UNIVERSITY OF BIRMINGHAM

Centre for Sustainable Cooling

Understanding the cold-chain challenge for Covid-19 vaccination

November 2020

KIGALI COOLING EFFICIENCY PROGRAM

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ACKNOWLEDGEMENTS

This report was produced and is being shared publicly due to the increased prominence to the issue of vaccine cold-chains in the context of the COVID-19 response and requests for information. While every effort has been taken to verify the information, due to the urgency it has not undergone a process of peer review and we do not guarantee accuracy of the data included in the work. It will be subject to update and revisions.

With thanks to

Dr Leyla Sayin, Research Associate to Professor Toby Peters – Lead author

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Dr Tim Fox – Editing

Sustainable Energy for All – Review and contributions

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Financial support

Kigali Cooling Efficiency Programme

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Published 18th November 2020

FOREWORD

Supported by UK Research and Innovation (UKRI), an international team of researchers led by the University of Birmingham is creating a roadmap and model for in-country COVID-19 vaccination cold-chain design using Bangladesh as a case study. The team from Birmingham and Heriot-Watt University with their counterparts in Bangladesh at BRAC University and Bangladesh University of Engineering and Technology are gathering the data using primary and secondary research to design novel methods and instruments to assess Bangladesh's current cold-chain capacity and seize the opportunity to align renewable energy and energy efficiency solutions with the mass vaccination of COVID-19 and potentially future needs.

Our work specifically aims to explore the nexus among COVID-19 vaccine deployment (and future emergency, pandemic and epidemic needs), sustainable cold-chain and clean energy infrastructure development. To achieve the aim, we apply a bottom-up whole systems approach, which includes collecting primary data for a robust assessment of the cold-chain capacity, identifying gaps, and providing possible solutions for COVID-19 vaccine delivery in case study sites, which could be generalised nationally. Our work will also include estimation of economic, environmental and social impacts of the current deployment plans if they are to be followed to.

This project will assist policy makers in developing the most sustainable interventions to support the medical supply chain at regional, national scale for COVID-19, but also to increase resilience against other potential future natural disasters and epidemics. It will also support decision-making in selecting the new cooling equipment, so that the equipment not only bridge gaps in routine immunisation programmes, but also could be re-purposed and address the needs in other sectors after the pandemic, providing lasting legacy.

Drawing on secondary research to date, we have published this briefing note to provide an overview of both the potential scale of the challenge as well as recommendations for action to ensure that the potential mass rollout of cold-chain technologies is sustainable.

Further details and data are available on request, please contact t.peters@bham.ac.uk

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EXECUTIVE SUMMARY

Despite calls for action[1], existing COVID-19 activities have been mainly focused on developing, testing and manufacturing an effective vaccine, and the clean cold-chain requirements for distributing the vaccines fast and at scale globally have largely been ignored. Vaccination of COVID-19 will require a new fast-track approach to assess, re-engineer and build out the cold-chain logistics assets.

Universal vaccine access is an existing major challenge in low-income countries, mainly due to the lack of robust cold-chains. Key barriers faced, especially in developing countries, include insufficient cold-chain capacity, outdated cold-chain equipment, inadequate maintenance and monitoring devices, lack of skills and training, limited or unreliable energy access, limited outreach, and lack of financing and sustainable business models. All these challenges result in cold-chain breaks, leading to vaccine wastage and missed opportunities for vaccination.

The COVID-19 pandemic, however, has brought to the fore the urgent need for a vaccine cold-chain to meet a different set of requirements – mass vaccination in a concentrated period of time. As an example, while child vaccination campaigns typically reach about 115 million infants annually worldwide, the COVID-19 vaccine could need to reach as many as 750 million people in Africa alone, health experts predict. This implies a very rapid expansion/redesign of the vaccine delivery mechanism and logistics chain, including the potential for incorporating synergistic temperature management services, and sustainable cooling technologies as legacy benefits to this approach as well as campaign approaches. However, such an expansion must not only recognise the potential volume uplifts, but also be mindful about the risks of using technologies that are environmentally harmful. In particular, the additional requirements should aim to avoid diesel-based cold-chains and refrigerants with high Global Warming Potential (GWP), which may require financial and technological support for developing countries. However, countries unfortunately seem to overlook the environmental impacts in their deployment plans. They do not realise the scale of the potential impact on their sustainability targets, goals and commitments and/or do not have the budget and skills to implement sustainable cooling technologies.

Alongside vaccines, disposable syringes, Personal Protective Equipment (PPE) and other vaccination supplies will be the items that will actually demand more volume in transport and storage. Therefore, we will also need to consider the waste management and disposal/recycling. Even though the deployment plans we have reviewed to date mention waste management strategies, they often overlook the reverse waste logistics challenge that is likely to be faced.

[1] How Do We Prepare for Covid-19 Vaccine Delivery? – Birmingham Brief, 14th May

While the quantum of expansion may be estimated considering population sizes, the actual cold-chain demand regarding volume and equipment type will also depend on specifications of the vaccine (such as volume per dose, dosage, temperature requirements and effectiveness) which are yet to be known. Furthermore, the ground level conditions to sustain such expansion, especially the "last-mile" of the vaccine chain, need to be better understood. The key supply chain challenge, especially in many developing countries with large percentages of rural populations, will be the last-mile distribution, which requires availability of vaccine holding systems at each vaccination site and outreach channel. The actual potential of the existing vaccine cold-chain infrastructure to meet demand whilst maintaining current immunisation services, the cold-chain space the private sector can offer, potential modal shifts (such as drones for outreach) and/or novel technologies (such as mobile cold-rooms and vaccine portable micro-chillers); the required energy supply, or the presence and appropriateness of alternative cooling facilities and energy sources need to be known, as well as the volume of waste so as to inform, cost and policy decisions on vaccine cold-chain expansion.

KEY CONCLUSIONS

- The COVID-19 pandemic and the measures to halt its spread have had far-reaching impacts on health, economies, social security and well-being; threatening the progress on Sustainable Development Goals (SDGs). Due to the pandemic, 71 million people are likely to be forced into extreme poverty in 2020. 130 million additional people face acute food insecurity; remote learning remains inaccessible to at least 500 million students; the incomes of 1.6 billion people employed in the informal sector have dropped an estimated 60 per cent. Women have 1.8 times more job vulnerability than men during the pandemic, despite representing 70 per cent of jobs in essential occupations, and are likely facing a serious increase in domestic violence since stay-at-home measures were implemented.
- An effective vaccine is seen as the world's best bet for overcoming the pandemic. To this end, governments, multilateral agencies and private sector have been investing heavily into research and development of COVID-19 vaccines. However, achieving herd immunity through vaccination means delivering the vaccine effectively and equitably to 60-70 per cent of the population. This translates into 4.7 to 5.5 billion people. In the likely case that the vaccine requires two doses, this equates to 9.4 to 11 billion doses to be manufactured and distributed (excluding allowances for effectiveness rates). Achieving this successfully will critically depend on robustness of cold-chains, given that vaccines lose their efficacy if exposed to a temperature beyond their recommended ranges for inappropriate amounts of time. However, little attention has been given to date to the requirements of distributing it rapidly at scale.
- Equitable distribution of the COVID-19 vaccine globally would prevent 61 per cent of subsequent deaths, but were it to be distributed to high-income countries first we would avoid only 33 per cent of those deaths.
- Planning robust outreach sessions is crucial to address gender barriers, such as limited access to family income to pay for transportation, constraints on leaving home without a male chaperone, and lack of time due to household chores.
- Access to vaccines is an existing major challenge in developing countries, mainly due to the lack of seamless, fully integrated, functioning cold-chains, which frequently result in distribution failure points, leading to vaccine wastage, missed opportunity for vaccination, and ineffective immunisation programmes. There is, thus, an immediate and urgent need to assess the specification and capacity of vaccine cold-chains, and to put in place robust, well thought, practical plans to strengthen existing capabilities where necessary, and to fill capacity gaps through new equipment procurements or through private cold-chains from medical as well as other sectors that can borrow capacity. This should also take into account the need of maintaining current immunisation services. Furthermore,

supply chain and logistics requirements for ancillary supplies should also be considered and planned for along with reverse logistics of waste management.

- Given the fact that large proportion of the populations live in rural, remote areas in developing countries, the key challenge for Covid-19 immunisation will likely be the last mile distribution. Therefore, ensuring that each vaccination site, whether it is a health centre or an outreach service point, is equipped with adequate cooling equipment to maintain efficacy of the valuable COVID-19 vaccine is crucial. The location of vaccination sites will need to be carefully chosen considering, among other things, geographical barriers and transport difficulties as well as availability of energy supply. Furthermore, in addition to traditional ground transport, cargo drones can be considered to deliver the vaccine to remote and hard to reach areas.
- The challenge does not exist in isolation. Existing vaccine campaigns must be simultaneously maintained. UNICEF and WHO estimate that up to 80 million children are at risk of missing out on vaccinations against vaccine-preventable diseases due to the pandemic. Capacity expansion must consider how to maintain existing programs in consideration of the risks posed by Vaccine Preventable Disease (VPD).
- There are currently eleven vaccines in their late stages of development, and some expecting their initial results before the end of 2020. Pfizer/Biontech, in fact, announced their Phase 3 trial results, suggesting the vaccine candidate could be 95 per cent effective. Similar to Pfizer/Biontech, Moderna's preliminary results suggest a 94.5 per cent efficacy rate. One of the drawbacks is that both of the candidates require two injections for full effectiveness. However, the real catch is that the Pfizer/Biontech's candidate requires a temperature of -70°C for transport and storage, and Moderna's -20°C. Both multiple dose and sub-zero temperature requirements may severely complicate vaccine delivery especially in countries with high ambient temperatures and less developed cold-chains. The existing vaccine cold-chains are typically designed for vaccines that require 2-8°C, and the number of medical freezers that can handle these temperatures is extremely limited, even in the most advanced developed countries. Cold-chain expansion required for COVID-19 vaccine would therefore demand significantly higher levels of investment in equipment and infrastructure, especially in developing countries. While Pfizer has designed a packaging that will keep the vaccines at -70°C for up to 10 days using dry ice, dry ice may be short in supply, especially in developing countries. In Bangladesh, for example, there is only one company making dry ice.
- Fortunately, nine of the promising vaccines out of eleven require temperatures of 2-8°C. If some of these vaccines were to be successful, then these vaccines can be directed to developing countries to ease distribution and increase coverage, and to lower the financial and technological support required. However, it is also important to recognise the possibility that the only vaccine available may demand ultra-low temperatures, at least for a while.
- One aspect of this massive challenge that is mostly overlooked is the opportunity it presents for building more sustainable and resilient cooling economy. With the urgent need for building new cold-

chains and re-engineering the existing ones, there is an opportunity to address gaps not only in medical cold-chains but also in other sectors, with zero/low carbon technologies with natural/low-GWP refrigerants. Overall, any deployment decision should be made considering targets related to the reduction of GHG emissions and other pollutants as well as SDGs, providing a lasting legacy.

- An insufficient supply of engineers, technicians and mechanics with the relevant skill set for cold-chain equipment and infrastructure installation, operation, maintenance and decommissioning, along with inadequate training to develop such skills, often result in incorrect deployment and poor performance, long response times to malfunctions and failures leading to broken cold-chains. These issues lead to unnecessary energy use and GHG emissions, environmental pollution and damage, vaccine degradation and waste, administration of ineffective vaccines, and ultimately a wide range of avoidable costs.
- Alongside vaccines, disposable syringes, Personal Protective Equipment (PPE) and other vaccination supplies will be the items that will actually demand more volume in transport and storage. Therefore, we will also need to consider waste management and disposal/recycling. Even though the deployment plans we have reviewed to date mention waste management strategies, they often overlook the reverse waste logistics challenge that is likely to be faced.

1 INTRODUCTION

1.1 OVERVIEW

Since the emergence of COVID-19 at the end of 2019, the virus has rapidly spread across the world to result in a truly global pandemic that has been affecting over 200 countries and territories, and at the time of this note (18 November 2020), the disease has infected more than 54.78 million people and claimed more than 1.32 million lives [1].

The COVID-19 pandemic is not only a human health crisis, but also a social, economic and political tragedy, affecting all populations of the world at different scales and with varying degrees of impact. In efforts to contain the spread of the virus, many governments introduced restrictions on the movement of people, and strict social-distancing measures that have had substantial and far reaching effects on economies, social well-being, and potentially mental health. So called "lockdowns", requiring populations to "stay at home", along with closures of businesses, educational establishments, leisure facilities, and other limits placed on society have led to, amongst other things, to reductions in household income, loss of employment, disruption to education, reduced production outputs and prioritised access to health services, as well as difficulties for consumers in sourcing supplies of food, general groceries and non-essential goods. The economic consequences of government responses to the pandemic, should they continue, are likely to cripple even the most resilient advanced economies of the world, and significantly impact on future progress towards achieving the Sustainable Development Goals (SDGs), potentially even reversing many of the hard won gains made to date.

The myriad of crises induced by the pandemic highlights the urgency in the drive to develop COVID-19 vaccine deployment strategies to distribute the vaccine effectively and equitably as soon as it is ready, which will help mitigate the health and socio-economic consequences of the current response to the virus, and provide the foundations for a lasting global recovery. There has been unprecedented effort by the governments and industry worldwide to instigate programmes for the development of a COVID-19 vaccine, and expectations are high for a successful outcome[2]. The challenge does not, however, end there. It has been estimated that at least 50 to 60 per cent of a given population needs to have developed immunity against COVID-19 to effectively reduce the spread of the virus, and in areas of high reproduction rates, this can increase to 75 per cent [3]. Therefore, after an adequate supply of an effective vaccine has been secured by a nation, it will have to be delivered to its population at a scale and speed of distribution not previously achieved in human history, with the additional challenge of simultaneously maintaining existing vaccination programmes for other critical life threatening diseases. Preparation for

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[2] Pfizer/Biontech have announced on 18 November 2020 that their vaccine candidate could be 95 per cent effective against COVID-19 [2]. The cold-chain requirements of the vaccine and related challenges will be discussed in section 3.

this unparalleled task requires countries to assess their current infrastructure and distribution resources with at least the same degree of urgency that they are addressing the development of the vaccines themselves. Indeed, distribution chain audits need to be rapidly undertaken; gaps in physical infrastructure, as well human resource capability, must be identified and procurements made to fill them; the political, financial and social investments needed to support a robust immunisation plan that will deliver the vaccine with no one left behind, must be committed, considering the fact that different Covid-19 vaccines under development demand different requirements (such as temperatures and volumes). Furthermore, equitable distribution across countries will be a key driver to success. One estimation suggests that if the initial doses produced are distributed to high income countries first, then only 33 per cent of death will be avoided. However, distribution to all countries proportional to their populations could prevent 61 per cent of subsequent deaths [4].

One poorly understood infrastructure challenge that is fundamental to the success of any COVID-19 vaccination programme, is the fact that vaccines need to be stored and transported in a seamless and unbroken temperature-controlled environment throughout the distribution journey, from point of manufacture to point of immunisation. This key requirement demands *all* countries, regardless of climate or level of economic development, to procure additional cold-chain[3] equipment as well as re-engineer the existing capacity to improve cold-chains' ability to meet the increases in volume and distribution speed necessary to ensure an uninterrupted availability of quality COVID-19 vaccines on the ground in every city, town, village and remote settlement or homestead across the globe. Apart from the existing government-controlled vaccine cold-chains, countries should also consider and identify the cold-chain space that the private cold-chain operators can offer.

In many African, South East Asian and South Asian countries, the diverse population settlements (e.g., urban, semi-urban, rural) present unique challenges to cold-chain capabilities and logistical responses. Access to energy and adequate transport infrastructure, such as paved roads, is often a key distribution challenge for countries in these regions and a substantial barrier to reaching out effectively to semi-urban and rural populations. Furthermore, the need to deliver vaccines via outreach to increase immunisation coverage, can present major challenges. Some countries in fact provide more than 50 per cent of their vaccination services via outreach, which places burdens on health care workers (who might have to walk long distances, often across difficult terrain) and impacts the ability of governments to deliver frequent immunization sessions [5].

[3] Cold-chains consist of several components, typically including at least pre-cooling, cold storage, and refrigerated transport. For the medical sector, the cold-chain is typically used for the transportation and storage of temperature-sensitive health products which include but are not limited to vaccines, blood products, and a range of medicines that support common health services.

There are also significant environmental risks associated with cold-chains which need to be recognised, assessed, and mitigated against. Not least amongst the environmental challenges of COVID-19 vaccine distribution is the potential for substantial emissions of greenhouse gases (GHGs) and other pollutants from cooling equipment, both from energy use (termed "indirect" emissions) and from leakage or spillage of refrigerant ("direct" emissions), which underpins a need to ensure that new and re-engineered cold-chains are sustainable in their procurement, operation and eventual decommissioning. For example, new builds and retrofits need to be efficient, low or zero carbon, and designed in line with circular economy principles that plan for reuse, remanufacture and recycling of infrastructure and equipment, as well as facilitate safe, sustainable waste management practices for the refrigerants, vaccine product packaging, vaccination supplies, protective personal equipment (PPE) and other potential pollutants associated with distribution through the cold-chain. The challenge for governments, industry and wider society is, therefore,: how to achieve efficient, large-scale COVID-19 immunisation in the most economically, socially and environmentally sustainable manner, whilst simultaneously providing a lasting legacy of sustainable distribution infrastructure from the urgent investment that must be made now.

1.2 ECONOMIC IMPACTS OF THE PANDEMIC

The unparalleled nature in modern times of the COVID-19 pandemic, as well as the uncertainties surrounding the evolving global situation, such as the rate and level of spread, duration of illness; long-term physical and mental health effects; behavioural changes; effects on social cohesion and society at large; and untested government policy responses, make it difficult to estimate with any degree of accuracy the ultimate scale of the economic impact. While development and widespread distribution of an effective vaccine could help to speed up the social and economic recovery in one area, the emergence of new infection hot spots in others may require the reintroduction of lockdown measures or even stricter enforcement. Vaccine efficacy is commonly reduced in the elderly and other key communities at risk of severe disease, hospitalisation and death. It is highly unlikely that vaccine-induced immunity can provide sterilising immunity in the upper respiratory tract, resulting in vaccine immunity that may protect the individual but not fully abort a limited period of viral shedding and risk of onward transmission.

The global economy has undoubtably been impacted by the effects of the pandemic and many economies show signs of emerging recession. All economies are likely to experience significant economic losses, but emerging and developing economies are especially vulnerable with per capita incomes expected to decline, and an increasing risk of falling below the poverty line.

The forecasts in June 2020 predicted a 5.2 per cent contraction in global GDP in 2020 – worse than the 2007–2009 financial crisis. According to IMF's latest World Economic Outlook, however, the forecasts are now less severe, and the contraction is expected to be 4.4 percent [6]. This slightly less severe projection is predicated on evidence of improvements in advanced economies in the second quarter of 2020 and an anticipation of stronger recovery in the third quarter. The latter partly compensates for the

downgrades in emerging and developing economies, therefore thus far preventing a recurrence of the 2007–2009 financial crisis. The final outcome however is difficult to predict given the reintroduction of partial and nationwide lockdowns in many countries in the fourth quarter of 2020 due to the second wave of COVID-19 cases which threatens to overwhelm health services. These restrictions are expected to have adverse implications on the growth in the fourth quarter of 2020 and the first quarter of 2021, affecting the services-dominated economies, including Spain, Italy and the UK, the most [7].

While the governments of mature advanced economies of the world have been able to benefit from international borrowing to fund public spending on emergency stimulus packages and social protection programmes, other less developed economies have been limited in their ability to offer similar lifelines to their populations, due to higher debt and borrowing costs. However, given the intrinsically global nature of the COVID-19 challenge, international cooperation and collaboration is going to be needed to tackle the health and economic consequences of the pandemic. Low-income economies in particular, need to be supported through debt relief, grants, and concessional financing to help them sustain their economic activity [6].

1.3 IMPACTS OF THE PANDEMIC ON DELIVERING THE SDGS

The Sustainable Development Goals (SDGs) were adopted in 2015 as part of the UN's 2030 Agenda for Sustainable Development with the aim of providing a universal framework to "*end poverty, protect the planet and ensure that all people enjoy peace and prosperity*" [8]. However, despite the commitment of 193 nations to the goals, progress on achieving them has been slow and uneven up to the close of 2019, and many areas of the SDGs were already in need of accelerated interventions to achieve the targets by 2030 [9]. Emergence of the pandemic during the course of 2020 has put additional strains on the ability of many countries, both advanced and developing, to support the goals and may not only slow progress towards achieving them but also reverse the gains that have already been made.

As a result of COVID-19, even more aggressive strategies will likely be required to put countries back on track for delivery of the SDGs, whilst in parallel rebuilding their economies and reducing the socio-economic inequalities that have been exposed, and in some cases exacerbated, by the pandemic [6], [9], [10]. Appendix A provides further details of the anticipated impact of Covid-19 on the 17 SDGs.

