government plays: it is government that has the mandate and resources to so rapidly ramp-up testing capabilities in this way.

While led by government, the LLN can be described as a partnership between government and private industry, with industry taking the lead in both providing the bulk of laboratory equipment, particularly in new equipment provided for expansion purposes, and for overseeing and managing, to varying extents, the day to day operations of each site. For example, AstraZeneca and GSK not only play the lead role at the Cambridge lab but are also significant participants in the other LLN labs. Both long-established pharma giants have a strong presence in the UK, with GSK having its global headquarters in London. Providing laboratory instrumentation and reagents to the LLN is US-based Thermo Fisher

Scientific. For ramping up laboratory automation capabilities, LLN has turned to Swiss-based TECAN. Another significant contributor to the LLN is Indian-based Brook Laboratories, providing sites with laboratory and testing supplies. This mix of companies shows that for building its laboratory testing capabilities, the UK both leveraged incumbent, UK-based pharma companies, while employing capabilities from established companies in the USA, Europe, and India. In this way, addressing the pandemic required a continued reliance on a very much 'global' pharmaceutical industry. In other words, building these capabilities could not be done through UK-based companies alone: confirming our assumption (2) *that governments will leverage domestic capabilities while also seeking out external knowledge and resource inputs where necessary*.

4.2 Lighthouse Lab: Milton Keynes

The lighthouse lab in Milton Keynes, the largest lab in the network, is led by and built on the existing laboratory facilities of the UK Biocentre. Established in 2014, the UK Biocentre is a non-profit organization offering services in sample collection kit assembly, DNA/RNA extraction, and sample storage (UK Biocentre 2021b). According to UK Biocentre's website, creating capacity for large-scale COVID testing has been accomplished by both repurposing existing laboratory facilities and building new lab facilities, along with increasing the number of employed scientists, from 35 to 200, 'working on shift patterns 24/7' and working exclusively on COVID testing—all routine research services have been halted. For testing at scale though, the lab also had to both develop and expand significantly its automated processes: 'To test tens of thousands of COVID-19 swabs every day requires an automated process - a seismic shift to industrial scale. So, whilst manually testing samples, we simultaneously developed a wholly automated process. Liquid handling robots and other kit and machinery now fill our laboratories' (UK Biocentre 2021a). Automation equipment and systems appear to be provided by TECHAN, an Austrian-based company specializing in automation systems for the pharmaceutical and healthcare industries. Additionally, a key supplier of laboratory equipment and testing supplies is the Indian-based company, Brooks Laboratories Limited.

In considering the Milton Keynes lab, a few things stand out which reinforce and build upon our assumptions of institutional recombination toward innovation under emergency response. First, the Milton Keynes lab is a total repurposing and expansion of a non-profit facility that prior to the pandemic engaged exclusively in the analysis and storage of biological samples for academic research, reinforcing the notion that it is much easier to swiftly repurpose public or non-commercial facilities than private facilities. In a sense, for rapid ramp-up, public capabilities, unencumbered by profit considerations and business uncertainty, can move more decisively. Once this public decision is made and resources are mobilized—easing uncertainty—private capabilities then come onboard. This also highlights how important public university research infrastructure, including organizations that service it, is for mounting an effective innovation response to a public emergency. Second, key to this infrastructure's rapid mobilization is its human resources, with the MKL employing hundreds of new university scientist and technologists. In other words, building facilities is not enough. Without the immediate access to human capabilities and a clear institutional umbrella of working norms, customs, and standards toward an emergency outcome, a rapid 'technological' response as shown with the LLN would likely not be possible.

Complementing the human capabilities, and no less important, are laboratory systems that are highly automated. Automated systems allow for testing that is rapid, accurate, and scalable. Building a highly automated testing system is expensive (equipment and integration) and generally takes time to get the system up and running properly. The Milton Keynes lab had the advantage in that it is an expansion of an existing facility that was already highly automated, making the scalability of operations a far quicker process than it would have been if building the facility from scratch. It seems apparent, that these capabilities, both the human (scientists and technologist) and the technological (automation) employed at the Milton Keynes lab are, due to costs, available to only a certain number of countries, either obtained indigenously or externally or both.

