Emergency driven capacity building: COVID-19 and the UK's response toward increasing critical testing capability and production of PPE

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Abstract

Covid-19 has forced many countries to rapidly increase their technological capabilities in diagnostics, personal protective equipment (PPE) and medicines. Global shortages of critical equipment and supplies induced by the pandemic 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. While shades of a new economic nationalism pervade much of the political discourse in support of this approach, there is surprising institutional variation in the Covid-19 industrial response of supplier countries. When viewed through an innovation system lens, we suggest that this inward focus on domestic capacity and production is actually coupled with intensified global outreach to new and existing suppliers. Contrary to some of the accompanying rhetoric, the actual policy and practice is one where no nation can do it alone. In this way, the pandemic can illuminate the adaptability of innovation systems and the continued importance of external sources of knowledge and resources under emergency conditions. This industrial policy response can also be viewed as largely temporary, although its influence on post-pandemic industrial strategy and future emergency response warrants further inquiry into how it has been implemented in various national contexts. As such, this paper looks at the COVID emergency industrial response of the UK for several reasons. In particular, we look at the UK's efforts at building their laboratory testing capabilities and for increasing production of PPE. The paper's early findings present useful building blocks of how industrial innovation systems can effectively respond and adapt, while also exposing some limitations to the innovation systems approach, specifically concerning local health capabilities, production, and delivery.

Keywords: Industrial innovation systems; Covid-19, medical equipment; R&D; manufacturing; industrial policy; health policy; UK.

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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 has issued a universal guideline to 'test, test, test' with understandable interest in, but incomplete and uncertain, clinical foreground detail but very little attention to the vital industrial background and national customisation needs of countries as they move to initiate testing in a supply constrained environment (Srinivas et al, 2020). In this way, policy needs to acknowledge that in different national and regional contexts, the co-evolution of key institutions regarding industrialisation and healthcare is not one of uniformity but of institutional variety (Srinivas, 2021); understanding this variety can be critical to both crafting and implementing an effective COVID response. The absence of attention to the industrial background has meant that countries have had to scramble to institute customised problem-solving, and to institute systems of incentives and norms and laws – through industrial policy – that ensure diagnostic and personal protective equipment (PPEs) are manufactured and used to clinical specifications. Consequently, the time for search and learning by firms has been highly compressed and highly uncertain. Rather than being able to presume that diagnostic and PPE for COVID-19 are traditional mature products, a series of biological and clinical uncertainties on the one hand, and economic and industrial uncertainties on the other have generated a number of consequential uncertainties for supplier countries about why, how, when, and what type of diagnostic capabilities to build and protective equipment to produce. Health policy and epidemiology alone are clearly insufficient practical responses to health management.

While shades of a new economic nationalism pervade much of the political discourse in support of the domestic capacity building, such rhetoric distorts, for most countries, both the real policy and industrial response to COVID. When viewed through an innovation system lens, we suggest that this inward focus on domestic capacity and production is coupled with intensified global outreach to new and existing suppliers. Contrary to some of the accompanying rhetoric, the actual policy and practice is one where no nation can do it alone. In this way, the pandemic can illuminate the adaptability of innovation systems and the continued importance of external sources of knowledge and resources, and this under emergency conditions. This industrial policy response can also be viewed as largely temporary, although its influence on post-pandemic industrial strategy and future emergency response warrants further inquiry into how it has been implemented 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 PPE. *In doing so, we look to uncover how the UK's industrial health innovation system responded and built capabilities for large-scale diagnostic COVID testing and production of PPE.*

In the case of increasing its testing capacity, we show that the UK leveraged and expanded its existing laboratory capacity with the help of 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 organisations) and through aggressive contracting with both existing and new global suppliers of PPE. In this sense, the UK epitomises 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.

The UK is a compelling case to begin our inquiry for several reasons. First, while the UK's COVID response is national, strategies for building domestic capabilities and securing access to PPE has been, 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. As such, it is expected that considerable institutional variety within the UK in carrying out domestic capacity building will be evident. Second, prior to the COVID pandemic, the UK was attempting to deal with another, although different national imperative, that being its divorce from the European Union, i.e., Brexit, and its subsequent need to establish both new trading partners and supply chains residing outside the EU. For example, recent years have seen increasing investment and trade between the UK and India, including localised investment such as the West Midlands India Partnership (manufacturing, life science, technology), where Indian firms are a leading regional FDI and employment generator in the UK. In looking at our two cases – the UK's Lighthouse Lab Network and securing of PPE – we aim to uncover evidence of these new partnerships playing a role in these two COVID response measures.