1.4 PANDEMIC AS AN OPPORTUNITY TO BUILD RESILIENT AND SUSTAINABLE COOLING ECONOMY

In 2020, 1.02 billion people among the rural and urban poor are at high risk from lack of cooling access [11]. Providing access to sustainable clean cooling for all that need it, among other things, can:

- reduce post-harvest food losses and thereby hunger, while raising the income of small farmers and fishers;

- increase market connectivity that would boost local economies and decrease poverty in rural agrarian communities;
- generate employment and reduce the incentive to migrate to city slums;
- help address gender barriers and broader inclusivity issues;
- reduce vaccine preventable deaths caused each year by inadequate refrigerated distribution.
- improving air quality and reducing the level of other pollutants in the environment;
- reduce energy costs through the provision of off-grid technology based on renewable energy; natural and waste thermal energy resources, and the use of passive cooling techniques;
- and build resilience against external shocks such as the impact of extreme weather events including heat and storms.

Once a vaccine is approved and manufactured, effective and equitable distribution will require a significant scale up in cold-chain related cooling capacity from infrastructure and equipment for product storage and transport through to the human resource needed to provide the workforce for its deployment, operation and maintenance.

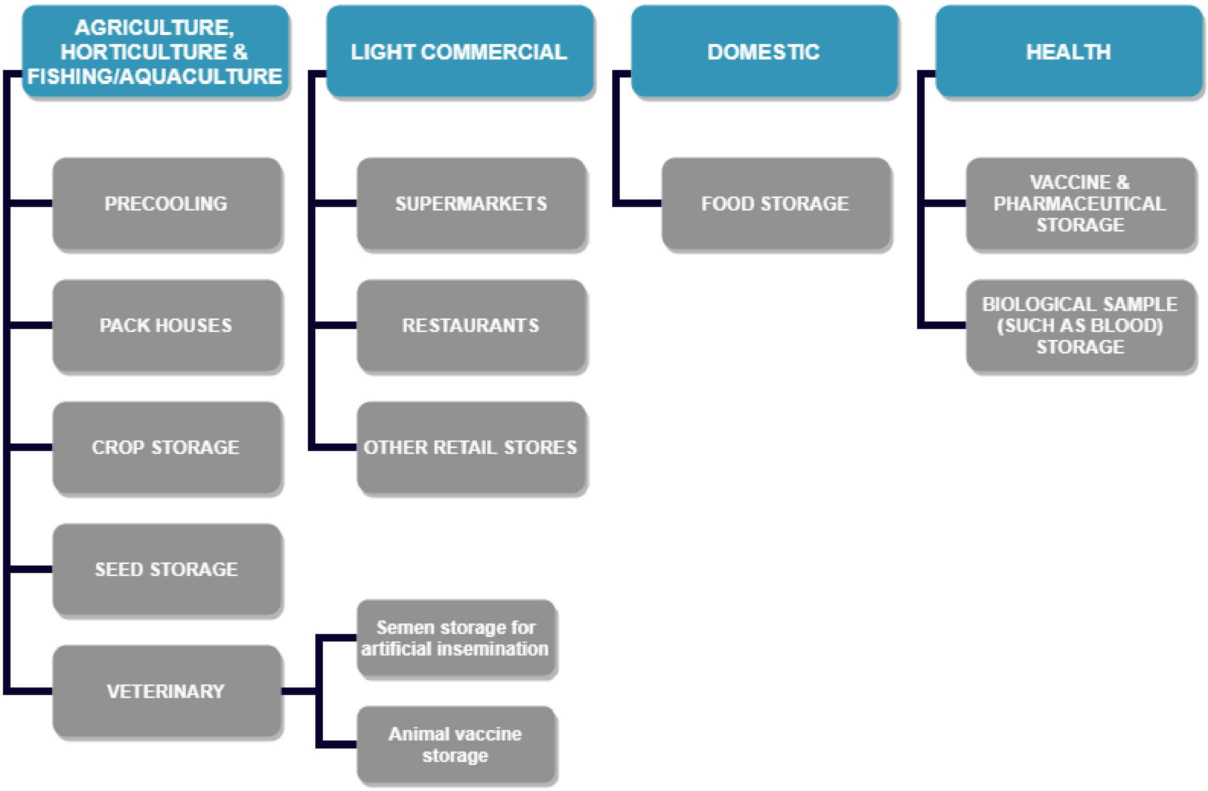


Figure 1: Examples of refrigerator use cases

Could this additional infrastructure and equipment be procured and deployed in such a way that it not only facilitates the COVID-19 response and bridges existing gaps in routine immunisation programmes, but also offers opportunities for re-purposing to help address the needs in other sectors, such as the agriculture, animal husbandry and/or light commercial elements of food supply systems (For example,

see Figure 1) post-pandemic? Smart planning at this stage of the pandemic response, along with system level thinking, could potentially help countries to achieve their long-term sustainability goals and deliver on their SDG commitments, thereby leveraging COVID-19 investments that might otherwise result in redundant infrastructure and stranded assets when this current global emergency recedes.

Given that cooling underpins so many aspects of a modern society, through a strategy of planned repurposing and reuse, the unprecedented logistical challenge of COVID-19 vaccine delivery presents a real opportunity for many countries to improve their current cooling systems with sustainable and clean technologies along with their workforce to service and maintain new cold-chains and the cooling sector as a whole, which would also open up sustainable job opportunities and help ailing economies recover better from the ongoing pandemic. This will not only help them deliver their SDG commitments, but also assist them in simultaneously achieving their Paris Agreement related GHG reduction targets and meeting their obligations under the Kigali Amendment to the Montreal Protocol. To achieve this, however, alongside system level thinking and planning, there is also a need for novel, innovative financial models and incentive schemes to enable the efficiency gains and emission savings that can be achieved by new sustainable cooling equipment to be realised.

1.5 WHAT IS THE WAY OUT?

While the question of how the COVID-19 pandemic will continue to evolve remains unanswered, there appears to be a consensus amongst the majority of scientists and politicians as to how it might conceivably be brought to an end. When enough of the population becomes immune to the disease, the spread will slow down and the number of vulnerable members of the community who develop severe disease should decline. The herd immunity threshold varies across countries depending on the reproduction number, which indicates the number of secondary infections per infected individual. In this regard, the threshold has been estimated to be at least 50 per cent to 60 per cent, but this can go even higher to 75 per cent in countries with a high reproduction number [3]. However, herd immunity alone may not be enough to protect the whole community and it is possible that the COVID-19 virus could become locally endemic to particular communities, similar to other seasonal respiratory viruses, for example as is already the case with influenza and respiratory syncytial virus.

Herd immunity can be achieved either by natural infection or through vaccination, although the immune responses derived from each method differ. Achieving herd immunity naturally (i.e. letting infection run through a susceptible population) would take a relatively long time, and likely lead to a widespread presentation of the disease, with the potential to overwhelm existing healthcare systems that in most cases have insufficient scale and resources for dealing with such an outcome. The result could be a large number of deaths in elderly and other vulnerable groups within infected populations. The politically preferred solution globally is therefore to achieve the required thresholds through vaccination. This, in turn,

requires a vaccine to be developed, tested, approved, manufactured, distributed and administered in mass quantities at a scale never before witnessed.

Currently, across the world, there are eleven vaccines in their late stages of development [12] and a breakthrough to availability is anticipated soon. Once a broadly effective vaccine is approved and an adequate supply is manufactured and secured, delivering it efficiently and equitably will critically depend

BOX 1 The Kigali Amendment and COVID-19

The Kigali Amendment to the Montreal Protocol was enacted in October 2016 by 198 governments and took effect from January 2019. The Amendment calls for the phase-down of hydrofluorocarbons (HFCs) by cutting their production and consumption, targeting a reduction of over 80 per cent by 2047 compared to baselines.

The Kigali Amendment has highlighted the linkages between cooling, energy demand, and climate change. However, meeting the Kigali Amendment's target could be very challenging given the increasing cooling demand and the need for providing a cooling for all approach to achieve SDGs. Further accelerating the uptake of energy efficient, natural and ultra-low-GWP cooling equipment is therefore crucial.

The rapid rise in refrigeration demand that will be required to deliver COVID-19 vaccines will add further to this challenge. Due to the need to vaccinate a large percentage of populations to achieve herd immunity, and with the pressure of reopening economies as quick as possible, Governments may have to lean towards unsustainable, inefficient and high GWP cooling technologies with lower capital cost. The COVID-19 deployment plans reviewed in this work to date do not consider the environmental impact of the cold-chain equipment required for the vaccination programme, and the focus is generally limited to building storage capacity due to urgency. However, the equipment deployed as part of the immunisation programme will be in place or in circulation for many years to come, potentially becoming a barrier for achieving the Kigali Amendment's targets. Additionally, such equipment is likely to be unnecessarily expensive to operate and maintain, and thus uneconomical in the long-term. Due to the relatively high upfront costs of new, cleaner, sustainable technologies, the associated lack of deployment and operational expertise and the perceived risks of new technologies, financial and technological support is needed for developing countries to accelerate and incentivise the uptake.

on the readiness of a fit-for-purpose cold-chain network. All the vaccine candidates require temperature management as well as close integrity monitoring throughout the supply chain journey. To achieve the necessary herd immunity thresholds, governments worldwide therefore need to develop robust immunisation plans that are supported by adequate fail-safe cooling technologies and temperature-controlled logistics. Given the service life of cooling equipment, any procurement actions or re-engineering/repurposing of existing cold-chain infrastructure undertaken to meet this challenge will have long-term effects potentially lasting well beyond the period of the pandemic itself. Therefore, now is the time for informed planning and decision making to improve the current vaccine cold-chains with sustainable technology choices, and likewise to establish new sustainable distribution infrastructure to deliver immunisation programmes. In fact, the scale of the COVID-19 response provides a unique opportunity to consider the cold economy as a whole, and to achieve long-term efficiency and sustainability gains by identifying synergies between sectors and areas where cooling demand can be aggregated and/or capacity shared, which would in turn build resilience against future external shocks, emergencies and/or disasters, such as those associated with climate change induced extreme weather events including heat waves and storm events.

2 CURRENT STATE OF THE VACCINE COLD-CHAIN

2.1 VACCINE FLOW AND THE COLD-CHAIN

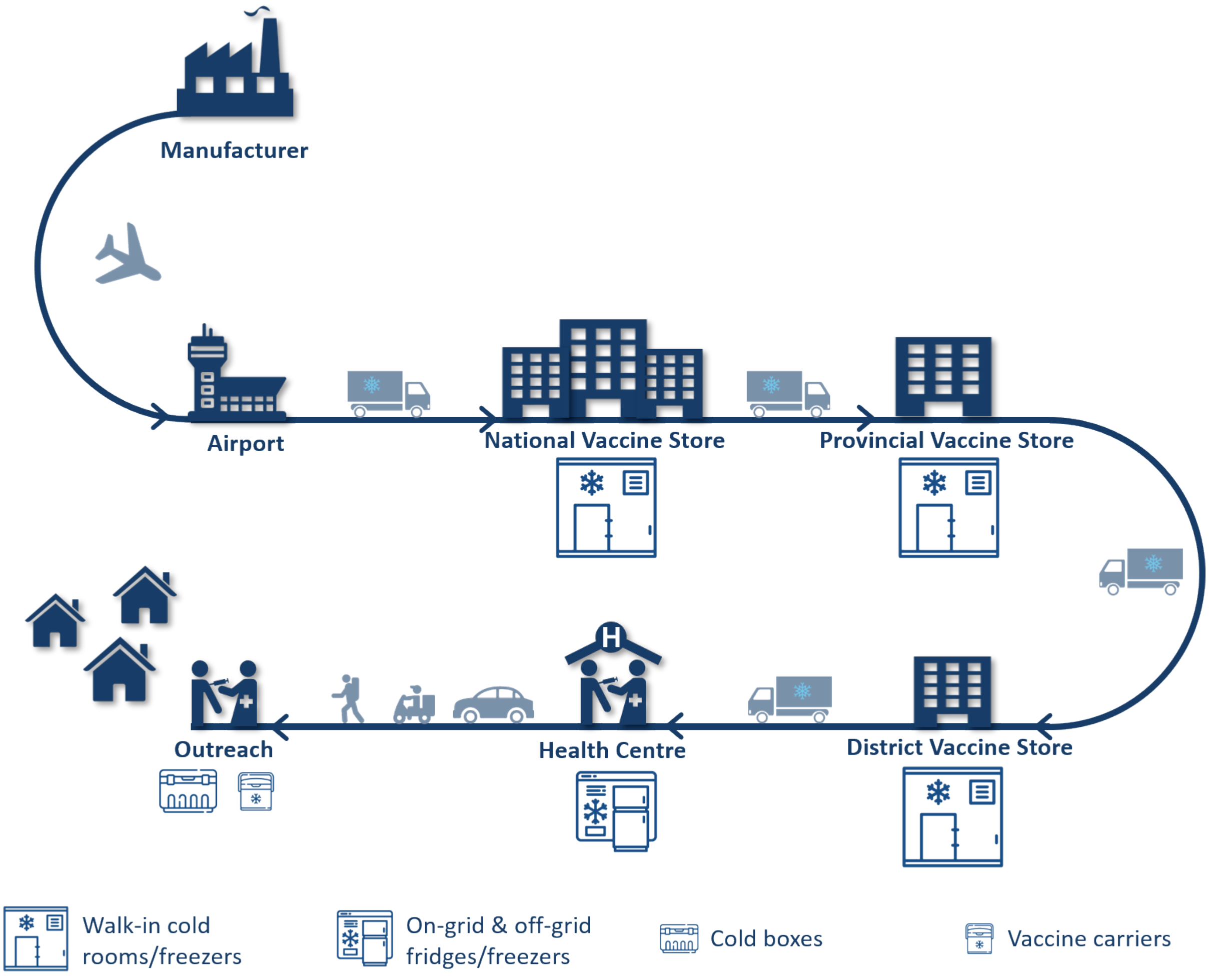


Figure 2: General structure of vaccine cold-chain in routine immunisation programmes[4]

The success of global, national and local immunisation programmes critically depends on robustness of vaccine cold-chains. Vaccines are biological substances that may lose their efficacy if exposed to a temperature beyond their recommended ranges for inappropriate amounts of time (both higher and lower temperature excursions, even for very short periods of time, can render a vaccine obsolete and freezing can be highly damaging for vaccines to be stored above 0°C [5]). The purpose of a vaccine cold-

[4] Manufacturer, National Vaccine Store, Provincial Vaccine Store, District Vaccine Store, Outreach, Cold box, Vaccine carrier, Van, Motorcycle : Icons made by Freepik from www.flaticon.com, Airport: Icon made by Creaticca Creative Agency from www.flaticon.com, Aeroplane: Icon made by Pixel perfect from www.flaticon.com, Cold room: Icon made by Good Ware from www.flaticon.com, Fridge/freezer: Icon made by xnimrodx from www.flaticon.com, Vaccination: Icon by Adioma

[5] Examples to freeze-sensitive vaccines include diphtheria, tetanus, hepatitis B and Haemophilus influenza type b [13].

chain is to maintain the quality of vaccines by ensuring they are handled, stored and transported within an appropriate temperature range, which is typically between 2°C and 8°C, from the time of manufacture to the moment of administration.

Figure 2 illustrates the typical vaccine flow for a routine immunisation programme, including the infrastructure and cooling equipment generally used for distribution from the point of manufacturer through to the health centre and/or outreach service point where it is administered.

2.2 COLD-CHAIN EQUIPMENT

According to the 'Efficiency for Access' coalition's forthcoming '2020 Off-Grid Market Survey'[6] (See Figure 3), vaccine and blood bank refrigerators are currently ranked as the most important devices for health care delivery. To efficiently and effectively deliver the COVID-19 vaccine to adequate percentages of the world's population, many more of these devices along with substantial amounts of other cold-chain related equipment will be required.

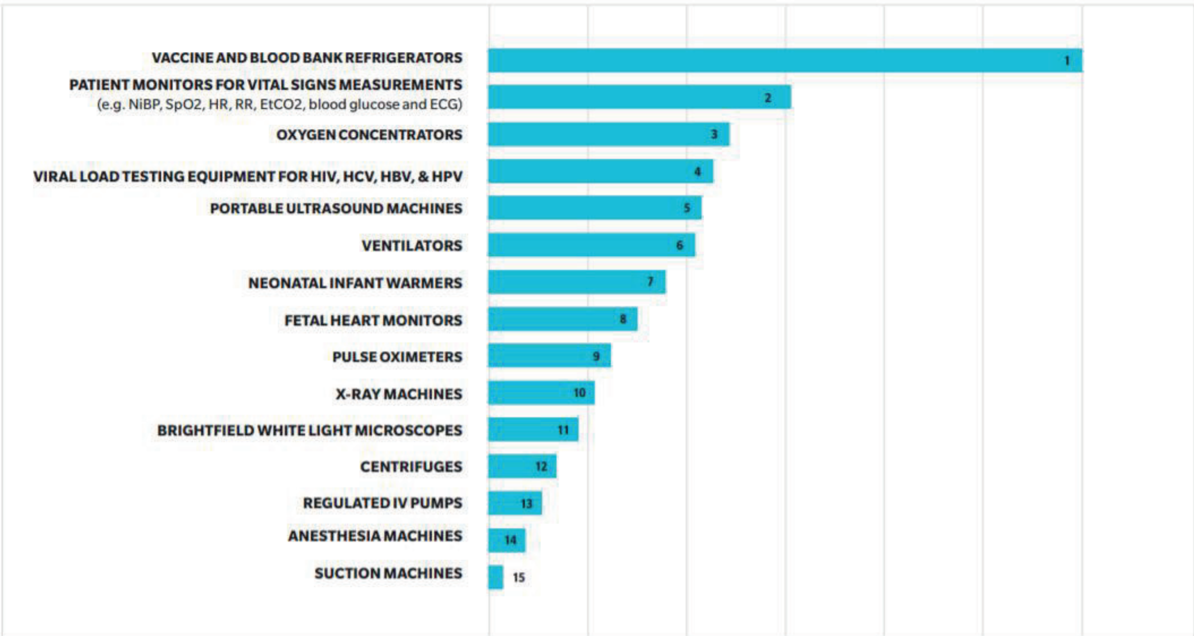


Figure 3: Importance of Medical Devices for Health Service Delivery (Source: CLASP [14])

Walk-in cold rooms (WICs) and freezer rooms (WIFs) are often used for bulk storage at national, provincial and district vaccine stores. They require a continuous supply of electricity and standby generators in case of a power outage. Vaccines are stored in specialised areas in the rooms before being shipped to lower-level storage facilities.

[6] "The 2020 edition of the Off-Grid Appliance Market Survey uses data collected from 133 industry, policy and development stakeholders to offer unique insights into the dynamic needs of consumers and the potential positive socioeconomic impacts of off-grid appliances."[14]

Ice-lined refrigerators (ILRs) run on mains electricity or generators. Many new ILR models can provide safe storage for vaccines at required temperature range between 2°C to 8°C longer periods of time with only 8 hours of power supply in 24 hours [15]. In case of a power outage, the ice lining maintains the required temperatures for vaccines. Some fridges can maintain temperature for up to 10 days, depending on the ambient temperature, frequency of lid opening, quantity of vaccines in the refrigerator and condition of the ice lining.

In current immunisation programmes, **on-grid freezers** are generally used for long term storage of vaccines that require sub-zero temperatures (such as OPV) at district level, and for preparation of ice and coolant packs at health centre level. As ILRs, on-grid freezers also run on mains electricity or generators, and they provide better temperature monitoring and safer storage than standard domestic freezers [15].

Solar powered refrigerators and freezers are designed to maintain vaccines at their appropriate temperature, without the need of electricity from the grid. Even though initial cost of solar powered systems is higher than electric refrigerators/freezers, they offer significant energy cost savings as well as reduce emissions. Solar powered refrigerators and freezers are especially recommended for areas with no access to the national power grid or with limited/intermittent power supply. They use solar energy to directly freeze water or other phase-change material (PCM). This stored energy is then used to provide continuous cooling, even when energy is unavailable or limited (such as during the night and cloudy days).