4.3 Lighthouse Lab: Glasgow

Hosted by the University of Glasgow at their Queen Elizabeth University Hospital Campus, the Lighthouse Lab Glasgow is led by Scottish SME BioAscent with governance and support provided by the Scottish Government, the University of Glasgow, and the University of Dundee (University of Glasgow 2021a). According to the lab's website, the Glasgow site was chosen, in part, due to its location within the University of Glasgow's Clinical Innovation Zone: 'a space that was designed to meet industrial scale-standards and was therefore readily able to be transformed into a testing facility in response to the COVID-19 UK outbreak'. The Clinical Innovation Zone, funded by the Scottish Government, is described by its Director, Prof. Anna Dominiczak as a 'triple-helix collaboration' between the NHS, industry, and academe. Furthermore, significant existing lab capacity at the University of Glasgow was leveraged and repurposed: 'The Lab is currently equipped with 20 protective cabinets sourced from the University of Glasgow, a fleet of fast high throughput ThermoFisher PCR machines and RNA extractors. Much of the equipment has been sourced from University of Glasgow labs and moved to the new testing centre in order to make rapid COVID-19 response work possible' (University of Glasgow 2021b). Leveraging Scottish life science capacities, the lab brought in expertise and leadership from Newhouse Scotland based BioAscent, a Scottish drug discovery service company. Founded in 2013, BioAscent specializes in 'high-throughput screening, assay development and sample logistics'. Dr Phil Jones, BioAscent's Chief Scientific Officer, leads the Glasgow lab as Director of the testing facility and Dr Stuart McElroy, BioAscent's Director of Biosciences, who is working as the Glasgow lab's Head Scientist (BioAscent 2021). About 800 volunteers in Glasgow came forward from their normal science work to help set up the lab (University of Glasgow 2021b).

The Glasgow lab holds much in common with the lab in Milton Keynes in terms of its institutional recombination of existing variety, but the importance of local capabilities is even more significant in that it underscores why IV cannot be understood in purely national UK terms, but is locally situated. In one sense, this is about the capabilities of the

University of Glasgow coupled with the leveraging of uniquely Scottish capabilities. Again, university research capabilities and infrastructure are shown to be paramount for this particular COVID response, with the University of Glasgow and its university hospital partnering with the University of Dundee—two premier Scottish research universities. According to the lab website, much of the equipment, including that from Thermo-Fisher has been repurposed from the University of Glasgow itself. The same goes for lab personal, many it seems coming directly out of University of Glasgow labs. This repurposing was likely critical in the rapid set-up of the lab.

Having the spatially proximate 'innovation zone' also appears critical to the lab's rapid set-up in two ways. First, the innovation zone has the space in which the lab could be set-up as an expansion of existing University of Glasgow laboratory space. The proximity of the innovation zone to the university's other biomedical research facilities and hospital likely facilitated the lab's development and operation. Second, the innovation zone brings together expertise and experience in academic–industry partnering toward innovation. Such experience can help facilitate the rapid integration of academic capabilities with those of industry and their aims—critical to bringing industry on-board in a constructive way. Finally, bringing in Scottish-based BioAscent to lead and run the lab operations is interesting in that it is a relatively new company when compared to the more established and larger pharma players. Although not confirmed through this research, BioAscent's significant role in the lab may be motivated by both the company's capabilities and Scottish aspirations for its bioeconomy (potential for organizational learning and partnering). Again, looking more closely at such implications could prove important in our understanding of the near and long-term implications of this COVID emergency response on regional and national innovation capabilities.

5. PPE: UK Context at Beginning of Pandemic

As the pandemic emerged in January 2020, the UK Government stated they had adequate supplies of essential PPE—this based on planning for a flu pandemic. Prior to the pandemic, the majority of PPE in the UK was manufactured and supplied from abroad, much from China. In this way, the UK was reliant on established global suppliers to maintain PPE stock and resupply. Prior to the pandemic, PPE was ordered and delivered to all 226 NHS Trusts on a 'just in time' basis. As the UK entered lockdown in late March 2020, problems were evident: while the UK GOV sought additional PPE through traditional global suppliers, it soon became clear that global supplies had either already been bought up or held by supplier countries. Shortages of critical equipment included: disposable gloves, disposable plastic aprons, disposable fluid repellent coverall gowns, surgical masks, fluid-resistant (type IIR) surgical masks, filtering facepiece respirators, and eye/face protection (eye shields, goggles, and visors). Regarding PPE delivery, the UK did not have a delivery system in place nor one planned that could either deliver 'daily' or 'rapidly' to all 226 NHS Trusts and to the thousands of social care facilities in need of PPE.