Overall, the paper's premise is to analyse whether industrial policy design that emerges from examples of local problem-solving in COVID-19 is better suited to health outcomes, and reflective of policy agenda-setting institutional norms of a country's industrial base. When imports are scarce, countries will be forced to realign their domestic priorities around industrial policy and a pandemic is likely to force their hand into rapid decisions and reliance on an existing, or newly redesigned institutional context for building capabilities for COVID testing and the production of PPE. In attempting to begin answering these questions, the paper, through its two case studies, has three interrelated aims. First, the paper aims to re-engage and update our understanding (in the literature) and application (in policy) of industrial innovation systems and how such systems respond to and adapt in emergencies. Second, we assess the applicability of an innovation systems approach to the understanding of local problem solving toward health innovation and delivery. Finally, the paper is a first step in developing a research approach and agenda toward capturing the wider institutional variety (i.e., norms, rules, standards and laws) of COVID industrial response among different countries and regions.

This paper is structured as follows. Section 2 builds our research framework and assumptions through a convergence of the innovation systems literature and the emerging literature on emergency response. Section 3 then explains our methodology and the case study approach. Section 4 presents our two cases (Lighthouse Lab Network and PPE production) including detailed examples of both efforts in England and Scotland. Findings from each are then discussed. From these findings, section 5 discusses the utility of the innovation systems approach to understanding emergency industrial response and puts forward a future research agenda with the proposed three-fold heuristic at its core. Section 6 concludes. We use "institutions" here not to mean organisations, but the evolving set of customs, norms, standards, and various rules that in this study shape and govern innovation and related industrial policies. Specific organisations and agents act under such institutional frameworks, and also shape institutions in turn over time. There are important implications of such institutional changes in the study of technological capabilities (see Srinivas, 2020).

2. Innovation systems and emergency response

Innovation systems can be described broadly as the set of institutions that contribute to the generation and diffusion of new technologies and provide the framework within which government and firms negotiate policies to influence the innovation process (Metcalfe, 1997). National responses to COVID-19 have generated interest among academics and policy makers as to how innovation systems have adapted and changed in meeting this necessary response. The push to develop new therapies and vaccines, in particular, has placed new scrutiny on the effectiveness and adaptability of innovation systems, from national innovation systems to those innovation systems that are more sectoral and regional in scope. For example, looking at the biomedical innovation system in the US, Sampat and Shadlen (2021) 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 no less important, are expected changes to other areas of the biomedical innovation system as a result of COVID-19, notably innovation sub-systems for 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. From an innovation systems perspective, the latter could look much different in terms of the necessary institutional directives and resource requirements. In this way, innovation is not just about developing new and improved products and processes, but also about building the capacities to effectively produce and deliver innovations. In responding to emergencies like COVID-19, such capabilities will need to be developed quickly and likely under unusually tight resource constraints.

In considering innovation systems in this way, it is first useful to understand the innovation process under emergency conditions. Importantly, we view emergencies as (1) quickly unfolding events that have widespread impact and require a rapid technological and logistical response; (2) the ensuing innovation challenge for addressing said emergency is based primarily on a lack of immediate capability and access and not on a lack of knowledge or know-how. As such, only some types of translatable knowledge and their communities are relevant, and there may be insufficient time or certainty to assemble them anew. 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. 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 and information informing those decisions is limited. Second, because of the short timeframes involved, available resources are also limited, and this difficulty can be compounded by the location of the emergency in that the 'epicentre' may be both resources limited and or logistically difficult to move resources quickly into. Third, pressures to rapidly develop and produce needed innovations to meet the emergency demand will have to coincide with pressures to deliver a said innovation more efficiently and rapidly than under normal conditions, i.e., 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. If innovation itself is generally constrained in emergency conditions, what assumptions can be made about how an overall innovation system will respond in such conditions? To answer this, we look at innovation systems in more detail.

2.1 Institutional actor-based interaction and collective learning

The core institutional actors comprising most innovation systems 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 organisations 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 that facilitate information sharing leading to cumulative knowledge and collective learning. The NIS concept also draws upon other ideas from innovation theory that posit learning and subsequent innovation as a non-linear and recursive process that relies on effective feedback loops between actors and institutions (see Nelson and Winter, 1982).