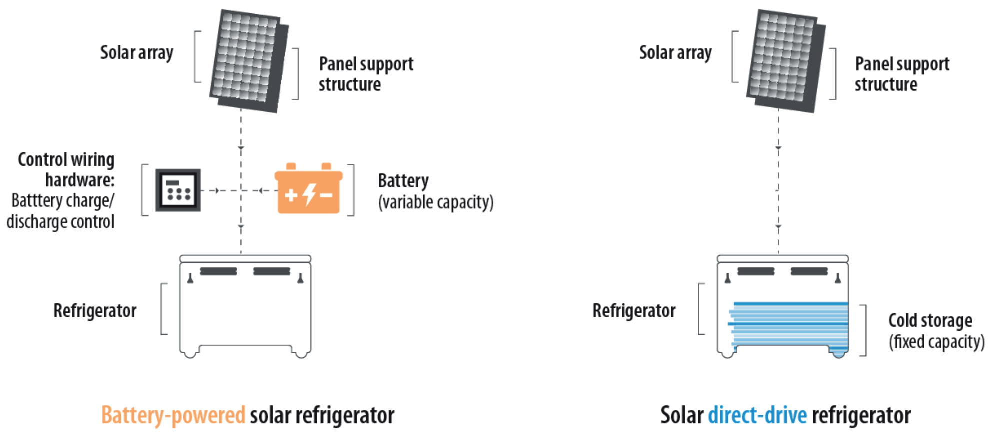


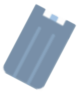
Figure 4: Difference between battery-powered and SDD equipment [16]

There are two types of solar powered refrigerators and freezers: **solar direct drive (SDD)** and **battery solar powered systems**. While SDDs are generally more expensive to buy and install than battery powered systems, SDDs require less maintenance as they do not need batteries to operate (See Figure 4). However, among other things, lack of

technical expertise, solar module theft and ongoing solar array maintenance may limit the efficiency and reliability of the solar equipment [16].

See Appendix B on selecting the right energy source for vaccine refrigeration.





Cold boxes are insulated storage boxes that are used to keep vaccines cold during transportation and/or short-term storage, such as in case of energy supply and equipment failure. **Vaccine carriers** have smaller volumes than cold boxes, and they are generally used by health workers during outreach immunisation sessions. Both cold boxes and vaccine carriers are passive systems[7] that require **ice or coolant packs**, and therefore freezers, to keep vaccines at required temperature ranges. With cold boxes and vaccine carriers, there is far less ability to ensure correct temperatures and usage, as they generally lack integrated temperature monitoring and data collection systems. The integrity of vaccines may be compromised if the boxes and carriers left open too long and/or wrong number of ice packs are used. We understand companies such as Sure Chill are developing active cooling equipment (micro-chillers with thermo-electric refrigeration) with extended hold-over capabilities (3 days+) in high ambient temperatures and data capabilities, that can be used as mobile vaccine fridges. Also, the World Health Organisation (WHO) is writing a new set of PQS standards for active cold boxes.


[8]

Temperature monitoring devices are used to measure and record temperature readings periodically from cold-chain equipment to ensure the vaccines are kept in the recommended temperature ranges along the entire cold-chain.


[8]

Voltage stabilizers are used to protect on-grid cold-chain equipment to protect refrigerators and freezers powered from damage caused by fluctuations in the energy supply.

Refrigerated vans are used for bulk transportation of vaccines between storage points. Refrigerated vans are equipped with a refrigeration unit and an insulated cargo compartment.

2.3 ENVIRONMENTAL IMPACTS

While a cold-chain is an integral part of delivering a successful immunisation programme, it results in an environmental cost. For example, considering both energy emissions (i.e. indirect emissions) and leakage of refrigerant gases (i.e. direct emissions), one estimate suggests that the world's cold-chains are

[7] Passive cooling systems are the ones that use no energy, as opposed to active cooling systems that use energy for cooling.

[8] Icon made by Freepik from www.flaticon.com

responsible for approximately 1 per cent of global GHG emissions and can represent as much as 3–3.5 per cent of GHG emissions in developing economies [17]. Recent estimates also indicate that the health care sector is responsible for approximately 5 per cent of global emissions, including refrigerants [18].

Grid powered (on-grid) refrigerators and freezers indirectly contribute to emissions from cooling through the consumption of electricity that is generated using a mix of energy resources that often include fossil fuels, particularly in the case of developing economies where the burning of coal, gas and oil in power stations is widespread. Replacing existing old legacy equipment with modern energy efficient technologies reduces electricity costs and emission contributions, especially if the on-grid supply is generated from non-renewable resources.

Moreover, many health facilities and communities in developing countries, particularly those in rural areas, suffer from inadequate power grid infrastructure, which results in unreliable and intermittent electricity supply, or indeed have no grid connection available (off-grid). Consequently, these facilities often rely on collocated, highly polluting diesel fuelled electricity generators either for back-up or continuous use. Likewise, the *refrigerated vans, trucks and* lorries used in the mobile stages of the cold-chain are often diesel fuelled thereby contributing to GHG emissions; sub-optimised delivery routes, journey delays due to congestion or poor road infrastructure further worsen the impact.

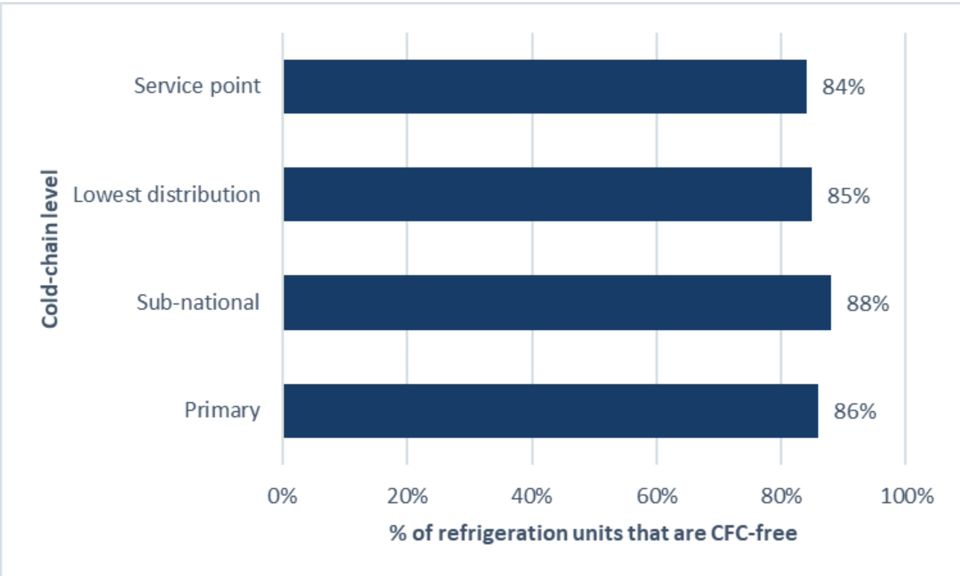


Figure 5: % of CFC-free equipment across cold-chain levels (The data was collected between 2009 and 2017 in 81 countries across all 6 WHO regions) (Adapted from Effective Vaccine Management (EVM) Global Data Analysis 2009)

In addition to the indirect emissions from energy use, direct emissions resulting from refrigerant leakages can be substantial (typically 70 per cent of cold-chain GHG emissions are associated with direct energy use and 30 per cent from refrigerant leakage, spillage or inappropriate disposal). Older, legacy cold-chain cooling equipment that utilises environmentally damaging high-GWP fluorinated refrigerants should be replaced with new modern equipment operating through the use of natural or synthetic refrigerants that

have minimal GWP/climate impact. However it is worth noting that in its PQS catalogue of approved equipment for vaccine cold-chain, WHO still lists equipment using R404A, which has a GWP of 3922, the highest of all the commonly used refrigerants and has been banned in Europe (recovered or reclaimed R4040A can be used until 2030) [19]. The WHO's recent effective vaccine management (EVM) assessment revealed that Chlorofluorocarbon (CFC) refrigerants are still in use in 81 countries across all WHO regions (Figure 5) [20]. Further data available from India's National Cold-chain Assessment conducted in 2014 revealed that the country has 18,267 CFC units operating across vaccine cold-chains, which accounts for 25 per cent of the total stock of equipment [21].

BOX 2 Status of cold-chain equipment in GAVI-eligible countries

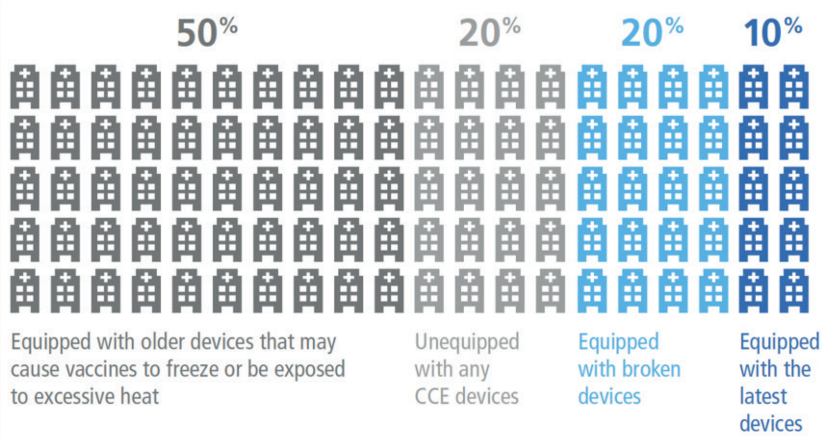


Figure 6: Estimations on the status of cold-chain equipment in several Gavi-eligible countries (Source: GAVI [15])

In 2014, GAVI[9] estimated that up to 90 per cent of health facilities were not equipped with adequate cold-chain equipment in several Gavi-eligible countries[10], 50 per cent being equipped with older devices that might compromise the integrity of vaccines, 20 per cent being equipped with no cold-chain equipment, and 20 per cent equipped with broken devices (See Figure 6). While there has been progress, still significant shortfalls remain.

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[9] Gavi, The Vaccine Alliance (GAVI) is an international organisation, created in 2010, that brings together "public and private sectors with the shared goal of creating equal access to new and underused vaccines for children living in the world's poorest countries" [22].

[10] See Link for list of GAVI-eligible countries.

2.4 WEAKNESSES OF THE CURRENT COLD-CHAIN

The current provision of cold-chains globally for vaccine distribution exhibits significant weaknesses that, when combined, substantially hinder worldwide efforts to deliver efficient, effective immunisation programmes at large scale.

2.4.1 INSUFFICIENT COLD-CHAIN CAPACITY

At the core of achieving targets for effective and equitable immunisation is the timely availability of efficient and reliable cold-chain capacity of sufficient scale. However, due to high populations and growth rates as well as needs to improve immunisation coverages, developing countries often struggle with insufficient capacity, both in terms of absolute equipment numbers and availability issues related to poor reliability and/or inadequate maintenance. This translates into:

- delays in new vaccine introductions to immunization programmes;
- increased supply intervals overwhelming the available cold-chain, consequently increasing the transportation cost per vaccine dose;
- high levels of vaccine wastage due to lack of alternative storage equipment (often due to equipment malfunction and/or energy supply failure);
- and disruptions in the vaccination services that threaten the integrity of immunization programmes.

2.4.2 OUTDATED COLD-CHAIN EQUIPMENT

Old, outdated legacy equipment used in distribution cold-chains can significantly affect the performance and efficiency of immunisation efforts through poor temperature control and inadequate data collection capabilities (recording and/or transfer), insufficient holdover times and a lack of freeze protection, putting the integrity of vaccines at risk. As shown in Figure 6 in Box 2, only 10 per cent of GAVI-eligible countries worldwide are equipped with the latest, modern equipment. As will be discussed in section 2.4.7 below, the relatively high capital costs of modern, highly efficient equipment is one of the major barriers to uptake of these new technologies, even though they generally provide cost savings on energy bills and reduced emissions.

2.4.3 INADEQUATE MAINTENANCE AND MONITORING

An effective cold-chain maintenance regime and operating system, that includes devices for real time monitoring, alarms for temperature excursions and equipment malfunction, and voltage stabilisers, as well as an adequate stock management system, is vital for ensuring the availability and quality of vaccines. Timely fault diagnosis and repairs, along with routine maintenance that follows equipment manufacturer

recommendations, avoid unnecessary and more expensive repairs, premature replacement costs, and vaccine product waste that could result in excessive immunisation cost burdens.

Indeed, the global cost of vaccine wastage due to products being exposed to temperatures outside of their recommended range is, in fact, estimated to be $34.1 billion annually, not including the substantial physical burden and financial cost of illnesses that could be avoided by ensuring on-time delivery of effective and potent vaccines [23]. An estimate published in 2019 suggests that 25 per cent of vaccines are still degraded by the time they reach their final destination, due to a lack of compliance, standardization, accountability and transparency across the air transport supply chain [24].

2.4.4 LACK OF RELEVANT SKILLS AND ADEQUATE TRAINING

An insufficient supply of engineers, technicians and mechanics with the relevant skill set for cold-chain equipment and infrastructure installation, operation, maintenance and decommissioning, along with inadequate training to develop such skills, often result in incorrect deployment and poor performance, long response times to malfunctions and failures leading to high cold-chain sickness rates (i.e. proportion of broken cold-chain equipment at any point in time, as defined by Government of India guidelines, which recommend that this should always be less than 2 per cent at any given point of time [25]), and inappropriate disposal. These issues not only reduce the availability of cold-chain capacity, but also lead to unnecessary energy use and GHG emissions, environmental pollution and damage, vaccine degradation and waste, administration of ineffective vaccines, and ultimately a wide range of avoidable costs.

BOX 3 Electronic Vaccine Intelligence Network in India

India launched the electronic Vaccine Intelligence Network (eVIN) in 2015, in partnership with GAVI. The eVIN is an electronic logistics management information system that provides real-time data on vaccine stock status and temperature across the entire vaccine cold-chain, which helps requirement estimation, emergency management, tracking of consumption patterns, and efficient stock reallocation [26].

The system has been implemented in more than 521 districts, across 21 states and union territories. eVIN achieved a reduction in the utilization of vaccines from a pre-eVIN level of 305.3 million doses to 214.9 million doses across the 12 states in which it was initially adopted, mostly on account of wastage and mismanagement [27].

2.4.5 LIMITED OR UNRELIABLE ENERGY ACCESS

Reliable and resilient energy access is critical for maintaining a cold-chain, and thus central to preserving vaccine efficacy. Infrequent energy supply can also damage cooling equipment and shorten its operational life.

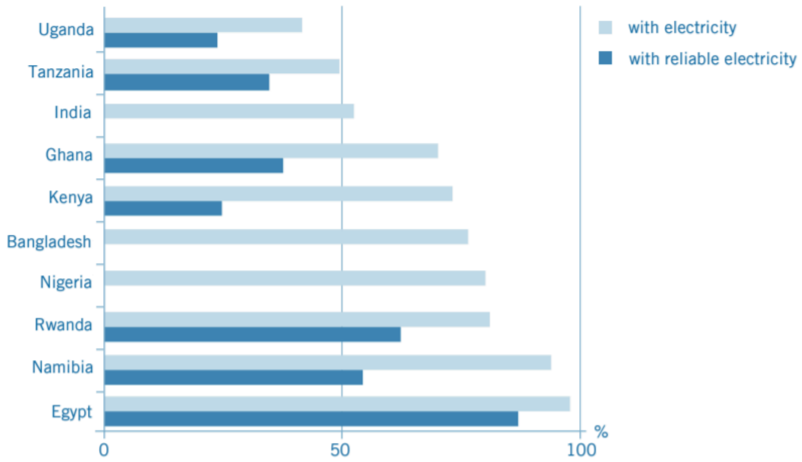

Figure 7: Electricity access rates in health facilities for the few developing countries with available data (Source: Practical Action, 2013)

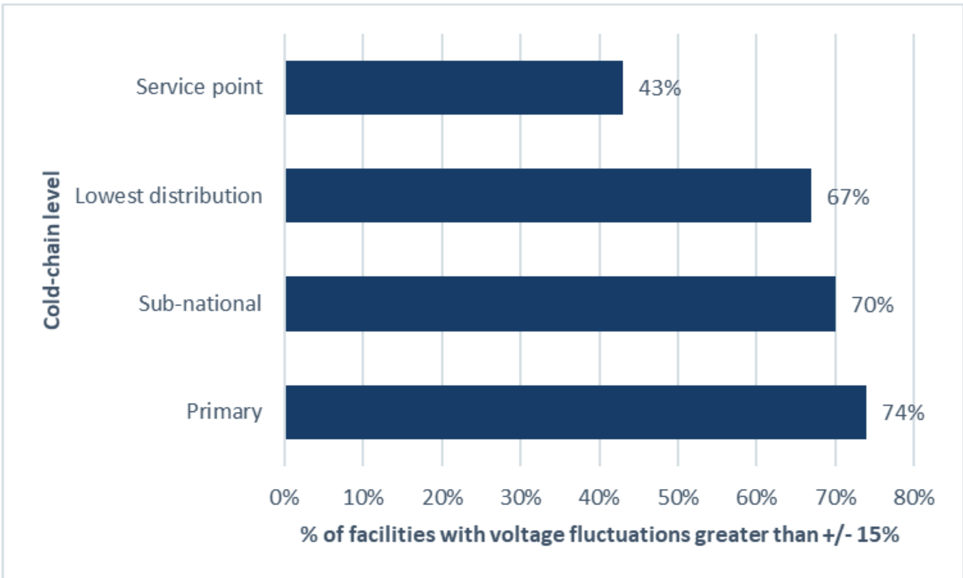

Figure 8: % of facilities with voltage fluctuations greater than +/- 15% (The data was collected between 2009 and 2017 in 81 countries across all 6 WHO regions) (Adapted from Effective Vaccine Management (EVM) Global Data Analysis 2009-2018)

Estimates made by the Practical Action charity in 2013 suggested that 46 per cent of health facilities in India, and more than 30 per cent of those in sub-Saharan Africa, did not have access to electricity (See Figure 7) [28]. Furthermore, recently published data available from the WHO's Effective Vaccine Management (EVM) assessment, revealed that many facilities across the vaccine cold-chains in developing

countries, especially the service points, suffer from unreliable energy supply (See Figure 8) [20], which is in line with the Practical Action estimates from 2013 presented in Figure 7.

2.4.6 LIMITED OUTREACH

In developing countries, a large proportion of the population typically live in rural, remote areas [29] with geographical barriers, inadequate infrastructure (such as a lack of transportation and poor road conditions), where access to health and immunisation services is generally severely limited. To increase immunisation coverage, the majority of immunisation services in these countries are delivered via outreach (in some cases, more than 50 per cent), which places delivery burdens on health care workers and reduces the ability to realise programmes that require frequent immunization sessions [5].

Furthermore, these countries may also have nomadic and/or seasonally mobile populations, or marginalised or disadvantaged groups, that are typically not registered at the place where they are temporarily residing, and have little or no contact with routine immunisation services, thereby creating issues in ensuring timely, inclusive, equitable and complete immunisation of populations, as well as proper recording and reporting of programme information and success factors [30].

2.4.7 LACK OF FINANCING AND SUSTAINABLE BUSINESS MODELS

The cost of fully vaccinating a child has been estimated to be in the range US$25–$45, but this does not include the non-vaccine costs involved in immunisation such as cold-chain equipment, staff, training, operation and maintenance [31]. However, despite these costs, in addition to saving an estimated 2 to 3 million lives each year, vaccination is considered to be a cost effective approach to disease control if the savings on the medical cost that would otherwise be incurred, as well as the productivity gains from ensuring a healthy population, are accounted for. Indeed, UNICEF estimates that every dollar spent on child immunisation provides US$44 worth of economic benefits [32]. Realising these benefits, however, requires that the weakest links in existing distribution cold-chains are strengthened, and new cold-chain infrastructure is provided in cases where it is needed but does not currently exist, so as to improve access to safe and quality vaccines. Achieving this sustainably, with minimal environmental footprint, demands significant investment in clean and energy efficient cold-chain solutions both for new builds and retrofits. In the case of developing countries, where the requirement for equipment and infrastructure is largest, and government monies are in short supply, international development assistance alone is not be enough to meet such investment needs. Much of the finance must therefore be mobilised from private sources, including corporate business, patient investing and the philanthropic sector, often locally. Innovations in financing mechanisms, incentives, business models, and financial supporting instruments can drive these new investments in energy efficient and sustainable cold-chain deployments.

For most cooling technologies, the main components in the life cycle cost of equipment ownership are energy consumption and maintenance. The initial capital investment required is in fact only a small fraction. In other words, the total cost of ownership of cooling systems is most effectively reduced by:

- installing equipment with the highest level of energy efficiency available;
- optimising preventive maintenance;
- applying systemic thinking to minimise the active cooling needs and therefore energy costs, such as through passive and behavioural solutions;
- and to further optimise the energy utilisation and/or efficiency, such as through deployment of thermal energy storage systems.

Furthermore, the higher upfront capital investment cost typically associated with a sustainable cooling equipment choice, when compared to procuring conventional cooling options, often acts as a major barrier to making the switch to such systems either for a new build or retrofit deployment. Underpinning the relatively high retail price is the current low level of volume demand for sustainable cooling technologies, which is partly due to a lack of awareness of the need for their adoption and an absence of government commitments to support the mass deployments that would lead to reduce costs, and the high costs incurred for shipping of equipment from manufacturers to locations that need them the most. With regard to the latter, many sustainable cooling technologies are developed and manufactured in the mature advanced economies of the 'Global North' but needed most acutely in the developing and least developed nations of the 'Global South', where vaccine cold-chain infrastructure deficits are most severe, power grid availability, reliability and connectivity are major issues, and lower operating costs would be extremely beneficial. For example, rural and remote, difficult to access regions in many developing countries often struggle with unreliable, severely constrained or non-existent power grids and would benefit significantly from sustainable off-grid efficient cooling equipment as an alternative to the current default option of adopting expensive to run diesel-fuelled generators.