As such, the UK needed to: (1) increase their supply of PPE and ensure future access to PPE and (2) put in place an effective delivery system to get essential PPE to not only hospitals but also social care facilities and front-line essential workers. In a sense, the UK response toward increasing PPE production and supply could be called a form of critical equipment policy (CEP), one which was implemented with some variation among the devolved administrations. We first look at the overall UK policy and then look at Scotland as a particular case of CEP.

5.1 UK Emergency Response to Improving PPE Supply

In April 2020, the UK government set up a dedicated unit for securing supplies of PPE. Staffed by NHS Supply Chain and the Government Commercial Function, this unit, in coordination with the Foreign Commonwealth Office and Department of Trade, was tasked at identifying PPE suppliers from across the globe (UK GOV 2020a). These efforts are in conjunction with courting and accepting donations of PPE from major companies, e.g. Apple, Kingfisher Group, BP, and Airbus. A third component of this emergency response was the implementation of a new 'Make' strategy for encouraging UK manufacturers to produce PPE with the aim to acquire 20 per cent of its PPE through domestic manufactures by the end of 2020. For example, companies such as Royal Mint, Burberry, Rolls-Royce, and McLaren committed to producing gowns and visors; Ineos, Diageo, and Unilever to produce hand hygiene products; and seeking companies to make face shields and eye protection. For the 'Make' strategy, a technical and safety assurance process has been set up involving regulatory bodies with support of the Health and Safety Executive and Public Health England (UK GOV 2020a). The 'Make' strategy was headed by Lord Deighton, the government's adviser on PPE who previously led the London 2012 Olympics and Paralympics. As of 25 June 2020, the UK government claimed that, through the Make strategy, more than thirty deals had been struck with UK companies: 70 million face masks agreed with Honeywell; Don & Low to manufacture 12 million metres squared of fabric for gowns; Jaguar Land Rover to manufacture 14,000 visors a week for healthcare staff. The UK government claims they are working with over 175 new suppliers for PPE and that sufficient stockpiles of essential PPE have been achieved. Devolved UK administrations, in Wales Scotland and Northern Ireland, have what appear to be separate, although coordinated, procurement programmes.

5.2 Scottish emergency response to improving PPE supply

In Scotland, a multi-agency team (NHS, Scottish Enterprise, Scottish Development International, and the National Manufacturing Institute Scotland, operated by University of Strathclyde) worked with industry to increase Scottish capacity to make key products, with this done through a wide range of producers. The strategy was to mobilize Scottish-based companies and support collaboration, including with international partners. It is a small example where industrial policy was implemented towards health policy outcomes. What follows is a list of critical equipment sourced and the companies involved (SCOT GOV 2020):

- Fluid-resistant (Type IIR) surgical masks: Alpha Solway, based in south-west Scotland, owned by MNC Globus, purchased new machines capable of making type IIR masks with production at their facility in Dumfries.

- FFP3 masks: Alpha Solway re-shored mask manufacturing from Taiwan and increased production; Don & Low imported and installed new machinery to manufacture filter material for masks.
- Eyewear (visors & goggles): Alpha Solway switched emphasis from making protective clothing for oil and gas industries to visors. Also producing eyewear were: 4C Engineering (an off-shore engineering company based in Inverness) and Aseptium (a decontamination company) & Lifescan (a J&J company); Skyrora (a Scottish company involved in rocketry), and Baker Hughes (a US oil drilling equipment company).
- Aprons: Berry BPI, part of US owned Berry Group, is a major UK-based plastics and rubber company, and Europe's biggest plastics recycler, already a supplier to the NHS, sourced and shipped to Scotland specialist machines for the manufacture of disposable aprons from their Greenock factory.
- Non-sterile gowns: Don & Low (a Scottish company owned by Thrace Group (Greece) repurposed production to produce material for gowns. These materials were then converted to gowns by Edmund Bell (Yorkshire) and Keela (Glenrothes), with additional support from Endura and Transcal (Livingston).
- Ventilators: JFD Ltd Aberdeen and Inchinnan leveraged their expertise in breathing equipment to design a new ventilator; Babcock's Zephyr Plus ventilator is being supported by Plexus and Raytheon.
- Hand Sanitizer: CalaChem Ltd produced sanitiser at its site in Grangemouth, with ethanol provided by Whyte & Mackay: whisky distillers.