Assumption 1: Under emergency response conditions, it is expected that interactions between organisational 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 organisational relationships emerging between government and industry.

2.2 Innovation systems and strategies for development

Although early frameworks of national innovation systems (NIS) were derived primarily from countries in the developed "North", these frameworks did pay particular attention to how some of these countries successfully developed, informing the later application of the NIS to developing countries (see Nelson, 1992,1993). For example, the story of Japan's NIS and the subsequent rise of South Korea, Taiwan, and Singapore (see

Lall, 1994; Freeman, 1995; Kim, 1993; Nelson, 1993; Mowery and Oxley, 1995) is one of 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 organisational practices from the advanced economies. While these practices represent primarily inward flows of technology and knowledge, their prominence in the early NIS literature gave rise to notions that effective innovation systems required a degree of openness and receptivity to external ideas and information: this openness would come to be recognised as the primary mechanism through which NISs react to ongoing competitive forces, and in doing so, how these systems develop and evolve over time.

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 Regional innovation systems 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). The first of these was the technology systems approach proposed by Carlsson and Stankiewicz (1995) which begins with a particular technology and looks at what actors and institutions influence its development and diffusion (Bergek et al., 2008a, b). The second was the sectoral systems of innovation approach developed by Breschi and Malerba (1997) who argued that innovation could be best understood by looking at a set of products and a distinct set of agents who interact through networks in the development, production and sale of those products. These agents hold sector specific knowledge and their interactions are influenced by institutions that may have both local and international dimensions. The third approach was the regional innovation systems (RIS) concept proposed by Asheim and Isaksen (1997) and Cooke et al. (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. For example, urban contexts have been crucial in setting COVID-19 pandemic response priorities, and cities and large towns are hubs of particular firms and supply logistics. The region thus has analytical value for industrial capabilities in this specific emergency. Central to this are the interactions between established actors and incumbent technologies and the emerging ideas and technologies introduced by new system entrants (Hekkert et al. 2007). Dynamic RISs are also characterised by global linkages and interactions (see Carlsson, 2006). In the literature, this interaction is facilitated through the research linkages of universities and the global R&D activities of multinational corporations (see Pietrobelli, 1996; Pavitt 2002). Therefore, pursuing global linkages would appear to be an obvious path, as capacity building mechanism, toward the development of an effective NIS.

Assumption 3: Under emergency response conditions, it is expected that institutional uncertainties and new organisational 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.

2.4 Innovation systems and pandemic response

In making assumptions about how innovation systems respond to emergencies, it is necessary to note that not all emergencies are the same, particularly when it comes to severity and scope. Unlike local outbreaks of TB and Ebola, COVID-19 is a truly global pandemic. The global scope of COVID-19 and subsequent shortages of critical equipment and supplies is what has driven most countries toward attempts at building domestic capabilities for developing therapies and vaccines, and also for scaling-up COVID-19 testing and production of PPE. In this way, the focus on building domestic capabilities is an imperative rather than a choice. *Although the context is different, it could be said that countries responding to COVID-19 through building domestic capabilities and selective external outreach are, in some respects, following the economic catch-up strategies employed by Japan, and later Taiwan, South Korea, and Singapore, for example*. 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. Also, these catch-up strategies were pursued for long-term purposes of economic development and competitiveness. While not the focus of this paper, how lasting the implications of this rapid COVID response will be on innovation systems going forward is a question that deserves further consideration and inquiry.

3. Methodology and case study approach

For exploring these assumptions, we look at two significant components of the UK's COVID response: (1) the UK's Lighthouse Labs network, established to increase the UK's laboratory based COVID testing capability; and (2) the UK's ramp-up system for PPE production. For each case, we look at the context and respective capabilities at the beginning of the pandemic, the overall strategy employed at the UK national level and how the respective strategies were implemented in both England and Scotland – this for purposes of showing intra-national variation. Importantly, we do not directly assess the effectiveness of these two strategies. Our aim is to identify the main resources and processes through which capabilities were developed and both the main and supporting actors involved. More specifically, we identify and analyse the interplay between the leveraging of local and regional capabilities and the integration of external sources of knowledge and capabilities. For doing so, we conducted a desk study of relevant journal articles, newspaper articles, government reports and facility websites. 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. Government reports and white papers were used to understand the government's rational and strategy toward increasing testing capability and PPE supplies. Facility and programme websites, particularly as they pertain to the Lighthouse Lab Network, were looked at to understand the implementation of the government's strategy and to capture the background and participating actors in each lab site and those actors involved in the PPE ramp-up strategy. In doing so, we also reflect and consider how effective the application of the innovation systems concept is for our understanding of institutional and industrial response to national and global level emergency situations.