The key challenge for many potential adopters of sustainable cooling equipment is that the cost savings that result from the higher levels of energy efficiency are realised over a relatively long time period, so they do not typically deliver the financial benefits associated with their use either immediately or in the near-term. This can discourage traditional investment, particularly in less developed economies where quick returns are expected to drive growth, and countries which have a high cost of capital. Other adoption barriers include:

- a lack of clearly defined and accepted performance measures;
- the additional training required to implement and maintain unfamiliar equipment;
- a lack of trust in new, innovative technology that has low market penetration;
- and competing investment priorities.

High capital and operational costs as well as other barriers can be addressed through procurement approaches tailored to individual countries, financial levers for manufacturers, increased price transparency, adequate installation and maintenance procedures, and innovative business models.

BOX 4 Cooling-as-a-Service

An example of a successful business model for vaccine distribution may be Cooling-as-a-Service (CaaS), which is an approach gaining momentum in the food supply cold-chain sector. CaaS is a pay-per-use model based on a servitization strategy, in which the service of cooling is provided without selling the equipment. In the context of vaccine distribution, CaaS could take away the burden of large upfront investment, operation and maintenance costs from governments, making access to sustainable cooling more attainable, consequently reducing the cold-chain failure. CaaS could also allow repurposing of technology to address a multitude of cooling needs. This characteristic of the model to enable asset utilisation optimisation is highly relevant due to the sudden but temporary need for a substantial and unprecedented deployment of cooling systems for COVID-19 vaccine distribution, and the long lifespan of the equipment versus the potential timeline for vaccine needs.

Innovative business models like CaaS are also effective vehicles to involve the private sector to complement the supply chain and leverage private capital towards sustainable cold-chain solutions. Innovative recapitalisation mechanisms based on commercial or blended finance through project finance, asset-backed finance or securitisation, can help create portfolios of green projects for private and institutional investors.

3 COVID-19 AND THE VACCINE COLD-CHAIN

3.1 LEADING COVID-19 VACCINE CANDIDATES

As of 16 November 2020, there are a total of 260 COVID-19 vaccine candidates in development, with 56 now being tried on humans in clinical trials around the world [33]. Previous experience suggests that around 7 per cent of vaccines in preclinical studies and 20 per cent in clinical trials succeed [34].

Eleven vaccine candidates are in the final stage of testing (Phase 3), and it will be clear whether these vaccines are successful or not before the end of 2020. Table 1 summarises the leading vaccine candidates that are in their late development stages, and their specifications [12].

Each Phase 3 clinical trial can involve several tens of thousands of participants, which commonly results in adverse events which require a pause to the trial to allow for proper investigation of any potential relationship to vaccination or regulatory body oversight. University of Oxford/AstraZeneca and Johnson & Johnson/Janssen, vaccine developers in late-stage clinical trials, have followed these events through their studies.

Vaccine developer/ manufacturer	Vaccine platform	Number of doses	Timing of doses	Phase	Route of administration	Anticipated temperature requirement for shipment and long-term storage	Anticipated duration of storage possible at 2-8°C
BioNTech/Fosun Pharma/Pfizer	mRNA[11]	2	0, 28 days	3	Intra-muscular injection (IM)	-70°C	5 days [35]
Moderna/NIAID	mRNA	2	0, 28 days	3	IM	-20 °C	30 days [36]
University of Oxford/AstraZeneca	Non-replicating viral vector	2	0, 28 days	3	IM	2-8 °C	N/A
CanSino Biological Inc./Beijing Institute of Biotechnology	Non-replicating viral vector	1	-	3	IM	2-8 °C	N/A
Gamaleya Research Institute	Non-replicating viral vector	2	0, 21 days	3	IM	2-8 °C	N/A
Johnson & Johnson/Janssen	Non-replicating viral vector	2	0, 56 days	3	IM	2-8 °C	N/A

[11] To date no mRNA vaccine has ever been approved for use (November 2020).

Bharat Biotech	Inactivated	2	0, 28 days	3	IM	2-8 °C	N/A
Beijing Institute of Biological Products/Sinopharm	Inactivated	2	0, 21 days	3	IM	2-8 °C	N/A
Sinovac	Inactivated	2	0, 14 days	3	IM	2-8 °C	N/A
Wuhan Institute of Biological Products/Sinopharm	Inactivated	2	0, 21 days	3	IM	2-8 °C	N/A
Novavax	Protein Subunit	2	0, 21 days	3	IM	2-8 °C	N/A

Table 1: Leading vaccine candidates and their specifications as of 16 November 2020 [N/A: Anticipated temperature requirement for shipment and long-term storage is already 2-8 °C]

Pfizer/BioNTech collaboration has already announced their Phase 3 trial results on 18 November 2020. Their primary efficacy analysis suggests that the vaccine candidate could be 95 per cent effective, with consistent results across age, gender, race and ethnicity demographics [2]. They said that they could apply for emergency use authorization by the end of November and the vaccine could be ready for distribution early 2021 [37]. Furthermore, Moderna's vaccine candidate showed an efficacy of 94.5 per cent, according to early data released on 16 November 2020 by the company. Like Pfizer/BioNTech, Moderna also intends to submit for an emergency use authorization in the coming weeks [38]. Furthermore, according to peer-reviewed results of a Phase 2 trial published on 18 November 2020, University of Oxford/AstraZeneca's candidate provokes a strong immune response in older adults [39]. University of Oxford/AstraZeneca expect to release their late-stage trial results by the end of 2020 [40].

All late-stage vaccine products have been reported as safe and immunogenic in phase 1/2 evaluation, and although no immune correlate of protection is known for COVID-19, the immunogenicity following vaccination has been robust and comparable to the immunity derived from natural infection. It is not yet known whether, or to what extent, natural or vaccine-induced immunity can provide durable protection to re-exposure to the virus and the subsequent risk of developing disease and/or onward viral transmission.

3.2 ACHIEVING HERD IMMUNITY AND VACCINE EFFECTIVENESS

For any vaccine, efficacy and duration of protection are key parameters to success. While duration of protection may remain uncertain for several years after the vaccine is distributed, WHO has developed a Target Product Profile (TPT) for the COVID-19 vaccines, stating that while the vaccines preferably

should have at least 70 per cent efficacy on a population basis, with consistent results in the elderly, around 50 per cent efficacy on a population basis may be acceptable [41].

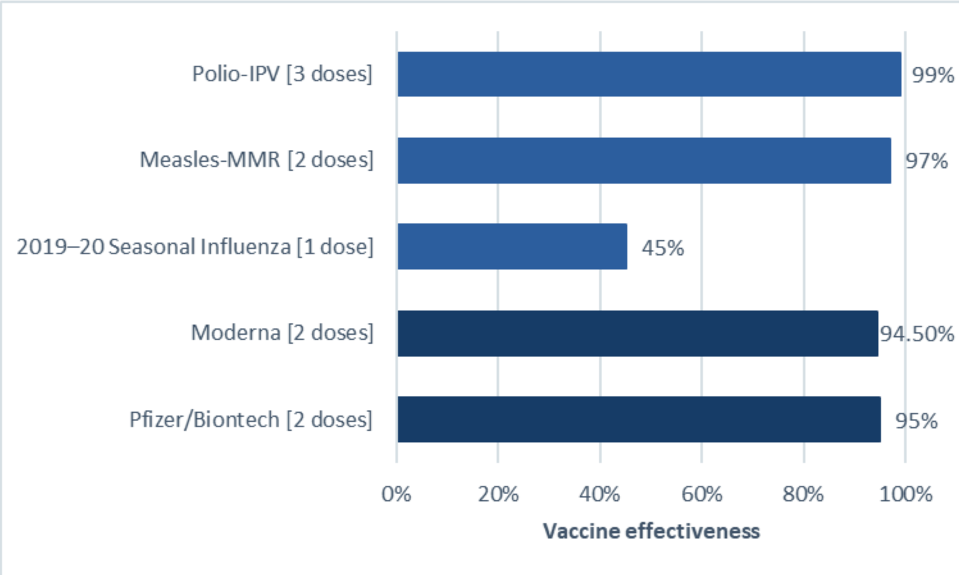

Figure 9: Expected vaccine effectiveness of Pfizer/Biontech and Moderna vaccine candidates compared to IPV [42] , MMR [43] and 2019-20 influenza vaccines [44]

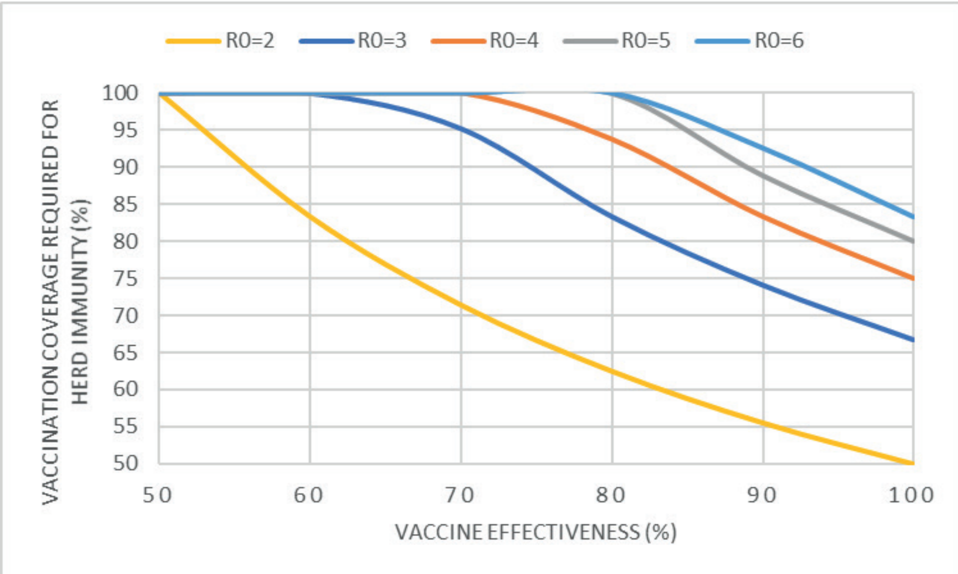

Figure 10: Vaccination coverage required to achieve herd immunity for different R_0 numbers and vaccine effectiveness levels

Under the best-case scenario with 100 per cent efficacy, the herd immunity threshold depends on R_0, the basic reproduction number, and calculated as $[1 - 1/R_0]$. The R_0 for COVID-19 has been estimated to be between 2.6-3.9 [3]. The numbers imply that around 60-75 per cent of population needs to be vaccinated to achieve herd immunity. However, if the vaccine is 95 per cent effective as, for example, Pfizer/Biontech's initial results imply, then these percentages would rise to 65-78 per cent [45] (See Figure 9 for effectiveness of different vaccines). The Figure 10 shows vaccination coverage requirements to

achieve herd immunity for different R_0 numbers and vaccine effectiveness levels. Once the herd immunity threshold is reached, recurrent vaccination will likely to be needed to attain a persistent herd immunity, as studies suggest that protection against coronaviruses are generally short-lived[12] [47].

3.3 POTENTIAL ROADBLOCKS AND STRATEGIES

3.3.1 PRODUCTION CAPACITY

Once a COVID-19 vaccine is approved, it must be produced quickly on a massive scale, international cooperation will be essential to provide inclusive, equitable access. The current production capacities are not large enough to satisfy the global demand for COVID-19 vaccines while providing the existing vaccines under routine immunisation programmes. Estimates of global production capacity suggest that just two billion doses could be produced in 2021 [48], corresponding to approximately 25 per cent of the world's nearly 8 billion population assuming that a 'one-dose' immunisation strategy is adopted. Given that nine of the eleven vaccine candidates in late stages of clinical trials require two doses, this number may reduce to ~12 per cent.

To cope with anticipated demand, many vaccine producers have already begun "at risk" manufacturing of their vaccine candidates in preparation for a rapid roll-out of immunisation programmes upon regulatory approval[13]. These risks are regarded as justifiable in the context of an urgent need to safely restart economies worldwide. However, UNICEF market assessment suggests that investments to support this production challenge will be "highly dependent on among other things, whether clinical trials are successful, advance purchase agreements are put in place, funding is confirmed, and regulatory and registration pathways are streamlined" [50].

3.3.2 VACCINE STORAGE AND DISTRIBUTION

Today's routine immunisation programmes typically target only new-borns, children and pregnant women in a given population, whereas COVID-19 vaccination will need to cover a substantial portion of the world's population at rapid speed to enable effective herd immunity to be established. As an example, while GAVI vaccination campaigns have reached 760 million people since the year 2000 [51], the COVID-19 vaccine could need to reach as many as 750 million people in Africa alone. In fact, it has been estimated that nearly 3 billion of the world's 7.8 billion people live in areas that lack temperature-controlled storage to deliver the COVID-19 vaccines [52].

[12] Pfizer/BioNTech's vaccine candidate is expected to provide protection "at least one year" [46].

[13] Pfizer/BioNTech expect to produce up to 50 million vaccine doses in 2020 globally, and up to 1.3 billion doses by the end of 2021 [2], and Moderna expects to produce approximately 20 million doses by the end of 2020, with an additional 500 million to 1 billion doses globally in 2021 [49].

India’s administrative coverage data, for example, shows that the total number of doses administered under the Universal Immunisation Programme (UIP) was around 400 million (covering a total of 56 million people) in 2019 [53]. The Health Ministry of India plans to immunise 200-250 million people (around 16 per cent of the nation’s population; significantly lower than the herd immunity threshold) against COVID-19 by the first two quarters of 2021 [54]. This will likely require 400-500 million vaccine doses, considering that nine of the eleven candidates in the late stages of development will require two doses to be effective (See Table 1). This means the number of COVID-19 vaccines to be delivered initially is equivalent to the amount of vaccinations currently administered under the UIP. Taking these calculations further, assuming a packed vaccine volume per dose of 5.2ml[14], the cold-chain volume required for 400 million doses equates to around 2 million litres if it is to be received in a single supply. If India were to achieve herd immunity, assuming a herd immunity threshold of 65 per cent of population, then the total vaccine volume that will be distributed across the country is around 9.5 million litres, not including the additional safety stock required to account for the potential vaccine wastage. These are simple estimates based on simple assumptions, but they provide insight into the scale of the storage and distribution challenge.

COLD-CHAIN EQUIPMENT DEPLOYMENT

There is a large variety of cold-chain equipment available in the marketplace globally with a wide range of specifications to meet different needs and applications. Prior to any procurement being undertaken, potential buyers, whether national governments, aid agencies or private corporations, should assess their existing cold-chain capability to have a better understanding of their needs and the gaps in capacity that need addressing at each point along the chain.

Given the current urgent need for high-volume and high-speed COVID-19 immunisation programmes to be delivered as soon as a vaccine becomes available, high levels of demand for passive and active cold boxes, vaccine carriers, and mobile cold rooms are anticipated in the immediate short-term to enable mobile outreach delivery challenges to be overcome. These pieces of equipment will provide an extended outreach capability, particularly in the case of developing countries, adding flexibility to programmes and increasing accessibility to the vaccine.

As the vaccine specifications are unknown, the deployment plans use different assumptions to estimate the scale of expansion required. For example, a reviewed country’s plan assumes the vaccine volume per dose to be 3.5ml. After assessing their cold-chain, they have calculated additional equipment to be procured so that the cold-chain can deliver the initial dose to 10 per cent of population, including the 10 per cent wastage rate. Furthermore, the deployment plan, including anticipated duration for different

[14] Packed vaccine volume per dose of influenza vaccines in multi-dose vials (10 doses per vial). No details have yet been provided on storage volumes of vaccines.

target populations, implies that the initial dose theoretically can be delivered to 20 per cent of population (which is their initial target) in 5 weeks, and they can be fully immunised in 10 weeks if the vaccine requires two doses. This implies that the herd immunity can be achieved in 40 weeks or 10 months, assuming a vaccination threshold of 80 per cent.

However, will the additional cold-chain equipment be enough if the vaccine volume per dose happens to be 5.2ml (or higher) instead of 3.5ml? In that case, the capacity planned seems not to be sufficient to hold the initial dose for 10 per cent of population, and the number of refrigerators and other cold-chain equipment as well as number of trips to deliver the vaccines will likely need to be doubled. If the government sticks to the initial numbers of equipment to be procured, then the government should receive the vaccine supply in much smaller batches from the manufacturer.

The deployment plans are also assuming there will be no transportation delays and supply will continuously be available. The speed of the flow will depend on number and capacity of trucks used to transport vaccines in country along with the stock management, ordering and handling practices at each level. This is also important to determine the number of cold boxes which will be used to store the vaccines in transport, and consequently ice or coolant packs required.

Each vaccine store will also have to consider reliability of energy supply, which is a key driver for the equipment type that will be chosen. In Bangladesh for example, 2017 estimations suggest that around 60 per cent of all health facilities are connected to the national grid, but 57 per cent of these facilities do not have regular energy supply [55]. Reliable energy supply is critical to maintain the integrity of vaccines, hence the facilities with unreliable energy supply will need diesel generators for back-up power, which are polluting. For facilities with no connection to the grid, solar fridges will need to be considered.

Procurement decisions should, however, be made with a view of not only the COVID-19 vaccine distribution needs of today, but also of the broader cooling needs of the future, and how the cold-chain equipment and infrastructure to be put in place can help deliver against the long-term sustainability targets, goals and commitments of the country in which it is to be deployed. If done right, the selected approach and equipment will not only contribute to the success of the immunisation programme, but also provide long-term economic, social and environmental benefits. With the arrival of new clean technologies for sustainable cold-chain storage and transportation, temperature monitoring, storage and inventory management, there is a high potential to improve on existing cold-chains.

WASTE MANAGEMENT

In addition to the volume of cold-chain storage required for the COVID-19 vaccines themselves, the storage capacity needed for Personal Protective Equipment (PPE) and supporting ancillary supplies, such as diluents, syringes, needles, alcohol prep pads, as well as for the reverse logistics of medical waste management, should be considered and addressed in planning the immunisation programme. In this

regard, the additional human resources required for waste management, as well as the need to continue with existing routine immunisation programmes, must be accounted for in the estimates to be made.

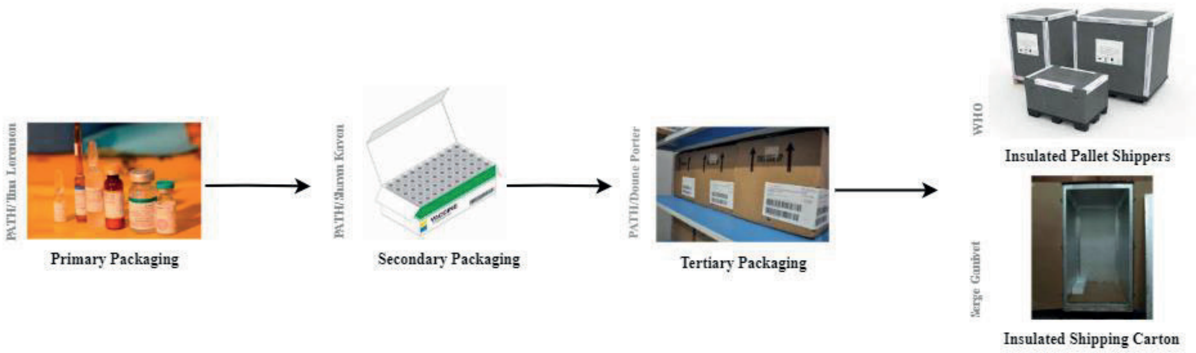

Figure 11: Levels of vaccine packaging

The Figure 11 illustrates the packaging hierarchy of vaccine products. At the bulk shipment end of this hierarchy, insulated shipping and insulated pallet shippers are typically used for international transportation. While insulated pallet shippers are re-usable, disposal of insulated shipping cartons, tertiary, secondary and primary packaging may be a challenge given the volume of vaccine requirements. Packaging materials can be considered as municipal solid waste, except for the primary packaging, which will need specialised treatment before disposal [56], along with other medical waste such as syringes[15], needles and Personal Protective Equipment (PPE) used during vaccination sessions. If not addressed beforehand, in the programme planning phase, this may pose a major logistical problem (particularly in outreach/mobile sessions) as the medical waste generated will need to be carried to proper treatment facilities. Although the deployment plans reviewed in this work acknowledge the need for waste management, the plans provided are generally too simplistic and the scale of the reverse waste logistics challenge that is likely to be encountered seems to be overlooked.

An absence of sustainable waste management practices in COVID-19 immunisation programmes may cause significant adverse effects on local ecology and wildlife, as well as impact on human health, at points along the vaccine distribution channel (especially if recyclable and/or eco-friendly packaging materials are not used), and potentially add further to the PPE waste that has been rapidly accumulating in the environment since the beginning of the pandemic.

SUB-ZERO TEMPERATURES

While research on vaccines is moving with unprecedented speed, some of the candidates imply significant challenges for the cold-chain with sub-zero temperature requirements, especially for developing countries.