In looking at both the UK and Scottish CEP, our findings very much support our assumptions regarding innovation under emergency response conditions, particularly in terms of institutional leadership, government and industry partnering, and the leveraging of regional capabilities. First, for the UK's CEP and that of the devolved administrations, government has taken the lead role in both implementing policy and coordinating the procurement and production strategy (assumption 1). For example, Government leadership seems critical in selecting and courting manufactures who are not traditional producers of PPE, i.e. without government support and championing, the uncertainty of such a change of operations would be too much for most companies to take on. Second, the UK and Scottish CEP are clearly two-tracked in that they seek out sources of PPE external to the UK while leveraging national and local PPE capabilities (assumption 2). What is interesting about the UK's CEP efforts, and is different than its testing capability strategy, is that it is less about leveraging existing PPE production capability and more about developing new PPE production capability, this through the 'Make' strategy. Finally, the fact that devolved administrations implement their own CEP and leverage, as the Scottish case exemplifies, their own, often regionally based capabilities, lends some support to our third assumption that *institutional interactions toward developing capabilities will occur most prominently at the local and regional level and that it will be local or regional capabilities that will be leveraged in this regard (assumption 3)*. This opens up questions or future research of what national industrial policy can or should do to boost the cohesion of existing, dynamic industry efforts.

6. Discussion: future research and policy recommendations

6.1 Findings and open questions

Overall, our findings regarding the UK's response to both increasing capabilities for COVID-19 testing and diagnostics and production and supply of PPE lend considerable support for our main assumptions about the importance of detailed analysis of local conditions to understand the institutional context for innovation under emergency conditions. That said, there are aspects of our assumptions that were not easily captured by our research approach. First, while our findings demonstrate a COVID-19 strategy where 'emergency' conditions require both rapid decisions and development ramp-up of capabilities, we do not capture an assumed 'speeding up' of learning processes, either institutional or organizational.

In other words, questions regarding how public and private capabilities were so quickly integrated are left unanswered and may require more attention to institutional change within the State (e.g. centralized discretion and a small group of decision-makers which might otherwise have been wider, slower, consultation). Second, our findings do not lend much insight as to whether and how local and global capabilities interface. We assume that much of this takes place at the regional level, but we do not find overwhelming evidence for this.

Future research could address both areas—learning processes and institutional coordination—in more detail, especially around which capabilities and locations are policy-induced to cope with the assumed ability of scarcity-induced innovations. Therefore, a fertile area for future research is on the learning processes, outcomes, and implications for the institutions and actors involved in both the LLN and the PPE 'Make' strategy. For example, what have firms such as Scotland's BioAscent and India's Brooks Laboratories, gained and learned by participating in the LLN and what might this mean for future emergency response efforts when crucial inputs are scarce? Also, not captured in our research findings is evidence of changes to regulatory processes, i.e. if regulatory approvals of new equipment were sped up (e.g. PPE), how were required safety and technical standards met; how have such process changes influenced post-COVID-19 regulatory practices? In some ways, answering these questions will take a more micro-oriented approach, one that looks more closely at organization and programme-specific decision-making and learning processes that should shape future industrial policy design, i.e. starting at the micro level and then connect to and build up to a more accurate institutional view.

6.2 A new variant of import substitution industrialization?

Earlier in the paper (Section 2.2), we suggested that national responses to COVID-19 through building domestic capabilities and selective external outreach have some similarities with traditional import substitution industrialization (ISI) as well as 'catch-up'. However, recognizing that only some institutional combinations are possible in emergencies (which could be induced by any stakeholder but most likely by emergency policy responses), and only some of these combinations are possible because of the presence of existing technological capabilities, we can provide some nuance to the concepts when tested in emergencies. Also worth noting is that ISI is not occurring in the traditional sense i.e. crucial imports are unavailable, so a country needs to combine its IV and 'build from scratch' its technological capabilities towards new economic development goals. Rather, in this case, crucial imports are unavailable and countries need to build through a directed policy-induced response to a crucial next stage of technological capability but with 'critical equipment' goals as priorities.