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 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, 2020). 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 were 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 & Bradley, 2020). As a result, the UK had to do the following, and do them quickly: (1) increase laboratory capacity; (2) create a testing system (3) secure future testing supplies; (3) implement an effective test and trace system; (4) and do this rapidly (one to two 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).

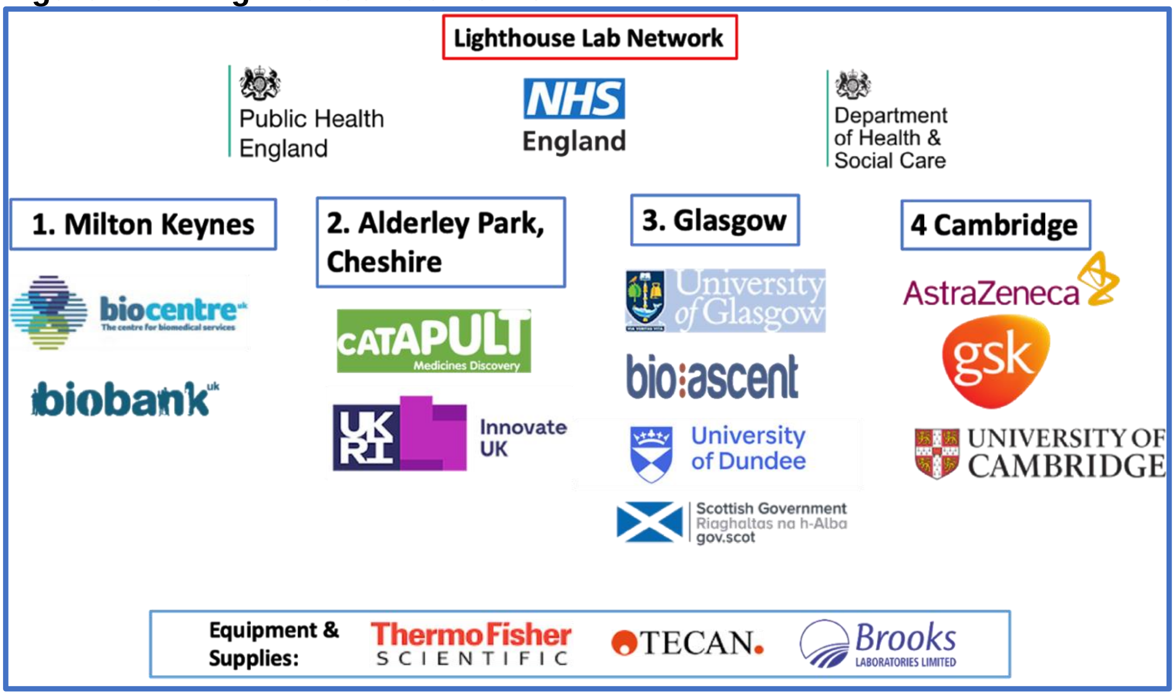
4.1 Building laboratory testing capacity: the Lighthouse Lab network

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), 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, 2020).

The Lighthouse Lab Network (LLN) also includes the establishment of two smaller labs for regional and complementary capacities: a lab in Northern Ireland run by Randox and a Cambridge based lab run by AstraZeneca and GSK. 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). See figure 1 for a visual overview of the Lighthouse Lab network.

Figure 1: UK Lighthouse Lab Network



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. An 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 Imperial Chemical Industries (ICI). ICI was originally set up after the first world war, an early state investment towards a private company to help catch-up the German chemicals 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 organisation established in 2014 (UK Biocentre, 2021). 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 diversity mentioned above, there are a number of additional 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 in either public or non-commercial sites and facilities. Additionally, all main LLN sites became operational within four 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 in the UK innovation system: 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 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 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 US, 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*. How much of an expanded or new role these non-UK companies are taking because of LLN inclusion is an interesting question. While we might expect that a company like Thermo Fisher Scientific is merely increasing its already prominent role in the UK, a smaller company like TECHAN or India's Brooks Laboratories, might well be significantly increasing its UK presence, both during the pandemic and possibly post-pandemic. While this question is not specifically addressed through this paper, the brief case studies below delve a bit deeper into the capabilities that these companies bring to specific LLN sites and the ways in which these government-industry partnerships leverage complementary capabilities.