[15] UNICEF is planning to stockpile 520 million syringes in its warehouses by the end of 2020, and eventually 1 billion syringes by 2021 [57].

Currently most of the vaccines used in routine immunisation programmes are required to be stored at temperatures between 2 - 8°C at all stages in the distribution cold-chain, with the exception of the oral polio vaccine (OPV) *(See Appendix C for recommended vaccine storage temperatures for vaccines used in immunization programmes).* OPV is stored at -15°C to -25°C in national and provincial facilities and it is recommended that it should be kept in the range 2 - 8°C at the district and health facility levels. However, although temperature-stability data studies at higher temperatures are ongoing, the Moderna and Pfizer/Biontech COVID-19 vaccine candidates require storage at -20°C and -70°C respectively, which represents a substantial challenge for the distribution cold-chain.

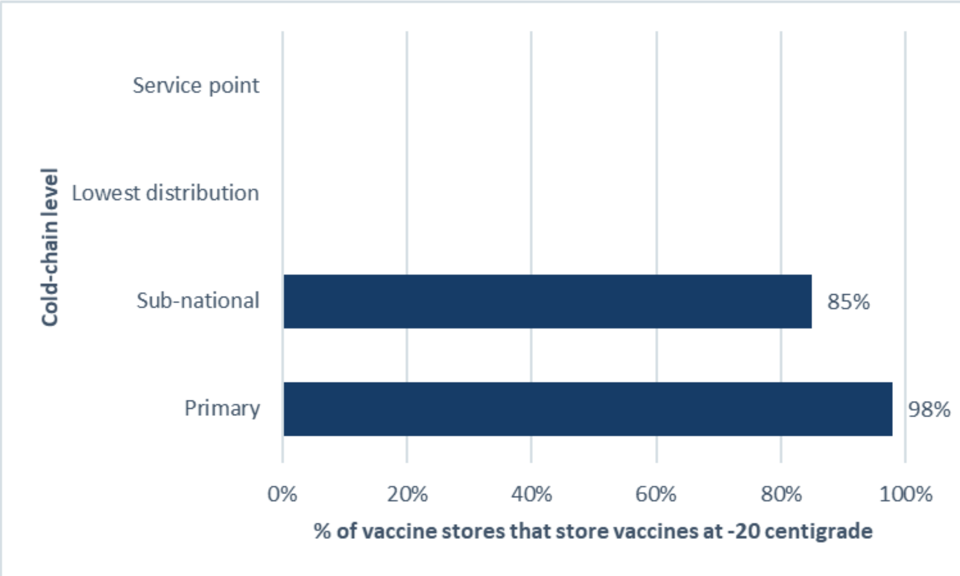

Figure 12: % of vaccine stores that store vaccines at -20C (The data was collected between 2009 and 2017 in 81 countries across all 6 WHO regions) (Adapted from Effective Vaccine Management (EVM) Global Data Analysis 2009-2018)

Even if vaccine developers aim for a storage set-point of -20°C, many service points in both advanced and developing countries, such as hospitals, clinics and pharmacies, will not have freezers with the temperature specification required for storage. It is in fact evident from WHO's effective vaccine management (EVM) assessment, that equipment for -20°C storage is not present at the district level and service points across all 81 countries assessed (See Figure 12) [20], let alone at the volume required for COVID-19 vaccines. Regarding the ultra-low -70°C storage requirement, the number of medical freezers that can handle these temperatures is extremely limited, even in the most advanced developed countries. Specifying a cold-chain for COVID-19 vaccine distribution that can handle such ultra-low temperatures would therefore demand significantly higher levels of investment in equipment and infrastructure than utilising, and adding to, existing capacity. Furthermore, such freezers cannot be procured locally in many developing countries. Delivering the freezers to these countries would not only take time, but also would be costly, as the freezers will likely have to be shipped via air given the urgency. In addition, the freezers typically operate most efficiently in ambient temperatures under 25°C, meaning that special temperature-controlled buildings

may be required, especially in countries located in high temperature zones. It would also limit future opportunities for cold-chain repurposing post-pandemic (either for the distribution of other vaccines and medical products, or products from other sectors such as agriculture and food supply) and require substantial levels of financial and funding support for developing countries. The latter would be needed not only for building storage and transport capacity that can operate within the required temperature range, but also for training staff who are not used to working with these temperatures.

These low temperature requirements will pose even greater last mile distribution challenges for developing countries with rural hard to reach populations. As both candidates can only be stored at regular vaccine refrigeration temperatures of 2 - 8°C for a limited length of time, doses will therefore need to be administered rapidly upon arrival, demanding unprecedented end-to-end speed of delivery through the distribution chain. This also increases the risk of vaccine wastage during immunisation sessions due to prolonged temperature excursions beyond their recommended range. Fortunately, both vaccine developers have been working on formulations to improve temperature-stability of their vaccine

BOX 5 Distribution of Ebola Vaccine

Vaccines are expected to meet WHO's mandatory vaccine characteristics criteria to be included in national immunization schedules. One of the criteria is that the vaccine should not require storage at less than -20°C, as the existing cold-chains are generally not designed to handle lower temperatures. However, exceptions can be made in certain situations, such as pandemics [59]. One example to this is the Ebola vaccine, which requires storage -70° to -80°C [60].

During the recent Ebola outbreak in West Africa, health workers transported the vaccine in a portable cold box known as Arktek [61]. Arktek is designed to store 5 liters of vaccines between 0-10°C for 35 days or more using only ice packs depending on the ambient temperatures [62]. A modified version of the Arktek that uses an alcohol based phase-change material rather than ice, is able to provide safe storage for vaccines at -80°C for up to 6 days [63], [64]. Each container costs around US$2,000 [65].

Democratic Republic Congo has managed to vaccinate over 300,000 people against Ebola [60]. Although this gives hope for COVID-19 mass vaccination that might require similar cold-chain temperatures, unlike COVID-19, Ebola was able to be contained to small regions. The scale of vaccination that needs to be achieved therefore is much bigger in the case of COVID-19.

candidates. While Pfizer/Biontech is working on a powder formulation of its COVID-19 vaccine that could eliminate ultra-low temperature cold-chain requirements [58], Moderna has announced that the vaccine candidate is now expected to remain stable at temperatures between 2 - 8° for 30 days, as opposed to previous estimate of 7 days [36].

TEMPERATURE REQUIREMENTS AND EQUITABLE ACCESS

A recent study by DHL highlights the issue of equitable access and its relationship to vaccine storage temperature. According to their estimations, at freezing temperatures the current vaccine cold-chain can only bring the vaccine to 2.5 billion people in around 25 developed countries. Due to an absence of suitably specified equipment capacity, Africa, South America and Asia cannot be readily supplied at scale. If the vaccine requires the conventional temperature range of 2 - 8°C, the number of potential

BOX 6 COVAX Initiative

Given that a vaccine based immunisation programmes are the most politically acceptable of the potential exit strategies out of the COVID-19 pandemic, funding support should be available at a global scale, not only for making advance purchase commitments to vaccines, but also to create incentives for capacity building in manufacturing and distribution as well as to put in place mechanisms that will ensure equitable access.

One such mechanism is the COVAX Initiative, which is directed by the Coalition for Epidemic Preparedness Innovations (CEPI), GAVI, and the WHO. The COVAX Facility aims to purchase 2 billion COVID-19 doses by the end of 2021 through collaboration with vaccine developers. In this regard, it acts as an insurance mechanism for produces by reducing the risk of production, though securing demand, and for high-income countries, by securing access to a portfolio of potential vaccines, without them having to commit to a specific candidate. As a result, lower income countries receive financial support and access to a vaccine once it is available [67]. The vaccines will be provided to all participating countries in an equitable manner based on their populations, prioritising healthcare workers first, then expanding to cover the vulnerable. Additional vaccines will then be offered based on “country need, vulnerability and assessed COVID-19 threat” [68]. Furthermore, under COVAX, GAVI has approved US$150 million in initial funding to help 92 low- and middle-income countries to prepare for the delivery of COVID-19 vaccines [69].

immunisations doubles to 5 billion. However, even in that case, the vaccine is unlikely to reach the majority of Africa due to high ambient temperatures and a lack of cold-chain infrastructure [66].

Fortunately, eight of the vaccine candidates in their late stages of development require conventional temperatures. If some of these vaccines were to be successful, then these vaccines could be directed to countries with less developed cold-chains, which would increase equitable access to vaccines as well as lower the financial and technological support required by reducing the need for special cold-chain equipment and additional training requirements.

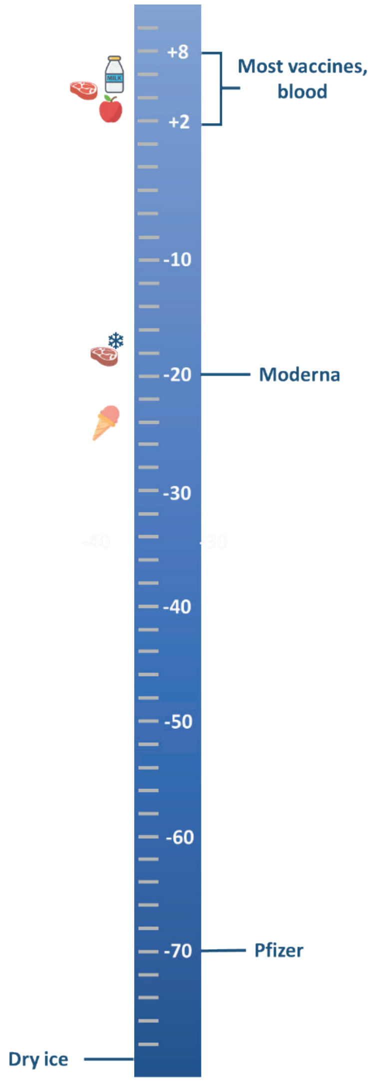

Figure 13: Cold-chain temperature requirements (°C)

ALTERNATIVE SOLUTIONS FOR CAPACITY BUILDING

Delivering COVID-19 vaccines to people in some of the most remote places of human habitation on Earth will require substantial investments and technological innovation. These concerns can be mitigated through support of NGOs and international organisations, and collaboration between private sector and public resources. Current government-controlled vaccine cold-chains used under routine immunisation programmes (See Figure 1), particularly in developing countries, will not cope with the demand, even if the vaccine requires a conventional temperature range of 2 - 8°C. To ensure the availability of quality COVID-19 vaccines in every community, village and settlement, it is clear that existing vaccine distribution cold-chain capacity needs to be substantially increased in terms of the equipment for storage and transportation, the skilled workforce for monitoring, maintenance and support, and the capability for rigorous temperature control, waste management and recycling. Disposable syringes, PPE equipment and other supplies will in fact demand more volume in storage and transport than the vaccine itself, but these should be manageable alongside the cold-chain.

If incentivised appropriately or driven by either shareholder or Corporate Social Responsibility (CSR) sensibilities, private cold-chain operators may allocate specific resources in their network to help meet the challenge. Governments therefore should explore the capacity as well as capabilities of the private cold-chains. As private sector often makes aggressive investments in technology and innovation, their capacity to achieve cold-chain success often exceeds what is possible within the public sector.

Another solution may be sharing capacity with the agriculture and food supply cold-chains where geographical reach overlaps, and utilisation levels and product flow logistics allow. This approach would

save time and decrease vaccine distribution cost, as it would reduce the additional cold storage and transportation requirements. For instance, in India, approximately 98.58 million metric tons of fruit [70] and 202 million litres of ice cream [71] were produced in 2019, both requiring storage and transportation in the temperature controlled environment of a cold-chain (See Figure 13[16]). There are many food cold-chains that, in fact, may offer existing capacity to vaccines if they happen to require the conventional temperature range, and for the Moderna vaccine, for example, an ice cream cold-chain may be considered. Furthermore, especially in agriculture-dominated developing countries where substantial amount of food flows from rural to urban communities, the counter flow of empty capacity from urban to rural could be utilised for vaccines if available. The key, however, would be ensuring that the vaccines are handled according to the requirements of WHO good storage practice (GSP) and good distribution practice (GDP) [72] to make sure the integrity of vaccines in maintained and cross-contamination is avoided. Additional training may therefore need to be provided to the operators of the food cold-chain. Another consideration is that, as discussed further in the next section, the entire cold-chain should be supported by adequate monitoring equipment to maintain the integrity of vaccines, and tracking systems for stock management and vaccination records to ensure all vaccine doses are delivered to their intended recipients.

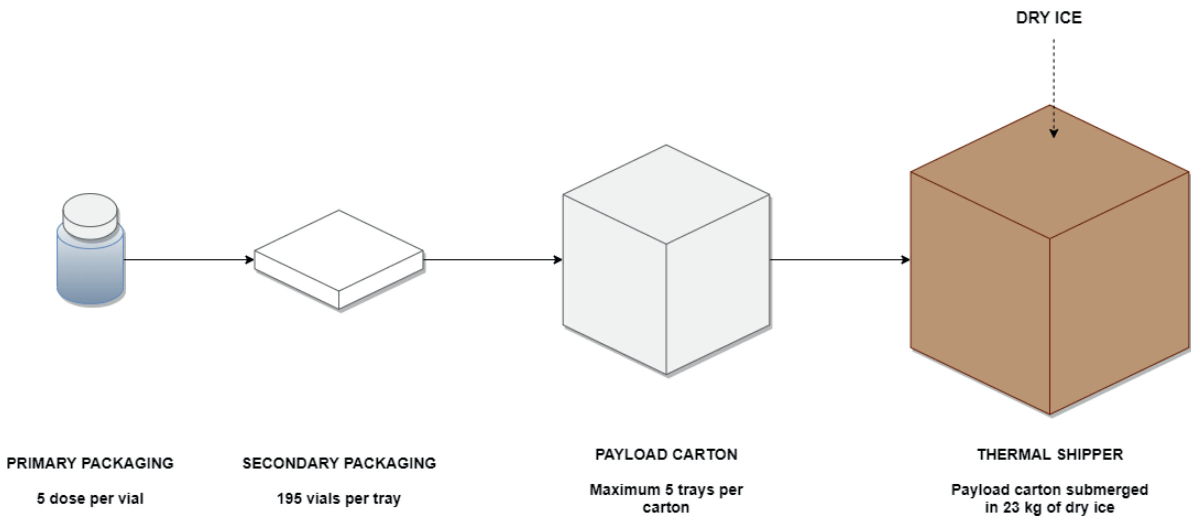

Figure 14: Pfizer/Biontech vaccine packaging overview (Adapted from [73])

[16] Ice cream: Icon made by Freepik from www.flaticon.com, Apple: Icon made by Vectors Market from www.flaticon.com, Meat: Icon made by DinosoftLabs from www.flaticon.com, Milk: Icon made by Good Ware from www.flaticon.com

In anticipation of the COVID-19 vaccine requiring sub-zero temperatures, UPS is constructing two substantial facilities for safe storage of millions of doses of COVID-19 vaccines at -70°C [74]. Additionally, to ease distribution, Pfizer has announced that it will provide a “dry ice pack” container (See Figure 14) for its vaccines that is able to maintain the required temperature of -70°C up to 10 days before requiring re-icing [75]. This has additional supply chain challenges in the developing world in terms of re-icing. As an example, Bangladesh only has one company making a limited quantity of dry ice. Following the removal of vaccine vials, however, they can be kept refrigerated at 2-8°C only for 5 days, posing a massive challenge to health centres and outreach sessions [35].

3.3.3 DATA MANAGEMENT AND MONITORING

Data management and monitoring technologies will play a vital role in ensuring the timely delivery of quality COVID-19 vaccines to their intended recipients, particularly in reducing vaccine wastage and associated costs. Vaccine wastage and/or administering ineffective vaccines due to cold-chain failures and lack of monitoring would result in loss of opportunities to vaccinate, as well as loss of time and resources. Such outcomes may reduce public confidence in the vaccine due to the need to re-vaccinate people who

BOX 7 The Project Last Mile

As model that has been able to make use of existing structures and networks to deliver vaccines in Africa’s most remote areas is the Project Last Mile. The Project Last Mile is a public-private partnership that makes use of Coca-Cola’s supply chain management and expertise to support African governments in reaching the “last mile” to deliver vaccines. Coca-Cola has penetrated the African market to the most remote areas, and it would take years for governments to achieve such a robust cold-chain structure. As distribution is not the end of the problem for successfully delivering vaccines, in some countries, Coca-Cola has trained the procurers of the refrigerators on how to use them, distribute them and maintain them.

To date, the Project Last Mile has supported public health systems across eight African countries. Examples to ongoing projects include, redesigning last mile distribution of medicines following the Ebola epidemic in Sierra Leone; improving delivery of medicines by optimizing route-to-market and logistics practices in Mozambique; increasing demand and utilization of HIV services by sharing strategic marketing skills in the Kingdom of eSwatini; and improving the uptime and management of vaccine cold-chain equipment in Nigeria [76].

received an ineffective vaccine. Furthermore, robust stock management systems will be particularly important to ensure availability of the vaccine for everyone in the target population when needed, including the service points. WHO's EVM global data analysis reveals that, in fact, only 17 per cent of service points use computerised stock management systems, which will need to be improved [20]. It is therefore essential to put all major stakeholders under a common information system that provides real-time information and visibility along the entire cold-chain

- to ensure vaccine quality from the point of manufacture through to the point of delivery
- to minimise vaccine wastage due to exposure to heat or freezing temperatures during storage, transport and immunisation sessions
- to ensure people receive the vital second dose, and to avoid administering the vaccine to those already exposed to the virus and double vaccination (which would require antibody testing)
- to detect and address the cold-chain equipment malfunction
- to ensure availability of vaccines as well as vaccination supplies and PPE at the service points
- to identify and manage risks in real time, such as power outages, weather conditions, transport delays and disruptions
- to detect counterfeit vaccines
- to ensure security and prevent thefts
- to provide records for auditing waste management

3.4 THE LAST MILE

3.4.1 WHY IS IT DIFFERENT FOR COVID-19 THAN THE ROUTINE IMMUNISATION PROGRAMMES?

In many countries, current vaccine based routine immunisations programmes are delivered through fixed sites (health centres), outreach sessions, and in some cases, mobile activities. Outreach strategies are typically followed to increase immunisation rates in rural and remote areas where there is no direct access to health centres. The WHO recommends planning outreach sessions for communities that are 5–10 km from a given health centre, and for communities with settlements more than 10 km away from the health

centre mobile activities can be planned to reach these more isolated populations from the district level (See Figure 15) [77].

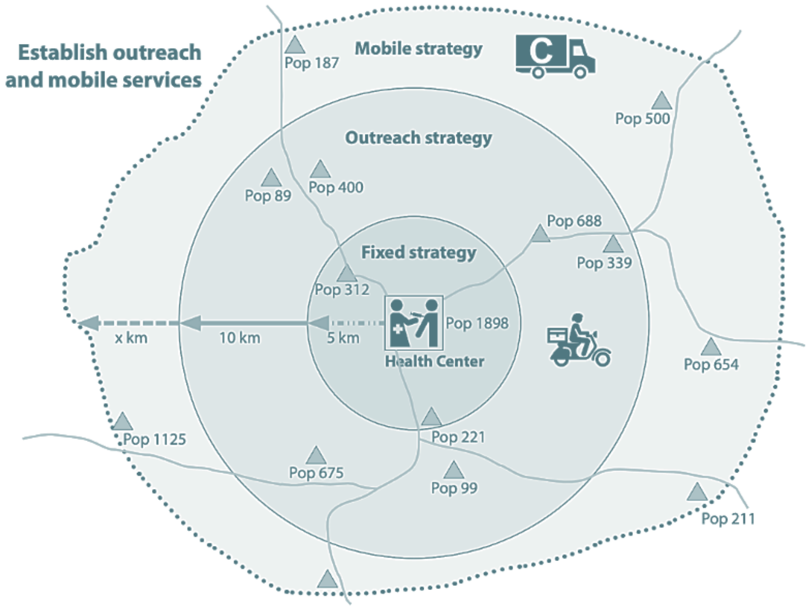

Figure 15: WHO service distance requirements for fixed, outreach and mobile strategy (Source: WHO)

Even though the methodology varies from country to country, for outreach sessions, the vaccine givers are typically sent 'out' from existing fixed sites (health centres) to administer vaccines to populations with limited access to health centres. One of the key differences to the immunisation programme that will be needed to tackle COVID-19, is the fact that outreach sessions in routine immunisation programmes are not mass vaccination attempts. Indeed, they are typically repeated periodically throughout the year to vaccinate a small percentage of the population, normally infants. Hence, due to time and capacity limitations, such as storage, transportation and human resources, the 'standard' outreach strategy used for routine immunisation programmes cannot be applied to the COVID-19 case.

Given that globally more than 44 per cent of the world's population lives in rural settings (for example, the figure is 65 per cent in India, 83 per cent in Rwanda and 63 per cent in Bangladesh) [29], upon availability of a COVID-19 vaccine to reach everyone equitably and to achieve a herd immunity threshold the need for outreach sessions will increase significantly. New, innovative outreach strategies will need to be developed for use in COVID-19 immunisation programmes.