We propose that, in the UK and elsewhere, this new variant of ISI does indeed emphasize new domestic production but differs from traditional ISI in that (1) it is a temporary emergency response to global shortages during a pandemic rather than a long-term development strategy. (2) As an emergency response, it has been devised and implemented in a matter of months, if not weeks in some cases, and that (3) ramping up domestic production has been coupled to varying extents with efforts to re-establish connections to existing or new global supply chains, both for capabilities and for supplies of critical equipment. In essence, scarcity induced innovation is experienced even in industrialized economies for brief periods of time, but because of the wider context of existing capabilities, there may be more latitude for some types of policy responses. The potential implications of this new ISI, both for industrial strategy and the organizational capabilities of governments and companies as well as future emergency response, warrant additional study.

6.3 Recommendations for post-COVID R&D policy

Published in July 2020 and later updated in early 2021, the UK Research and Development Roadmap is a working policy initiative that puts forward a wide range of policy recommendations for building the UK's capabilities for research and development, focusing on areas such as entrepreneurship, workforce skills and retention, research and development infrastructure, regional 'levelling up', university–industry collaboration, and international partnering, among others. While comprehensive, it is not a strategy for explicitly preparing national capabilities to meet the next pandemic like emergency. It is our view, however, that capabilities leveraged by the UK, and the ways by which they were used in its response to the pandemic, as exemplified by the LLN and 'Make' strategy, need to be highlighted as they can sharpen some of the recommendations in the Roadmap, particularly in terms of infrastructure and resilience.

First, the UK's LLN was greatly enabled by pre-existing, and highly capable publicly funded R&D infrastructure, this in the form of laboratory facilities and, in some cases, related innovation zones. It was these *publicly funded facilities* that the UK was able to either rapidly repurpose and/or expand to address the need for national COVID testing capability. Innovation zones brought with them experience in public–private partnering—this is important and UK roadmap correctly calls for such partnering to be strengthened—but public anchoring of these facilities (public funding and aims) needs to be recognized.

Recommendation (1): The UK R&D Roadmap should call for strengthening government support, including the expansion of public science and research facilities with a clear economic development argument. Doing so will more immediately enhance the UK's bioeconomy and better ensure future pandemic readiness.

Second, these publicly funded facilities and innovation zones all had either strong university affiliation or were housed within university research operations and infrastructure. In this way, university R&D infrastructure was critical in the repurposing and expansion of testing facilities, providing additional facility space, hundreds of trained scientists and technologists, as well as testing and diagnostic equipment. Because this university based infrastructure is less wedded to a particular domain or product—unlike more commercially driven facilities—it offers more adaptability in the face of a rapidly unfolding emergency.

Recommendation (2): The UK Roadmap should strengthen support for university-based R&D and related infrastructure, this includes the funding of 'basic' research—which plays a critical role in the training of future scientist, technologists, and engineers—and different approaches toward its translation.

Third, the UK's COVID emergency response was greatly aided by the successful integration of highly skilled scientists and technologists, coming from both industry and university, with laboratory and testing facilities that were highly automated. In this way, automation allowed for testing speed and scale, while human capabilities provided an essential layer of system deployment, reliability, and upkeep, as well as analytical and diagnostic rigour. In other words, these automated capabilities could not perform without human understanding and oversight of the system and science involved.

Recommendation (3): The UK R&D Roadmap should increase funding for both the training of new scientists and technologist and the greater automation of public laboratory facilities, while committing more funding and study toward improved human–machine interfaces for scientific research and processes of production, including manufacturing.

Finally, both the UK's LLN and 'Make' strategy showed the need for both domestic capability and access to global suppliers and producers. For the LLN, this involved incumbent global pharma-companies, UK-based biotech firms, and outreach to new international partner companies. For the 'Make' strategy, this involved repurposing some domestic manufacturing capability with renewed outreach to global suppliers of PPE, both new and incumbent.