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 organisation offering services in sample collection kit assembly, DNA/RNA extraction, and sample storage (UK Biocentre, 2021). 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, 2021) Automation equipment and systems appear to be provided by Tecan, an Austrian based company specialising 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 innovation systems and 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, are able to move more decisively. Once this public decision is made and resources mobilised – easing uncertainty – private capabilities then come onboard. This also highlights how important university research infrastructure, including organisations that service it, is for mounting an effective innovation response to a public emergency. Second, key to this infrastructure's rapid mobilisation are 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, 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. For the Milton Keynes lab, this required continued access to equipment from non-UK based companies, particularly Thermo-Fisher Scientific and TECAN. Unlike the UK, costs and lack of access to such capabilities place many countries and their innovation systems at a severe disadvantage when it comes to responding to the pandemic.

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 (U Glasgow, 2021). 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" (U. Glasgow, 2021). 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 specialises 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 (U. Glasgow, 2021).

The Glasgow lab holds much in common with lab in Milton Keynes, but the importance of local capabilities is even more significant. 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 labs 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 facilitating 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 led and run the lab operations is interesting for several reasons. BioAscent is a relatively new company and fairly small when compared to the more established and larger pharma players. Although not confirmed through this research, it does appear that BioAscent's significant role in the lab may be partly based on the Scottish Government's political desire to have a Scottish based company lead the lab and to facilitate the potential growth and prominence of BioAscent (increase its organisational learning and market positioning), as a result of its leadership role in the lab, as opposed to bringing in an already long-established big pharma player. In other words, choosing BioAscent may have just as much to do with post-COVID aspirations for the Scottish bioeconomy as with bringing in the most capable company to lead the lab. 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 systems.

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 of it 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; eye/face protection (eye shields, goggles, 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 2020). These efforts in conjunction with the 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% 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, 2020). 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 June 25, 2020, the UK government claimed that, through the Make strategy, more than 30 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 mobilise Scottish-based companies and support collaboration, including that 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 major 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 and 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 – whiskey distillers.

In looking at both the UK and Scottish CEP, our findings very much support our assumptions regarding innovation systems 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).*

6. Discussion and future research

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 innovation systems under emergency response 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 organisational. In other words, questions regarding how public and private capabilities were so quickly integrated are left unanswered. Second, our findings don't 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 don't find overwhelming evidence for this. In some respects, the UK government at the national level may play a larger role than initially assumed.

Future research could address both areas – learning processes and institutional coordination – in more detail. Furthermore, a fertile area for future research is on the learning processes, outcomes, and implications for the institutions and actors involved in both the Lighthouse Lab Network 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? In some ways, answering these questions will take a more micro oriented approach, one that looks more closely at organisation and programme specific decision making and learning processes, i.e., starting at the micro level and then connect to and build up to a more accurate institutional view. Such a view could be based on innovation system constructs, but it need not be.

6.1 A new variant of import substitution industrialisation (ISI)?

Earlier in the paper (section 2.4) we suggested *that national responses to COVID-19 through building domestic capabilities and selective external outreach is similar to the economic catch-up strategies employed by Japan, and later Taiwan, South Korea, and Singapore* – these strategies informing our understanding of innovation systems. Going further, it could also be suggested that the emergency industrial response of most countries to the global shortages of diagnostic and critical protective equipment caused by Covid-19 is akin to a 21st century microeconomic variant of import substitution industrialisation (ISI). Practised widely from the 1950s to the 1980s, particularly among countries in Africa and Latin America, ISI is essentially a trade and economic strategy that aims to replace foreign imports with domestic production (see Heidhues & Obare, 2011 & Adewale, 2017). Early variants of import substitution were developed and implemented in a context where the world was divided quite sharply into industrialised versus industrialising countries, and 'development' involved a country being much better able to develop their technological capabilities. 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, 2004; 1994).

We propose that this new variant of ISI does indeed emphasise 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, countries have been pursuing industrial self-reliance with considerable global outreach and input. Although likely temporary (the imperative should ease with an ease of the pandemic), the potential near and long-term implications of this new ISI, both for industrial strategy and the organisational capabilities of governments and companies, as well as future emergency response, warrants additional study.

7. Conclusion

Global shortages of critical equipment and supplies induced by the 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 Lighthouse Labs Network and increasing it 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 organisations) and through aggressive contracting with both existing and new global suppliers of PPE.