3.4.2 PLANNING THE LAST MILE

Above all else, the key challenge for COVID-19 immunisation programmes will be the last mile of distribution and ensuring that each vaccination site is equipped with adequate cooling equipment, both fixed at site and mobile for outreach, to meet the local needs (such as target population, terrain, road conditions, electricity access) to maintain efficacy of each valuable dose. The success of immunisation will

critically depend on delivering quality vaccines to every community, village and settlement, many of which will be in remote and difficult to reach locations.

The COVID-19 vaccination programmes will need to be designed and planned around outreach sessions, especially in developing countries with large percentages of rural population that need to be reached in order to establish the required herd immunity threshold. Given the need to vaccinate a large percentage of populations efficiently and equitably in a short period of time, taking a campaign-style approach, which includes fixed designated 'hub' vaccination sites that are easily accessible and supported by effective public transportation services, as well as door-to-door immunisation, could be a viable and effective option. Spatial planning may be needed to choose the optimal locations for vaccination sites and 'hubs' to aggregate distribution and efficiently reach as many people as possible, this can, in turn, optimise the use of limited availability of appropriately skilled staff and reduce costs related to storage, transportation and human resources. Even in urban settings, the utilisation of hospitals and other health facilities may not be feasible as they could already be overwhelmed by increased patient numbers due to the pandemic, and the difficulty of maintaining appropriate social distancing measures in busy, space constrained environments. Alternative facilities with cold storage, potentially including those in other sectors such as supermarkets, restaurants, pharmaceutical stores, hotels or conference/exhibition centres, could be designated as service points in order to cope with distribution needs.

To ensure uninterrupted delivery of quality vaccines and minimise the vaccine wastage due to lack of reliable electricity, the vaccination programmes should be supported by sustainable off-grid cooling equipment along with temperature monitoring systems. After the immunisation session is over in one

BOX 8 The Location-Allocation

Robust quantitative analysis will benefit equitable and efficient last mile delivery of vaccines, as without such evidence for informed decision making, distribution choices could be subject to political considerations and potential biases. For example, to identify the optimal locations for vaccination sites, 'Location-allocation models' can be used (examples can be found in [78]–[80]). Location-allocation models are optimisation models that are used to locate the optimal point for service providers across a region given the distribution of demand for that service. In this case, the service provider is the COVID-19 vaccination sites, and demand is the population to be immunised in the defined region for achieving herd immunity.

See Appendix D for an illustrative example.

location, the off-grid equipment can then be moved and redeployed in other locations, adding flexibility and accessibility to the vaccination programmes.

3.5 DESIGN FOR COVID-19 COLD-CHAIN

3.5.1 WORK BACKWARDS

Planning for COVID-19 vaccination programmes should start from the last mile considering many location specific factors such as population densities, population characteristics, travel time, terrain and distance to the vaccination sites, availability and allocation of resources and weather patterns in order to deliver quality vaccines to their intended recipients and achieve herd immunity. Geographic information systems (GIS) can provide a useful planning tool in that they offer geographic data, through interactive maps or other infographics, to assist in obtaining data on travel time, geographic features, poor road conditions, traffic patterns, etc. To summarise, the following aspects should be considered when planning for last mile delivery and putting in place a programme risk register along with risk mitigation strategies.

i. Determine the amount of vaccine required and location at which it will be administered in order to cover every person and community. Target individuals may need to be identified via house-to-house screening, especially in developing countries. Particular attention should be given to:
    - Communities in remote, hard to reach areas as well as nomadic and seasonal migrant populations.
    - People who have migrated from urban to rural areas due to pandemic.
    - Populations carrying a disproportionate share of the disease burden.
    - Marginalised and disadvantaged groups.
    - Age-wise population distribution.
    - Mobility of elderly.
    - Border populations.
    - Communities in areas of civil conflict or insecurity.

ii. Determine the extra dry storage required for vaccination supplies.

iii. Develop a robust waste management plan.

iv. Choose the location of vaccination sites, taking into account:
    - Travel time and distance.
    - Geographical terrain and features such as mountains, rivers, valleys etc.
    - Adequacy of infrastructure to support delivery.
    - Availability of appropriate transportation facilities.
    - Anticipated traffic conditions en-route.

v. Ensure the vaccination sites have adequate energy supply and storage capacity for waste materials (particularly those that are contaminated) as well as vaccines. Energy supply may not be available or reliable, especially in rural areas of developing economies. It is good practice to identify alternate storage points in advance to mitigate equipment failure and/or energy supply failure.

vi. Ensure the vaccination sites have an adequate appropriately skilled workforce for vaccine delivery and administration.

vii. Assess and plan for the extra time required to maintain social distancing during vaccination sessions, and unanticipated social and cultural issues that might arise.

viii. Investigate setting up an electronic immunization registry system to avoid administering the vaccine to those already exposed to the virus, to avoid double vaccination, and to ensure people receive the vital second dose if the vaccine requires two dose administration to be effective.

ix. Explore opportunities for modal shifts in transportation. In addition to traditional ground transport, it might be possible to use cargo drones to deliver the vaccine to remote and hard to reach areas in the country, particularly where the terrain is difficult to traverse.

x. Consider potential natural barriers that might jeopardise the success, such as extreme weather events including excessive heat/cold, floods, blizzards etc. As an example, every year 10-30 per cent of Bangladesh is impacted by flood waters (the 2020 flood event was particularly bad with areas experiencing repeated inundation over a period of more than 3 months).

3.5.2 IMMUNISATION STRATEGIES

The true specifications of the vaccines will only be known once they are approved and produced, including the packed vaccine volume per dose, the number of doses required to be effective, the route of administration, the duration of protection, efficacy on different age groups as well as the temperature requirements. The required cold-chain volume to equipment, deployment strategies, target groups, even the level of training required for medical staff (See Section 4.4) will critically depend on these specifications that are yet to be known. All vaccine deployment plans to-date, therefore, will be revised as more information become available. However, much can be done today. For each uncertainty driver, most likely outcomes can be identified, and potential deployment plans can be developed along with contingency plans and regulatory pathways that would enable governments to adapt and respond quickly to changing circumstances during the immunisation programme, such as unforeseen side effects of the vaccine and outbreaks.

The COVID-19 vaccination programmes should ensure an even coverage across all local areas in the urban and rural regions to be successful, and achieve herd immunity across countries. Having reviewed the current deployment plans, however, as the initial vaccine supply is likely to be limited, many governments are considering some form of a prioritisation strategy along with initial population coverage targets. It seems pragmatic to set the most vulnerable in populations to be the first in line to receive the

vaccine along with healthcare workers and carers who sit on the likely lines of transmission to vulnerable groups. Once a vaccine is approved, prioritising those at higher risk, such as older individuals and those with existing health conditions, as well as health care workers can be justified. However, at this point, it is not possible to come to a firm decision on prioritisation strategy as the vaccines are still under development and full information on their effectiveness across different age groups is not available. Furthermore, studies in older adults lag behind those performed in younger cohorts, meaning there will be a delay in understanding the response to vaccination in these important members of the community. In any case however, the prioritisation plans need to be communicated with the public clearly and openly, including the justification of prioritisation and an anticipated timeline for groups who are not prioritised to receive the vaccine, to prevent impatience among public which will adversely affect the programme's flow.

In its report published in October 2020 [81], The National Academy of Medicine suggests distributing the vaccine in four phases once it is ready. First population group includes health workers, first responders, people with underlying conditions, and older adults living in congregate or overcrowded settings. The prioritisation strategy suggested in the report is in line with the one under the COVAX Initiative, which is prioritising healthcare workers first, then expanding to cover the vulnerable. The report further suggests that people with high Social Vulnerability Index should be prioritised within each group to account for the COVID-19's disproportionate burden on minorities, women, the poor, and other vulnerable groups.

However, the prioritisation approach may cause virus to mutate against the vaccine. Instead, countries may use a campaign approach - immunise 60-70 per cent of one geographical location and temporarily segregate from the non-immunised regions, and move to another location, eventually achieving the herd immunity threshold across the country. This approach could also allow the last-mile equipment (a cold store and cold-boxes/vaccine carriers) to be migrated to other locations as this vaccination progresses.

4 ADDITIONAL CHALLENGES

4.1 ROUTINE IMMUNISATION PROGRAMMES

The routine immunisation programmes have inevitably been disrupted by the pandemic in many countries, due to lockdowns, social distancing regulations, and delays on vaccine supplies. UNICEF and WHO estimate that up to 80 million children are at risk of missing out on vaccinations against vaccine-preventable diseases due to the pandemic [82]. Prolonged delay on vaccination programmes may result in outbreaks of Vaccine Preventable Disease (VPD) and high impact diseases (HIDs) [83], [84].

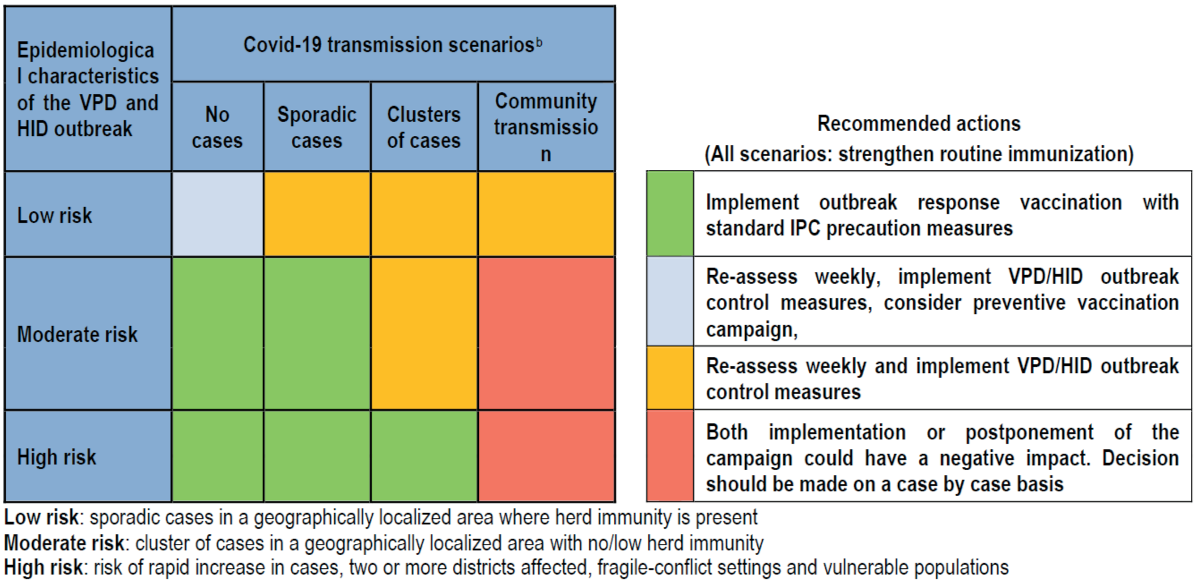

Figure 16: Recommended interventions according to VPD/HID outbreak epidemiological risk and COVID-19 scenario (Source: WHO [84])

It is therefore important to allocate resources by considering potential outbreaks, making sure routine immunisation programmes continue along side with the COVID-19 vaccination. Figure 16 demonstrates recommended interventions by WHO according to VPD/HID outbreak epidemiological risk and COVID-19 scenario. However, WHO also recommends carefully reconsidering, and postponing if necessary, the planned new vaccine introductions (other than COVID-19) into the routine immunisation programmes due to the likely shift of healthcare capacity towards COVID-19, and the anticipated demand reduction that would reduce the success of the new vaccine introduction [85].

Note that, clinical trials looking at the co-administration of experimental COVID-19 vaccine candidate with a licenced influenza vaccine have started, and it remains unknown until further trials are conducted as to whether new COVID-19 vaccines can be co-administered with other vaccines as part of an expanded programme of immunisation (EPI) schedule without compromising the immunogenicity to one or more of the antigens. Given the lack of excess disease burden in children and pregnant women, the priority non-COVID-19 vaccines to focus on are influenza and pneumococcal vaccines.

4.2 SOCIAL RESISTANCE

People might show reluctance or refuse to be vaccinated all together despite the availability of the vaccine, which may make achieving herd immunity difficult. Potential social resistance to vaccines therefore need to be addressed before the deployment through a Risk Communication and Community Engagement (RCCE) plan, to ensure participation and engagement of target groups and general population, to increase vaccine acceptance and demand, and to reduce rumours and misinformation about the vaccine. Resistance is especially expected from older adults and people with co-morbidity, which may easily hinder the success from the start, as they are identified among the priority groups in many current deployment plans. Furthermore, certain communities may exhibit higher resistance than others. It is important to identify these communities and make targeted plans to address the resistance issue in advance. Influencers, people who have experienced COVID-19, religious and community leaders can be involved to overcome the resistance, and educational programmes may be set out to address misinformation about vaccines, theological concerns, cultural tides, and other resistance issues.

4.3 ADDITIONAL MEDICAL STAFF

As a substantial portion of the population is needed to be vaccinated, additional staff will likely to be required. If the vaccine is delivered at a rate of 84 dose/day by each medical staff (assuming 7 working hours a day, and delivering each dose takes 5 minutes), then a single health worker could deliver 1,680 per month (assuming 20 working days per month). Following the India example, to deliver the initial target of 400 million doses by June 2021, suppose in 6 months, around 39,683 medical staff will be needed. On the other hand, if India aims to achieve herd immunity in one year, then around 90,278 medical staff should be available to deliver the vaccine[17].

Furthermore, in order to deliver the vaccine efficiently and effectively, training should be provided not only to newly recruited staff but also the current ones, as the unfamiliarity of the current staff with the COVID-19 vaccine, combined with the time pressure, can lead to an increase in immunisation errors. Level of training required will also depend on the route of administration. Currently, all leading vaccine candidates require intra-muscular injection (See Table 1), which must be performed by healthcare professionals. On the other hand, oral vaccines can be delivered without any medical training and can even be self-administred, which not only increases the patient compliance but also limits the contact between vaccine givers and recipients. Furher advantage is the reduced waste due to lack of syringe requirements. However, there is currently only one oral COVID-19 vaccine cadidate, Vaxart, which is in its early clinical trials (Phase 1) [12]. On top of that, as the target population of COVID-19 vaccine is

[17] Assuming the vaccine will require two doses to be effective.

vastly different than one in routine immunisation programmes in many countries, staff may have difficulty addressing the potential adverse effects of the COVID-19 vaccine [86].

5 THE NEED FOR DATA

The objective of our work is to undertake an in-country assessment of current cold-chain capacity (both vaccine specific and more broadly), and its potential to meet anticipated COVID-19 vaccine distribution needs. The work has particular focus on the last mile of delivery, and point of vaccine use as an initial scoping study has shown these to be the critical areas for maintaining integrity. Our aim is to present practical, scalable and achievable strategies for fast-track expansion of the vaccine cold-chain in environmentally, economically, and socially sustainable ways that will deliver a positive legacy for helping meet the goals and targets of the Paris Agreement, UN SDGs and Kigali Amendment to the Montreal Protocol.

Application of the methodology to be developed in the project will enable formulation of effective strategies, facilitate informed decision making on sustainable technology choices, and establish recommendations for policy-makers and other stakeholders that not only address the immediate need for mass vaccination against COVID-19, but also deliver national preparedness for future emergencies or disasters requiring cold-chain capacity as well as meeting wider, long-term cold-chain infrastructure needs sustainably. This could include using existing infrastructures (e.g. food) and sustainable cooling networks synergistically to meet the country's vaccination needs rather than building new cold-chains as well as considering and evaluating decentralised cooling hubs as "lifeboats" close to demand and drones/electric cargo bikes and off-grid solar fridges for last-mile remote outreach.

The combination of top-down policy options available and bottom-up approach proposed in this project is particularly important for designing effective and efficient vaccine cold-chains and administration strategies that are in line with local needs and circumstances.

5.1 THE AREAS OF DATA/DATASETS WE PROPOSE TO CAPTURE AND WHY?

Building on the first of a kind Cooling for All Needs-based Assessment & Country-Scale Cooling Action Plan Methodology and using the Contextual Analysis which provides an overview of the context related to cooling of the selected country including analysis of climatic, demographic, socio-economic statistics, infrastructure, we propose countries carry out the following tasks:

- Gaining a detailed in-depth understanding of vaccine cold-chain logistics (storage and mobile) from central storage/ warehouses to the last-mile/outreach; documenting experiences of previous vaccination programs, in routine and mission modes.
- Gathering evidence on the condition of the last mile and point of use elements of existing cold-chain infrastructure used for vaccine distribution, identifying gaps, and highlighting opportunities related to potentially complementary alternatives through primary and secondary research.

- Working with:
    - Vaccine and immunization sector experts (especially the COVID-19 vaccine developers) to define the specification of the cold-chain parameters the vaccine candidates require (such as the required temperatures and doses to be delivered) and using site studies to quantify existing gaps;
    - Energy sector experts to understand the availability of current and near to market state-of-the-art energy technology suites, technology maturity/ adoption, and in-country decarbonization targets, as well as modelling the environmental and economic impacts of using fossil-fuel solutions and the benefits and barriers of using clean/ renewable energy alternatives;
    - to assess the financial implications, exploring current and potential financing channels, and considering new value chains and funding mechanisms;
    - synthesize findings to identify sustainable options and assess the economic, environmental, and social impacts.
- Identifying the gaps in the current COVID-19 vaccine deployment plans, and their economic, environmental and social implications if they are to be followed.

5.2 THE KEY PEOPLE TO BE INTERVIEWED

The sector experts and stakeholders to be interviewed include:

- International level: GAVI, WHO, UNICEF
- National level: Ministry of Health, Ministry of Energy, Electricity Utility Company, Ministry of Infrastructure / Rural Development, National Vaccine Storage Centre, Medical Technology Institute, Worker Development Agency, Blood Transfusion Centre, cold storage warehouses
- Sub-national level: Provincial hospital, district hospital
- Local level: Community health centre/worker, private medical stores, local shops, community/village leaders, NGOs

N.B., We have developed questionnaires for each group – please contact us for further information.

5.3 HOW THE DATA CAN BE USED

The data should be collated according to the key sectors and elements for forming a sustainable cold-chain for mass COVID-19 vaccination from first mile to last mile.

Our research and assessment require both the qualitative and quantitative data for modelling and scenario development and analysis, in order to identify the needs from technology, infrastructure, finance, policy and skills perspectives. We separate quantitative data (to be used for calculation to quantify the problem,

capacity and needs) and qualitative data (to be used as quotes evidencing the current situation, problems and needs).

We are developing scenarios for the cold-chain including static and mobile segments, on how and what are needed to deliver the cold-chain capacity required for mass vaccination of COVID-19. In particular, the scenarios will include how other non-vaccine cooling capacity could potentially be harnessed for COVID-19 mass vaccination, and what technologies, finance, policy and institutional support need to be in place for delivering the cooling and cold-chain capacity required.

We are developing a multicriterial integrated vaccine cold-chain methodology with the objective to investigate the implication of demand for COVID-19 vaccines on the supply, logistics, energy, as well as associated costs and emissions. The initial methodology of the multicriterial integrated vaccine cold-chain for the mass scale COVID-19 vaccination is as follows:

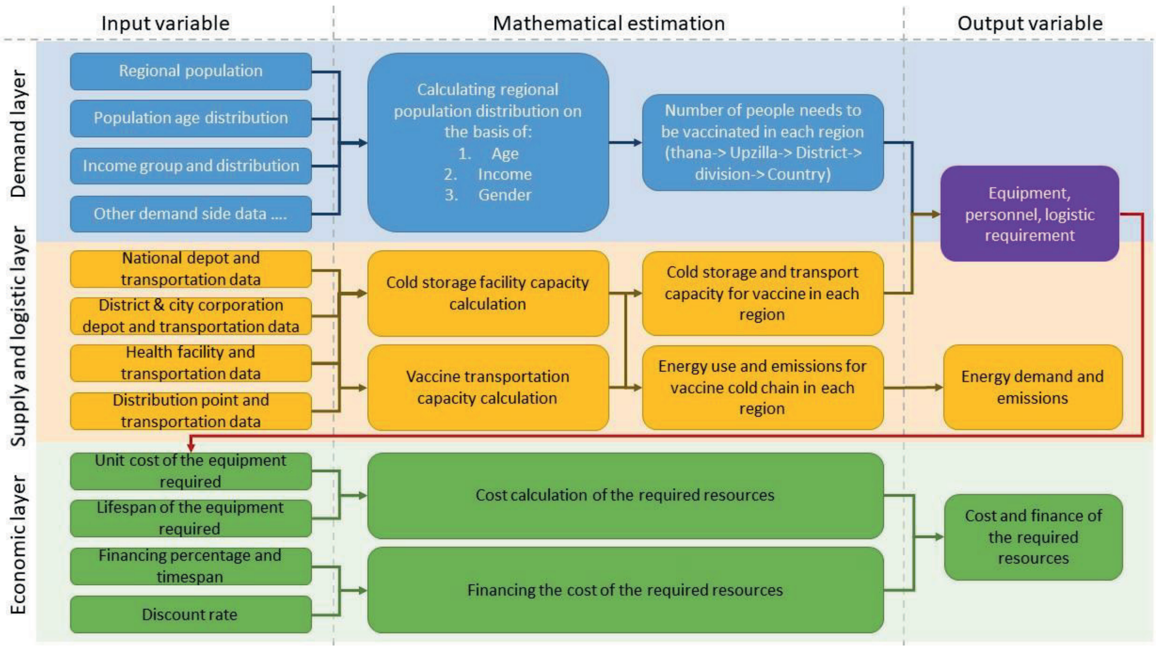

Figure 17: The initial methodology of the multicriterial integrated vaccine cold-chain for the mass scale COVID-19 vaccination (Created by Dr Kumar Biswajit Debnath, Heriot-Watt University)

APPENDIX A THE ANTICIPATED IMPACT OF THE COVID-19 PANDEMIC ON DELIVERY OF THE 17 SDGS

NO POVERTY

- Even before the pandemic, projections suggested that 6 per cent of the world's population would still be suffering from extreme poverty in 2030 [87]. With increased job losses and lockdowns due to pandemic, as many as 71 million people are expected to be pushed back into extreme poverty in 2020 (with majority coming from countries that are already struggling with high poverty rates and numbers of poor), the first increase since 1998 and having the effect of negating gains since 2017 [88].
- Sectors are unevenly hit by the pandemic. While jobs that are suitable for remote working are relatively safe, workers that are in accommodation and food services, transportation, retail, and wholesale are affected [6]. However, looking at the situation holistically, all sectors are likely to be affected one way or another. Adverse effects of the pandemic on some sectors will inevitably spill over to other sectors, even if they are not directly affected by the pandemic, as the demand for goods and services will decline due to income reductions.
- Incomes of 1.6 billion people employed in the informal sector have dropped an estimated 60 per cent [89].