Recommendation (4a): The UK R&D Roadmap should incentivise UK-based bio-facilities and companies to seek out and forge supply and production relationships with non-traditional or non-incumbent companies in order to increase potential supply of critical supplies and equipment—much sourced from abroad and which may not yet export to the UK, and/or to work on aligning global health research to domestic economic strengths;

Recommendation (4b): The UK R&D Roadmap should support a broad UK manufacturing base with an emphasis on adaptable manufacturing systems as an explicit economic development strategy, and which represent systems that can be repurposed and scaled when necessary, e.g. future pandemic.

7. Conclusion

Global shortages of critical equipment and supplies induced by COVID-19 have forced countries that traditionally import such equipment and supplies to build and ramp up their indigenous testing capacities and scale up production of PPEs. As part of its emergency response to COVID-19, the UK focused on developing its laboratory testing capability through the establishment of the LLN and increasing the supply and production of PPE, in part through an indigenous 'Make' strategy. In building the Lighthouse Labs Network, we show that the UK leveraged and expanded its existing laboratory capacity with the help of local public-private partnering, incumbent international partners and newly established global suppliers. For increasing its access to PPE, the UK has pursued a strategy that aims to increase domestic production of PPE through non-traditional suppliers of PPE in the UK (UK companies and organizations) and through aggressive contracting with both existing and new global suppliers of PPE.

In this sense, the UK epitomizes this dual track industrial strategy, where the immediacy of the pandemic has forced the UK to rapidly leverage domestic capabilities while seeking secure links to global suppliers for the same types of capabilities and products. These findings support, in part, our three main assumptions regarding how innovation systems behave under emergency response conditions: (1) *the government will take 'the leading' role in directing and coordinating the ramp up of capabilities for innovation, production and scale-up, with the main institutional relationship coming between government and industry; (2) strategies will primarily focus first on leveraging, developing, and protecting domestic capabilities while also seeking out external knowledge and resource inputs where necessary; and (3) that institutional interactions toward developing capabilities will occur most prominently at the local and regional level and that it will be local or regional capabilities that will be leveraged.*

However, some aspects of our assumptions, including *the speeding up of decision making and learning processes* and *the increasing regional interfacing of local and global capabilities* were not readily apparent through our findings. As such, we suggest some areas for future research centred on firm learning and local coordination associated with the LLN and 'Make' strategy. These findings for an emergency context can further refine the theoretical framework of IV.

Finally, we propose that the UK's COVID response is akin to a new *variant of ISI* that emphasizes 'temporary' domestic capability building, 'rapid' implementation, and 'selective outreach' to global producers and suppliers; this in turn informs our policy recommendations that emphasize the importance of publicly funded R&D infrastructure. We need to wait to assess whether a 'critical equipment policy' could be a capability that the UK institutionally builds into health policy priorities as well as its economic development strategies. If it remains part of the former (health policy) but is a policy orphan in the industrial system (despite imports being substituted for in the short-term), we are likely to find no long-term benefit from the pandemic. This acknowledges the short-term wide ranging institutional variety while intense learning and collaboration is underway but long-term narrowing again of institutional variety as policy-induced pressures cease.

For instance, the biological lab efforts and clinical relations to public health also reveal urgent new priorities for the WHO and health policy agencies that cannot be divorced from technological and industrial agenda-setting. Procurement rules for example affect both industrial norms and standards but also health policy outcomes. Future research is needed to understand how local public health norms and delivery strategies can be tied into more standardized industrial procurement rules. Standardization as we know it today emerged over a longer timeline; thus, short-term, scarcity-induced innovation in PPE could be seen to showcase new IV and additional standards that are essential to build critical equipment policies. These may call for new design or materials specifications, rapid roll-out, small batch testing norms to be changed, or resilience in use.

Overall, the paper's findings present useful building blocks of how industrial innovation systems can effectively identify, leverage, respond, and adapt the IV under emergency conditions. To do this, the variety of institutions and organizations being formed and recombined as well as those weeded out, will need careful attention to understand health policy outcomes and economic development impact.

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Data availability

The data underlying this article will be shared upon reasonable request to the corresponding author.

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