In this sense, the UK epitomises 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 innovation system's 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. Finally, we propose that the UK's COVID response is akin to a new *variant of import substitution industrialisation (ISI*) that emphasises 'temporary' domestic capability building, 'rapid' implementation, and 'selective outreach' to global producers and suppliers. Overall, the paper's findings present useful building blocks of how industrial innovation systems can effectively respond and adapt, while also exposing some limitations to the innovation systems approach, specifically concerning local health capabilities, production and delivery.

References

Adewale, A. R. (2017). Import substitution industrialisation and economic growth–Evidence from the group of BRICS countries. *Future Business Journal*, *3*(2), 138-158.

Ahmad, J. (1978). Import substitution – A survey of policy issues.
The Developing Economies, 16 (4) (1978), pp. 355-372

Amsden, A. H. (2004). Import substitution in high-tech industries: Prebisch lives in Asia!. *Cepal Review*.

Amsden, A. H. (1994). Why isn't the whole world experimenting with the East Asian model to develop?: Review of the East Asian miracle. *World Development*, *22*(4), 627-633.

Asheim, B.T., Isaksen, A., 1997. Localisation, agglomeration and innovation: towards regional innovation systems in Norway? Eur. Plann. Stud. 5, 299–330.

Baraniuk, C. (20 April 2020). How the UK's Coronavirus
Testing regime totally unravelled. Wired: https://www.wired.co.uk/article/uk-coronavirus-testing

Bergek, A., Hekkert, M., Jacobsson, S., 2008a. Functions in innovation systems: a framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policy makers. Innovation Low Carbon Econ.: Econ. Institu Manage. Approaches, 79.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008b. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37 (3), 407–429.

BioAscent (2021): https://www.bioascent.com

Breschi, S., Malerba, F., 1997. Sectoral systems of innovation: technological regimes, Schumpeterian dynamics and spatial boundaries. In: Edquist, C. (Ed.), Systems of Innovation. Frances Pinter, London

Carlsson, B., 2006. Internationalization of innovation systems: a survey of the literature. Res. Policy 35 (1), 56–67.

Carlsson, B., Stankiewicz, R., 1995. On the nature, function and composition of technological systems. In: Carlsson, B. (Ed.), Technological Systems and Economic Performance: The Case of Factory Automation. Kluwer Academic Publishers, Dordrecht, pp. 21–56.

Cooke, P., Uranga, M.G., Etxebarria, G., 1997. Regional innovation systems: institutional and organisational dimensions. Res. Policy 26, 475–491.

Evenett, S.J and L.A. Winters. (2020). Preparing for a second wave of COVID-19: A trade bargain to secure supplies of medical goods.

Freeman, C., 1995. The national innovation systems in historical perspective. Cambridge J. Econ. 19 (1).

Heidhues, F., & Obare, G. A. (2011). Lessons from structural adjustment programmes and their effects in Africa. *Quarterly Journal of International Agriculture*, *50*(892-2016-65193), 55-64.

Hekkert, M.P., Suurs, R.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecasting Social Change 74 (4), 413–432.

Gray, H (2018) *Turbulence and Order in Economic Development: Institutions and Economic Transformation in Tanzania and Vietnam*, Oxford University Press.

Kim L., 1993. National system of industrial innovation: dynamics of capability building in Korea. National innovation systems: A comparative analysis, 357–383.

Kirkpatrick, D. and Bradley, J. (April 16, 2020). U.K. Paid $20 Million for New Coronavirus Tests. They Didn't Work. New York Times: https://www.nytimes.com/2020/04/16/world/europe/coronavirus-antibody-test-uk.html

La Marca, A;, Capuzzo, M., Palgia, T., Roli, L., Trenti, T., Nelson, S.M., 2020. 'Testing for SARS-CoV-2 (Covid 19): a systematic review and clinical guide to molecular …', Reprod. Biomed. Online. 41 (3), 483-499.

Lall, S., 1994. The East Asian miracle: Does the bell toll for industrial strategy? World Dev. 22 (4), 645–654.

LLN (2020). Lighthouse Lab Network (last accessed in August 2020): https://www.lighthouselabs.org.uk

Lundvall, B.A., 1992. Introduction. In: Lundvall, B. (Ed.), National Systems of Innovation toward a Theory of Innovation and Interactive Learning. Pinter Publishers, London, pp. 1–19.