ZERO HUNGER

- Before the pandemic, there were almost 690 million undernourished people in the world, and 135 million were suffering from acute hunger. It is estimated that the pandemic could put an additional 130 million people at risk by the end of 2020 [90].
- Disruptions in food production and distribution reduce food availability and resilience.
- Loss of employment and income impact people's ability to buy food.
- Food loss is expected to increase due to transportation challenges and reduced labour availability [91].
- School closures may result in higher food insecurity and risk of malnutrition for children from low-income households, as children's access to free or subsidized school meals are disrupted [6].

GOOD HEALTH AND WELL-BEING

- Disruptions to immunization programs may reverse decades of progress against vaccine-preventable diseases [92]. Global inequities in terms of vaccine access were already prevalent prior to the pandemic. In 2019, coverage for the vaccine protecting against diphtheria, tetanus, and pertussis (DTP3), which requires storage between 2°C and 8°C, was at 85 per cent globally, down slightly from 86 per cent in 2018. A total of 85 countries have yet to achieve the targeted vaccination rate of 90 per cent for DPT3 [93]. UNICEF and WHO estimate that up to 80 million children are at risk of missing out on vaccinations against vaccine-preventable diseases due to the pandemic [82].
- The healthcare systems are overwhelmed because of the pandemic, causing delays in treatments for other illnesses and services such as cancer screening and check-ups.
- Many people fear to visit health centres, which may increase the death rate due to other illnesses.

QUALITY EDUCATION

- School closures around the world to contain the spread have decreased the access to quality education. UN estimates that more than 1.5 billion students are out of school due to the pandemic. Remote learning may be less effective and is estimated to be inaccessible to at least 500 million students [94].
- Early marriages, children forced into militias, sexual exploitation, teen pregnancies and child labour are expected to increase due to school closures [95].

GENDER EQUALITY

The pandemic has been disproportionately affecting women in many ways:

- Increased demand for women to undertake unpaid care work have forced women to leave their jobs or move from stable and protected jobs to more informal jobs [96].
- It is estimated that women have 1.8 times more job vulnerability than men during the pandemic [97].
- Globally, women make up the 70 per cent of the health workforce, putting them at a greater risk [96].
- Domestic violence has increased by 30 per cent in some countries [9].

- A significant rise in unintended pregnancies are expected due to interrupted access to family planning supplies. Women may be forced into early marriages, causing them to leave their education and careers [9].

CLEAN WATER AND SANITATION

- Two out of five people in the world do not have a basic hand-washing facility with soap and water. With sanitation being fundamental for fighting the virus and preserving the health and well-being, importance of providing access to safe water for vulnerable people is now even more profound [98].

AFFORDABLE AND CLEAN ENERGY

- The drop in oil prices may negatively impact the development and use of sustainable energy technologies, and increase the global oil demand, unless strong government policies to support sustainable energy are put in place [99].

DECENT WORK AND ECONOMIC GROWTH

- Job losses resulting from the crisis threatens mass unemployment.
- All economies are likely to experience significant economic losses, but emerging and developing economies are especially vulnerable with per capita incomes expected to decline, increasing their risk of slipping back to poverty.

INDUSTRY, INNOVATION AND INFRASTRUCTURE

- More and more businesses and services have been relying on information and communication technologies since the beginning of the pandemic. It is now even more important to close the gaps in access to these technologies to enable remote working if possible, to provide online education as well as to offer health and sanitation advice for everyone [100].
- Businesses may cut down their R&D budgets due to adverse economic impacts of the pandemic.

REDUCED INEQUALITIES

- The pandemic has brought existing inequalities to the fore, affecting the poorest and most vulnerable communities (including refugees and migrants) the most [101].
- People that are in the lower parts of the wage distribution face a greater chance of losing their jobs than the ones at the upper [6].
- Women have been disproportionately affected by the pandemic in many areas: health, economy, security and social protection [10].

SUSTAINABLE CITIES AND COMMUNITIES

- Populations living in informal settlements and slums face greater risks due to high population densities that make self-isolation and social distancing more difficult, hence contagion more likely [102].

RESPONSIBLE CONSUMPTION AND PRODUCTION

- Safety measures have led to an increase in production and use of plastic products, such as plastic packaging, bags and gloves.

CLIMATE ACTION

- Greenhouse gas emissions are expected to drop about 6 per cent in 2020 due to travel bans and reduced production. This improvement however is temporary [103]. Climate change mitigation measures may be deprioritized by governments, decreasing the chances of meeting targets and commitments to tackle the climate change.

LIFE BELOW WATER, LIFE ON LAND

- Increased number of PPE and other unrecyclable waste found in nature have been threating lives both in water and on land [104].

PEACE, JUSTICE AND STRONG INSTITUTIONS

- Governments have been relying on digital technologies and advanced analytics to tack, trace and contain the spread, which may potentially raise human rights issues regarding collection and sharing of personal data, mass surveillance, limiting individual freedoms [105].

PARTNERSHIPS FOR GOALS

- The pandemic has sparked a backlash against globalization

APPENDIX B SELECTING THE RIGHT ENERGY SOURCE FOR VACCINE REFRIGERATION

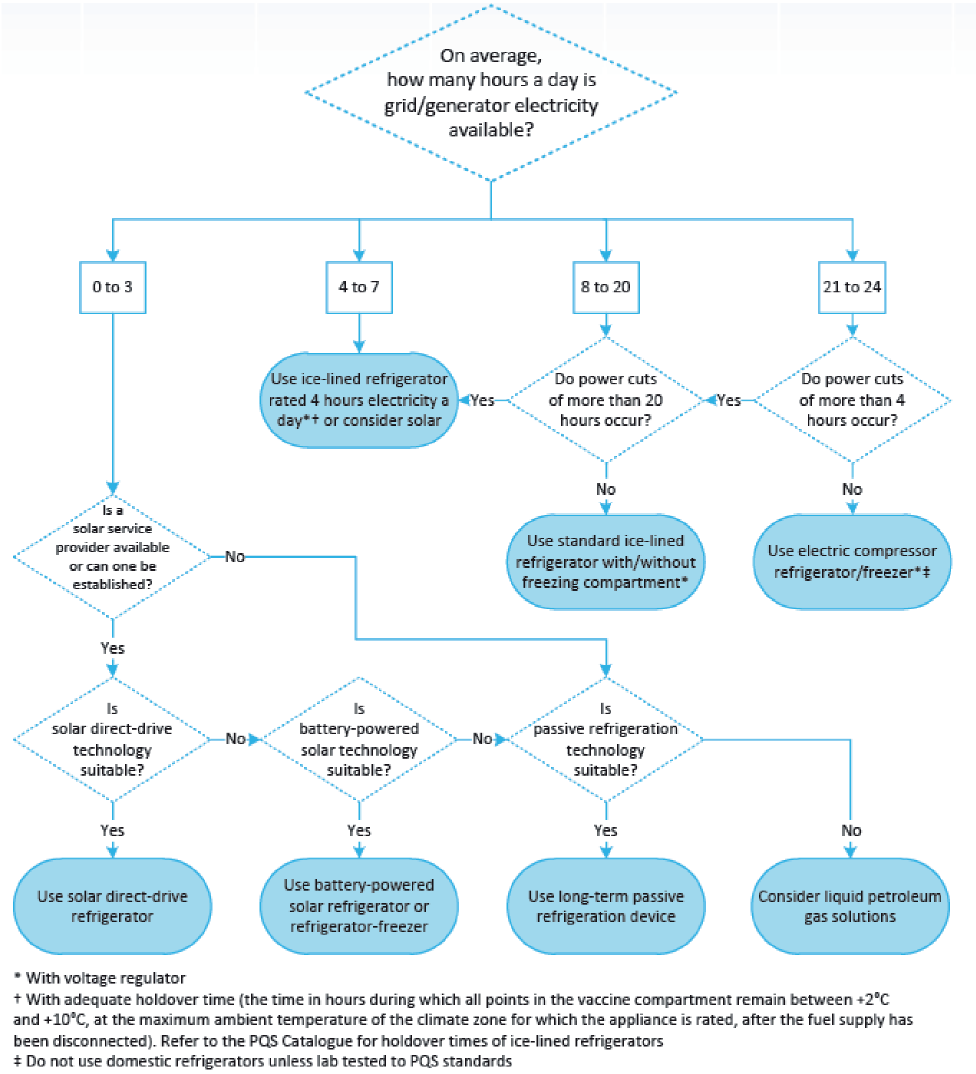

Figure 18: Selecting the most appropriate energy source for vaccine refrigeration [16]

WHO provides guidance on selecting the right energy source for vaccine refrigeration (See Figure 18). Following the Figure 4 provided by WHO, if a location only has access to 0-7 hours of energy supply per day (mains or generator), then solar, long-term passive or liquid petroleum gas (which can be expensive) refrigeration equipment should be considered. ILRs may also be suitable for locations with 4-7 hours energy supply. While the WHO guidelines help identifying locations that require off-grid equipment considering the energy supply reliability, they do not consider all situations where off-grid equipment provide benefits. One study suggests that the cost per dose of vaccine may be lower for solar off-grid than on-grid equipment even in locations with higher energy supply reliability [106]. Furthermore, as the cost of solar equipment decreases, uptake of solar off-grid refrigerators will consequently become profitable for locations even with higher energy supply reliability, and cost savings may become more predominant along with reduced environmental footprint.

APPENDIX C RECOMMENDED VACCINE STORAGE TEMPERATURES FOR VACCINES USED IN IMMUNIZATION PROGRAMMES

<table>
<tr><th rowspan="2">Vaccine</th><th rowspan="2">Primary vaccine store[18]</th><th colspan="2">Intermediate vaccine store</th><th rowspan="2">Health centre</th><th rowspan="2">Health post</th></tr>
<tr><th>Region</th><th>District</th></tr>
<tr><td>OPV</td><td colspan="2">-15°C to -25°C</td><td colspan="3" rowspan="16">All vaccines are recommended to be stored at +2°C to +8°C.</td></tr>
<tr><td>BCG</td><td colspan="2" rowspan="7">WHO no longer recommends that freeze-dried vaccines be stored at -20°C. Storing them at -20°C is not harmful but is unnecessary. Instead, these vaccines should be kept in refrigeration and transported at +2°C to +8°C.</td></tr>
<tr><td>Measles</td></tr>
<tr><td>MMR</td></tr>
<tr><td>MR</td></tr>
<tr><td>YF</td></tr>
<tr><td>Hib freeze-dried</td></tr>
<tr><td>Meningococcal A&C</td></tr>
<tr><td>HepB</td><td colspan="2" rowspan="8">+2°C to +8°C
These vaccines are freeze sensitive and must never be frozen.</td></tr>
<tr><td>IPV</td></tr>
<tr><td>DT</td></tr>
<tr><td>DTP</td></tr>
<tr><td>DTP-HepB</td></tr>
<tr><td>Hib liquid</td></tr>
<tr><td>Td</td></tr>
<tr><td>TT</td></tr>
<tr><td colspan="6">Diluent vials must NEVER be frozen. If the manufacturer supplies a freeze-dried vaccine packed with its diluent, ALWAYS store the product at between +2°C and +8°C. If space permits, diluents supplied separately from vaccine may safely be stored in the cold-chain between +2°C and +8°C. [107]</td></tr>
</table>

[18] Stores that receive vaccines directly from the manufacturers.

APPENDIX D THE LOCATION-ALLOCATION: AN ILLUSTRATIVE EXAMPLE

The following example aims to illustrate the basic concept of employing Location-Allocation models, along with additional barriers such as geographic features and poor road conditions.

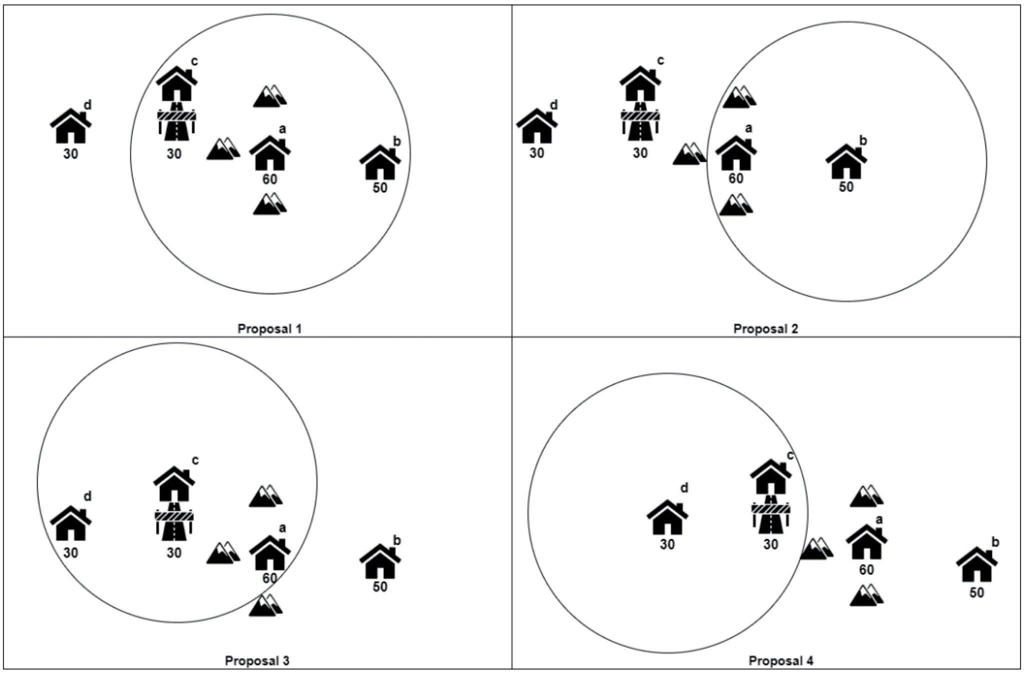

Figure 19: Selecting the vaccination sites[19]

The Figure 19 above shows a hypothetical district with four villages a, b, c and d, along with their locations and populations. Circles demonstrate the coverage area of corresponding villages in case they are selected as vaccination sites. Village 'a' is located on hilly terrain, and village 'c' suffers from poor road infrastructure. Assuming that the programme budget only allows for one vaccination site to be put in place, if Village 'a' is selected as the vaccination site, then 140 people can be vaccinated. Similarly, 110 people can be vaccinated in the case of village 'b' being selected, 120 people for village 'c', and 60 people for village 'd'. If the site location decision is based purely on population reached, then village 'a' would be the designated vaccination site. However, due to the geographical barriers to accessing village 'a', this action would be sub-optimal. The same reasoning applies to village 'c', which has the second-largest coverage. As village 'd' has the lowest coverage area, village 'b' would likely be the optimal location for the vaccination site. For the other villages outside the coverage area, more targeted strategies can be considered, such as door-to-door immunisation possibly supported by alternative distribution methods, such as drones.

[19] House, Mountain: Icons made by Freepik from www.flaticon.com, Road block: Icon made by surang from www.flaticon.com

REFERENCES

[1] 'WHO Coronavirus Disease (COVID-19) Dashboard | WHO Coronavirus Disease (COVID-19) Dashboard'. https://covid19.who.int/?gclid=CjwKCAjwzvX7BRAeEiwAsXExozrVzhwHiSNcX3HXKvDcgvHQAvu2r9p8faIAYCZ2cyeV61wPlKVTxoC4h8QAvD_BwE (accessed Nov. 06, 2020).

[2] 'Pfizer and BioNTech Conclude Phase 3 Study of COVID-19 Vaccine Candidate, Meeting All Primary Efficacy Endpoints | Pfizer'. https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-conclude-phase-3-study-covid-19-vaccine (accessed Nov. 19, 2020).

[3] OECD, 'Flattening the COVID-19 peak: Containment and mitigation policies', 2020. https://read.oecd-ilibrary.org/view/?ref=124_124999-yt5ggxirhc&Title=Flattening%20the%20COVID-19%20peak:.Containment%20and%20mitigation%20policies (accessed Nov. 06, 2020).

[4] 'COVID-19 A GLOBAL PERSPECTIVE, 2020 GOALKEEPERS REPORT', 2020. Accessed: Nov. 07, 2020. [Online]. Available: https://www.gatesfoundation.org/goalkeepers/.

[5] 'In-depth Evaluation of Reaching Every District Approach, 2007', p. 53, 2007.

[6] 'World Economic Outlook, October 2020: A Long and Difficult Ascent', *IMF*. https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020 (accessed Nov. 06, 2020).

[7] 'Coronavirus second wave hits Europe in force', *Economist Intelligence Unit*, Nov. 03, 2020. https://www.eiu.com/n/coronavirus-second-wave-hits-europe-in-force/ (accessed Nov. 08, 2020).

[8] 'Sustainable Development Goals', *UNDP*. https://www.undp.org/content/undp/en/home/sustainable-development-goals.html (accessed Nov. 06, 2020).

[9] 'UN/DESA Policy Brief #81: Impact of COVID-19 on SDG progress: a statistical perspective | Department of Economic and Social Affairs', Aug. 27, 2020. https://www.un.org/development/desa/dpad/publication/un-desa-policy-brief-81-impact-of-covid-19-on-sdg-progress-a-statistical-perspective/ (accessed Nov. 06, 2020).

[10] 'Gender equality and women's empowerment', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/gender-equality/ (accessed Nov. 09, 2020).

[11] Sustainable Energy for All, 'Chilling Prospects: Tracking Sustainable Cooling for All 2020', 2020. [Online]. Available: https://www.seforall.org/system/files/2020-07/CP-2020-SEforALL.pdf.

[12] 'Draft landscape of COVID-19 candidate vaccines'. https://www.who.int/publications/m/item/draft-landscape-of-covid-19-candidate-vaccines (accessed Nov. 06, 2020).

[13] 'WHO | Validation of the shake test for detecting freeze damage to adsorbed vaccines', *WHO*. https://www.who.int/bulletin/volumes/88/8/08-056879/en/ (accessed Nov. 11, 2020).

[14] 'Off-Grid Appliance Market Survey 2020 Report', *Efficiency for Access*. https://efficiencyforaccess.org/publications/off-grid-appliance-market-survey-2020 (accessed Nov. 06, 2020).

[15] GAVI, 'Cold chain Equipment Optimisation Platform'. Accessed: Oct. 18, 2020. [Online]. Available: https://www.gavi.org/sites/default/files/publications/Cold-chain-equipment-technology-guide.pdf.

[16] 'WHO | Introducing solar-powered vaccine refrigerator and freezer systems - A guide for managers in national immunization programmes', *WHO*. http://www.who.int/immunization/documents/9789241509862/en/ (accessed Nov. 06, 2020).

[17] B. R. Heard and S. A. Miller, 'Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System', *Environ. Sci. Technol.*, vol. 53, no. 1, pp. 251–260, 02 2019, doi: 10.1021/acs.est.8b05322.

[18] 'Climate-Smart Healthcare: Low-Carbon and Resilience Strategies for the Health Sector', *Climate & Clean Air Coalition*. https://www.ccacoalition.org/en/resources/climate-smart-healthcare-low-carbon-and-resilience-strategies-health-sector (accessed Nov. 07, 2020).

[19] 'WHO | World Health Organization', *WHO*. https://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/ (accessed Nov. 08, 2020).