Lundvall, B.Å., 2007. National innovation systems—analytical concept and development tool. Ind. Innovation 14 (1), 95–119.

Mackintosh, M., Banda, G., Wamae, W., & Tibandebage, P. (Eds.). (2016). *Making medicines in Africa: The political economy of industrializing for local health*. Springer.

Metcalfe, S., 1997. Technology systems and technology policy in an evolutionary framework. In: Archibugi, D., Michie, J. (Eds.), Technology, Globalisation and Economic Performance. Cambridge University Press, Cambridge, pp. 268–296.

Miettinen, R., 2002. National Innovation System. Scientific Concept or Political Rhetoric. Edita, Helsinki.

Mowery, D.C., Oxley, J.E., 1995. Inward technology transfer and competitiveness: the role of national innovation systems. Cambridge J. Econ. 19 (1), 67–93.

Nelson, R.R., Winter, S., 1982. An evolutionary theory of economic change. Cambridge, Belknap

Nelson, R.R., 1992. National innovation systems: a retrospective on a study. Ind. Corporate Change 1 (2), 347–374.

Nelson, R., 1993. National innovation systems: a comparative analysis. University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship.

Papaioannou, T., & Srinivas, S. (2019). Innovation as a political process of development: are neo-Schumpeterians value neutral?. *Innovation and Development*, *9*(1), 141-158.

Patel, P., Pavitt, K., 1994. National innovation systems: why they are important, and how they might be measured and compared. Econ. Innovation New Technol. 3 (1), 77–95.

Pavitt, K., 2002. The globalizing learning economy. Acad. Manage. Rev. 27 (1), 125–127

Pietrobelli, C., 1996. Emerging Forms of Technological Cooperation: The Case for Technology Partnerships—Inner Logic, Examples and Enabling Environment. Science and Technology Issues. UNCTAD, Geneva: United Nations.

Pharmaceutical-technology.com (last accessed on 21 August 2021). AstraZeneca R&D Facility, Alderley Park, Cheshire: https://www.pharmaceutical-technology.com/projects/astrazeneca-alderley/

Ramalingam, B. (2015). *Case Study: Innovations in Emergency Disease Responses*. Working paper. Brighton: Centre for Research in Innovation Management, University of Brighton.

Sampat, B. N., & Shadlen, K. C. (2021). The COVID-19 Innovation System: Article describes innovations that emerged during the COVID-19 pandemic. *Health Affairs*, *40*(3), 400-409.

SCOT GOV (2020). Coronavirus (COVID-19): report on Personal Protective Equipment supplies Supporting our Front Line Services and Building Self Sufficiency

Srinivas, S.,Prasad, R., Rao, P. (2020) The clinical foreground and industrial background: customising national strategy for COVID-19 testing, IKD Working Paper 87.

Srinivas, S. (2012). *Market menagerie: Health and development in late industrial states*. Stanford University Press.

Srinivas, S. (2021). Heuristics and the microeconomics of innovation and development. *Innovation and Development*, *11*(2-3), 281-302.

UK Biocentre. Last visited 16 August 2021: https://www.ukbiocentre.com

UK Biocentre (last visited 16 August 2021): https://www.ukbiocentre.com/covid-19

UK GOV (2020). Opportunities to contribute to the national diagnostic effort for COVID-19. 8-April-2020.

UK GOV (2020): https://www.gov.uk/government/news/olympics-chief-brought-in-to-boost-ppe-production

UK GOV (September 2020) Policy Paper: Personal protective equipment (PPE) strategy: stabilise and build resilience (29 September 2020: https://www.gov.uk/government/publications/personal-protective-equipment-ppe-strategy-stabilise-and-build-resilience/personal-protective-equipment-ppe-strategy-stabilise-and-build-resilience

UK DOHSC (2020). Coronavirus (COVID-19) Scaling-up our testing programmes. Department of Health & Social Care, 4-April-2020.

University of Glasgow (2021): https://www.gla.ac.uk/colleges/mvls/llig/headline_733867_en.html

University of Glasgow (2021): https://www.gla.ac.uk/colleges/mvls/llig/headline_733865_en.html

Watkins, A., Papaioannou, T., Mugwagwa, J., & Kale, D. (2015). National innovation systems and the intermediary role of industry associations in building institutional capacities for innovation in developing countries: A critical review of the literature. *Research Policy*, *44*(8), 1407-1418.