[20] 'WHO | Effective Vaccine Management (EVM) Initiative', *WHO*. http://www.who.int/immunization/programmes_systems/supply_chain/evm/en/ (accessed Nov. 06, 2020).

[21] 'National Cold Chain Assessment 2014 | Manualzz', *manualzz.com*. https://manualzz.com/doc/10658702/national-cold-chain-assessment-2014 (accessed Nov. 06, 2020).

[22] 'Our Alliance'. https://www.gavi.org/our-alliance (accessed Nov. 07, 2020).

[23] A. Nagurney, 'Keeping coronavirus vaccines at subzero temperatures during distribution will be hard, but likely key to ending pandemic', *The Conversation*. http://theconversation.com/keeping-

coronavirus-vaccines-at-subzero-temperatures-during-distribution-will-be-hard-but-likely-key-to-ending-pandemic-146071 (accessed Nov. 06, 2020).

[24] 'How to become CEIV Pharma Certified'. 2019, Accessed: Oct. 19, 2020. [Online]. Available: https://www.iata.org/contentassets/494bc14afd934b0193735e9a47091d72/iata_ceiv-pharma_how20to20become20ceiv20pharma20certified.pdf.

[25] 'National Cold Chain & Vaccine Logistics Action Plan'. 2016, [Online]. Available: https://www.technet-21.org/en/forums/discussions?controller=attachment&task=download&tmpl=component&id=640.

[26] 'Handbook for Vaccine & Cold Chain Handlers - India - 2016', *TechNet-21*. https://www.technet-21.org/en/library/main/2244-handbook-for-vaccine-cold-chain-handlers-india-2016 (accessed Nov. 06, 2020).

[27] 'Improving Vaccination Systems - eVIN | UNDP in India'. https://www.in.undp.org/content/india/en/home/projects/gavi1.html (accessed Nov. 06, 2020).

[28] Practical Action (Organization), Ed., *Poor people's energy outlook 2013: energy for community services*. Rugby: Practical Action Publishing, 2013.

[29] 'Rural population | Data'. https://data.worldbank.org/indicator/SP.RUR.TOTL?end=2019&most_recent_year_desc=false&start=1960&type=shaded&view=map (accessed Nov. 06, 2020).

[30] R. Mihigo, N. AbdelAziz, T. Badr, H. O'Malley, and I. Chaudhri, 'Global Vaccine Action Plan: Regional vaccine action plans 2016 progress reports', WHO, 2016. [Online]. Available: https://www.who.int/immunization/sage/meetings/2016/october/3_Regional_vaccine_action_plans_2016_progress_reports.pdf?ua=1.

[31] R. M. Mihigo, J. C. Okeibunor, H. O'Malley, B. Masresha, P. Mkanda, and F. Zawaira, 'Investing in life saving vaccines to guarantee life of future generations in Africa', *Vaccine*, vol. 34, no. 48, pp. 5827–5832, Nov. 2016, doi: 10.1016/j.vaccine.2016.06.036.

[32] 'Immunization programme'. https://www.unicef.org/immunization (accessed Nov. 06, 2020).

[33] 'COVID-19 vaccine tracker'. https://vac-lshtm.shinyapps.io/ncov_vaccine_landscape/ (accessed Nov. 06, 2020).

[34] 'What we know about COVID-19 vaccine development'. https://www.who.int/publications/m/item/what-we-know-aboutcovid-19-vaccine-development (accessed Nov. 06, 2020).

[35] R. Langreth and R. Griffin, 'Pfizer Covid Vaccine Trial Reports No Major Safety Issues', *Bloomberg.com*, Sep. 15, 2020.

[36] 'Moderna Announces Longer Shelf Life for its COVID-19 Vaccine Candidate at Refrigerated Temperatures | Moderna, Inc.' https://investors.modernatx.com/news-releases/news-release-details/moderna-announces-longer-shelf-life-its-covid-19-vaccine/ (accessed Nov. 17, 2020).

[37] 'Pfizer and BioNTech Announce Vaccine Candidate Against COVID-19 Achieved Success in First Interim Analysis from Phase 3 Study | Pfizer'. https://www.pfizer.com/news/press-release/press-release-detail/pfizer-and-biontech-announce-vaccine-candidate-against (accessed Nov. 11, 2020).

[38] 'Moderna's COVID-19 Vaccine Candidate Meets its Primary Efficacy Endpoint in the First Interim Analysis of the Phase 3 COVE Study | Moderna, Inc.' https://investors.modernatx.com/news-releases/news-release-details/modernas-covid-19-vaccine-candidate-meets-its-primary-efficacy/ (accessed Nov. 17, 2020).

[39] M. N. Ramasamy *et al.*, 'Safety and immunogenicity of ChAdOx1 nCoV-19 vaccine administered in a prime-boost regimen in young and old adults (COV002): a single-blind, randomised, controlled, phase 2/3 trial', *The Lancet*, vol. 0, no. 0, Nov. 2020, doi: 10.1016/S0140-6736(20)32466-1.

[40] K. Kelland, 'AstraZeneca COVID-19 vaccine shows promise in elderly, trial results by Christmas', *Reuters*, Nov. 19, 2020.

[41] 'WHO Target Product Profiles for COVID-19 Vaccines'. https://www.who.int/publications/m/item/who-target-product-profiles-for-covid-19-vaccines (accessed Nov. 06, 2020).

[42] 'Polio Vaccine Effectiveness and Duration of Protection | CDC', Jun. 20, 2019. https://www.cdc.gov/vaccines/vpd/polio/hcp/effectiveness-duration-protection.html (accessed Nov. 17, 2020).

[43] 'About Measles Vaccination | Vaccination and Immunizations | CDC', Jan. 09, 2020. https://www.cdc.gov/vaccines/vpd/measles/index.html (accessed Nov. 17, 2020).

[44] F. S. Dawood, 'Interim Estimates of 2019–20 Seasonal Influenza Vaccine Effectiveness — United States, February 2020', *MMWR Morb. Mortal. Wkly. Rep.*, vol. 69, 2020, doi: 10.15585/mmwr.mm6907a1.

[45] T. Britton, F. Ball, and P. Trapman, 'A mathematical model reveals the influence of population heterogeneity on herd immunity to SARS-CoV-2', *Science*, vol. 369, no. 6505, pp. 846–849, 14 2020, doi: 10.1126/science.abc6810.

[46] J. Miller, D. P. Mancini, C. Cookson, and H. Kuchler, 'Pfizer and BioNTech's Covid-19 vaccine found to be 90% effective', Nov. 09, 2020. https://www.ft.com/content/9bde4bff-acf0-4c2a-a0d0-5ed597186496 (accessed Nov. 12, 2020).

[47] H. E. Randolph and L. B. Barreiro, 'Herd Immunity: Understanding COVID-19', *Immunity*, vol. 52, no. 5, pp. 737–741, May 2020, doi: 10.1016/j.immuni.2020.04.012.

[48] T. Moore, 'Coronavirus: Only one in 10 to be protected from COVID-19 in first year of vaccine use', *Sky News*. https://news.sky.com/story/coronavirus-only-one-in-10-to-be-protected-from-covid-19-in-first-year-of-vaccine-use-12072473 (accessed Nov. 06, 2020).

[49] R. Staff, 'Moderna sees 20 million doses of COVID-19 vaccine candidate by year end', *Reuters*, Sep. 18, 2020.

[50] 'UNICEF to lead procurement and supply of Coronavirus vaccines', *Unicef UK*. https://www.unicef.org.uk/press-releases/unicef-to-lead-procurement-and-supply-of-coronavirus-vaccines/ (accessed Nov. 06, 2020).

[51] 'Facts and figures'. https://www.gavi.org/programmes-impact/our-impact/facts-and-figures (accessed Nov. 07, 2020).

[52] 'Vaccine storage issues could leave 3B people without access', *AP NEWS*, Oct. 19, 2020. https://apnews.com/article/virus-outbreak-pandemics-immunizations-epidemics-united-nations-fc4c536d62c5ef25152884adb1c14168 (accessed Nov. 16, 2020).

[53] 'WHO | Data, statistics and graphics', *WHO*. http://www.who.int/immunization/monitoring_surveillance/data/en/ (accessed Nov. 06, 2020).

[54] V. Mukka, 'A COVID-19 Vaccine Is Part 1 – Part 2 Will Be India's Mighty Logistics Challenge', *The Wire Science*, Oct. 13, 2020. https://science.thewire.in/health/a-covid-19-vaccine-is-part-1-part-2-will-be-indias-mighty-logistics-challenge/ (accessed Nov. 06, 2020).

[55] National Institute of Population Research and Training (NIPORT) and ICF, 'BANGLADESH Health Facility Survey 2017', Dhaka, Bangladesh, 2019. [Online]. Available: https://dhsprogram.com/pubs/pdf/SPA28/SPA28.pdf.

[56] 'Immunization handbook for Medical Officers, Unit-5 Safe Injections and Waste Disposal', 2017. Accessed: Nov. 06, 2020. [Online]. Available: https://www.technet-21.org/media/com_resources/trl/6112/multi_upload/Unit5-SafeinjectionsandWasteDisposal(2017).pdf.

[57] 'UNICEF to stockpile over half a billion syringes by year end, as part of efforts to prepare for eventual COVID-19 vaccinations'. https://www.unicef.org/press-releases/unicef-stockpile-over-half-billion-syringes-year-end-part-efforts-prepare-eventual (accessed Nov. 06, 2020).

[58] A. Dunn, 'Pfizer's top scientist tells us the pharma giant is already thinking about a new version of its coronavirus vaccine for 2021 that can overcome one of its biggest limitations', *Business Insider*. https://www.businessinsider.com/pfizer-is-developing-powder-version-of-its-covid-19-vaccine-2020-11 (accessed Nov. 12, 2020).

[59] 'WHO | Assessing the Programmatic Suitability of Vaccine Candidates for WHO Prequalification (Revision 2014)', *WHO*. https://www.who.int/immunization/documents/policies/WHO_IVB_14.10/en/ (accessed Nov. 16, 2020).

[60] 'Pfizer's COVID-19 vaccine may be over 90% effective, so what happens next?' https://www.gavi.org/vaccineswork/pfizers-covid-19-vaccine-may-be-90-effective-so-what-happens-next (accessed Nov. 16, 2020).

[61] 'The race to develop an Ebola vaccine'. https://www.gavi.org/vaccineswork/race-develop-ebola-vaccine (accessed Nov. 16, 2020).

[62] 'Arktek Passive Vaccine Storage Device', *Engineering For Change*. https://www.engineeringforchange.org/solutions/product/arktek-passive-vaccine-storage-device/ (accessed Nov. 16, 2020).

[63] M. Friend and S. Stone, 'Challenging requirements in resource challenged environment on a time challenged schedule: A technical solution to support the cold chain for the VSV-Zebov (Merck) Ebola vaccine in Sierra Leone Guinea', Oct. 2015, pp. 372–376, doi: 10.1109/GHTC.2015.7343999.

[64] 'IV's Global Good Fund: A Legacy of Impact Invention'. https://www.intellectualventures.com/buzz/insights/ivs-global-good-fund-a-legacy-of-impact-invention (accessed Nov. 16, 2020).

[65] 'How a deep-frozen vaccine reached 400,000 people, helped stop Ebola and holds hope for coronavirus'. https://www.telegraph.co.uk/global-health/science-and-disease/deep-frozen-vaccine-reached-400000-people-helped-stop-ebola/amp/ (accessed Nov. 16, 2020).

[66] 'Delivering Pandemic Resilience | DHL |', *DHL*. https://www.dhl.com/global-en/home/insights-and-innovation/thought-leadership/white-papers/delivering-pandemic-resilience.html (accessed Nov. 06, 2020).

[67] 'COVAX: Working for global equitable access to COVID-19 vaccines'. https://www.who.int/initiatives/act-accelerator/covax (accessed Nov. 06, 2020).

[68] '172 countries and multiple candidate vaccines engaged in COVID-19 vaccine Global Access Facility'. https://www.who.int/news/item/24-08-2020-172-countries-and-multiple-candidate-vaccines-engaged-in-covid-19-vaccine-global-access-facility (accessed Nov. 06, 2020).

[69] 'Gavi to provide US$ 150 million to support low- and middle-income countries' readiness to deliver COVID-19 vaccines'. https://www.gavi.org/news/media-room/gavi-provide-us-150-million-support-low-and-middle-income-countries-readiness (accessed Nov. 06, 2020).

[70] 'India - fruit production 2008-2019', *Statista*. https://www.statista.com/statistics/621173/fruit-production-in-india/ (accessed Nov. 06, 2020).

[71] 'India - ice cream production volume 2020', *Statista*. https://www.statista.com/statistics/761794/india-ice-cream-production-volume/ (accessed Nov. 06, 2020).

[72] '54th report of the WHO Expert Committee on Specifications for Pharmaceutical Preparations'. https://www.who.int/publications-detail-redirect/978-92-4-000182-4 (accessed Nov. 06, 2020).

[73] Centers for Disease Control and Prevention (CDC), 'August 2020 ACIP Meeting', Sep. 01, 2020. https://www.youtube.com/watch?v=Xw54csbihMQ&list=PLvrp9iOILTQb6D9e1YZWpbUvzfptNMKx2&index=8&t=0s&ab_channel=CentersforDiseaseControlandPrevention%28CDC%29 (accessed Nov. 17, 2020).

[74] C. Leffert, 'UPS Readies Freezer Farms to Ship Virus Vaccine — If We Get One', *Bloomberg.com*, Aug. 03, 2020.

[75] C. P. and J. S. Hopkins, 'Pfizer Sets Up Its "Biggest Ever" Vaccination Distribution Campaign', *Wall Street Journal*, Oct. 21, 2020.

[76] 'Where we work – PLM – Project Last Mile'. https://www.projectlastmile.com/where-we-work/ (accessed Nov. 16, 2020).

[77] World Health Organization, Ed., *Immunization in practice: a practical guide for health staff*, 2015 update. Geneva: World Health Organization, 2015.

[78] J. Lim, E. Claypool, B. A. Norman, and J. Rajgopal, 'Coverage models to determine outreach vaccination center locations in low and middle income countries', *Oper. Res. Health Care*, vol. 9, pp. 40–48, Jun. 2016, doi: 10.1016/j.orhc.2016.02.003.

[79] N. Hashim, S. s Shariff, and S. Deni, 'Capacitated Maximal Covering Location Allocation Problem During Flood Disaster', *Adv. Sci. Lett.*, vol. 23, pp. 11545–11548, Nov. 2017, doi: 10.1166/asl.2017.10325.

[80] G. Polo, C. Acosta, R. Dias, and F. Ferreira, 'Location-Allocation and Accessibility Models for Improving the Spatial Planning of Public Health Services', *PLoS ONE*, vol. 10, Jan. 2015, doi: 10.1371/journal.pone.0119190.

[81] National Academies of Sciences, Engineering, and Medicine, 'Framework for Equitable Allocation of COVID-19 Vaccine', 2020. doi: 10.17226/25917.

[82] 'Come Together: How the Fight to End Polio Can Help the COVID-19 Recovery', *unfoundation.org*, Oct. 20, 2020. https://unfoundation.org/blog/post/come-together-how-the-fight-to-end-polio-can-help-the-covid-19-recovery/ (accessed Nov. 06, 2020).

[83] V. Singh, 'The Effect of COVID-19 Pandemic on Immunization Services in India - Possible Challenges and way forward', *Epidemiol. Int. E-ISSN 2455-7048*, vol. 5, no. 2, Art. no. 2, Jun. 2020.

[84] W. H. Organization, 'Framework for decision-making: implementation of mass vaccination campaigns in the context of COVID-19: interim guidance, 22 May 2020', Art. no. WHO/2019-nCoV/Framework_Mass_Vaccination/2020.1, 2020, Accessed: Nov. 06, 2020. [Online]. Available: https://apps.who.int/iris/handle/10665/332159.

[85] 'Immunization in the context of COVID-19 pandemic'. https://www.who.int/publications-detail-redirect/immunization-in-the-context-of-covid-19-pandemic (accessed Nov. 06, 2020).

[86] 'MODULE 3 – Mass vaccination campaigns - WHO Vaccine Safety Basics'. https://vaccine-safety-training.org/mass-vaccination-campaigns.html (accessed Nov. 06, 2020).

[87] T. L. P. Health, 'Will the COVID-19 pandemic threaten the SDGs?', *Lancet Public Health*, vol. 5, no. 9, p. e460, Sep. 2020, doi: 10.1016/S2468-2667(20)30189-4.

[88] 'Projected poverty impacts of COVID-19 (coronavirus)', *World Bank*. https://www.worldbank.org/en/topic/poverty/brief/projected-poverty-impacts-of-COVID-19 (accessed Nov. 06, 2020).

[89] 'UN report finds COVID-19 is reversing decades of progress on poverty, healthcare and education | UN DESA | United Nations Department of Economic and Social Affairs', Jul. 07, 2020. https://www.un.org/development/desa/en/news/sustainable/sustainable-development-goals-report-2020.html (accessed Nov. 09, 2020).

[90] 'Goal 2: Zero Hunger', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/hunger/ (accessed Nov. 06, 2020).

[91] J. Bongaarts, 'J. Sachs, G. Schmidt-Traub, C. Kroll, G. Lafortune, G. Fuller, F. Woelm The Sustainable Development Goals and COVID-19. Sustainable Development Report 2020 Cambridge University Press, 2020. 510 p', *Popul. Dev. Rev.*, vol. 46, no. 3, pp. 630–631, 2020.

[92] 'At least 80 million children under one at risk of diseases such as diphtheria, measles and polio as COVID-19 disrupts routine vaccination efforts, warn Gavi, WHO and UNICEF'. https://www.who.int/news/item/22-05-2020-at-least-80-million-children-under-one-at-risk-of-diseases-such-as-diphtheria-measles-and-polio-as-covid-19-disrupts-routine-vaccination-efforts-warn-gavi-who-and-unicef (accessed Nov. 06, 2020).

[93] 'Vaccination and Immunization Statistics', *UNICEF DATA*. https://data.unicef.org/topic/child-health/immunization/ (accessed Nov. 09, 2020).

[94] https://plus.google.com/+UNESCO, 'Why the world must urgently strengthen learning and protect finance for education', *UNESCO*, Oct. 16, 2020. https://en.unesco.org/news/why-world-must-urgently-strengthen-learning-and-protect-finance-education (accessed Nov. 09, 2020).

[95] UNESCO, 'Adverse consequences of school closures', *UNESCO*, Mar. 10, 2020. https://en.unesco.org/covid19/educationresponse/consequences (accessed Nov. 06, 2020).

[96] 'UN Secretary-General's policy brief: The impact of COVID-19 on women | Digital library: Publications', *UN Women*. https://www.unwomen.org/en/digital-library/publications/2020/04/policy-brief-the-impact-of-covid-19-on-women (accessed Nov. 06, 2020).

[97] 'COVID-19 and gender equality: Countering the regressive effects | McKinsey'. https://www.mckinsey.com/featured-insights/future-of-work/covid-19-and-gender-equality-countering-the-regressive-effects (accessed Nov. 09, 2020).

[98] 'Water and Sanitation', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/water-and-sanitation/ (accessed Nov. 06, 2020).

[99] 'ACCELERATING SDG7 ACHIEVEMENT IN THE TIME OF COVID-19 | Environmental Migration Portal'. https://environmentalmigration.iom.int/accelerating-sdg7-achievement-time-covid-19 (accessed Nov. 06, 2020).

[100] 'Infrastructure and Industrialization', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/infrastructure-industrialization/ (accessed Nov. 06, 2020).

[101] Martin, 'Reduce inequality within and among countries', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/inequality/ (accessed Nov. 09, 2020).

[102] 'Cities', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/cities/ (accessed Nov. 06, 2020).

[103] 'Climate Change', *United Nations Sustainable Development*. https://www.un.org/sustainabledevelopment/climate-change/ (accessed Nov. 06, 2020).

[104] S. Cheval, C. Mihai Adamescu, T. Georgiadis, M. Herrnegger, A. Piticar, and D. R. Legates, 'Observed and Potential Impacts of the COVID-19 Pandemic on the Environment', *Int. J. Environ. Res. Public. Health*, vol. 17, no. 11, Art. no. 11, Jan. 2020, doi: 10.3390/ijerph17114140.

[105] 'Ensuring data privacy as we battle COVID-19', *OECD*. https://www.oecd.org/coronavirus/policy-responses/ensuring-data-privacy-as-we-battle-covid-19-36c2f31e/ (accessed Nov. 06, 2020).

[106] L. Haidari, S. Brown, P. Wedlock, D. Connor, M. L. Spiker, and B. Lee, 'When are solar refrigerators less costly than on-grid refrigerators: A simulation modeling study☆', *Vaccine*, 2017, doi: 10.1016/j.vaccine.2016.11.103.

[107] W. H. Organization, 'Temperature sensitivity of vaccines', Art. no. WHO/IVB/06.10, 2006, Accessed: Nov. 06, 2020. [Online]. Available: https://apps.who.int/iris/handle/10665/69387.