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How to End the COVID-19 Pandemic by March 2022

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Abstract

How can the world reach herd immunity against COVID-19 before the second anniversary of the pandemic, or March 2022? A study of vaccine demand and supply answers this question. A target of vaccinating 60 percent of the population in each country by March 2022 is likely sufficient to achieve worldwide herd immunity under a baseline scenario with limited mutation. Achieving this target appears feasible given stated production capacity of vaccine manufacturers and the pace of current and historical vaccination campaigns. Considering existing pre-purchase contracts for vaccines, achieving this target requires addressing a procurement gap of just 350 million vaccine courses in low- and middle-income countries. Immediate additional donor funding of about $4 billion or in-kind donations of excess orders by high-income countries would be sufficient to close this gap. There are additional challenges along the path to achieving world-wide herd immunity---including supply chain issues, trade restrictions, vaccine delivery, and mutations. Overall however, this analysis suggests multilateral action now can bring an end to the acute phase of the pandemic early next year.

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How to End the COVID-19 Pandemic by March 2022

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1 Introduction

The contribution of this paper is to: (i) show that there exists a feasible path to reach worldwide herd immunity against COVID-19 by March 2022; (ii) quantify the gap in pre-purchases of vaccines needed to reach herd immunity; and (iii) describe donor financing solutions to address this gap.

First, we show that standard epidemiological models combined with data on vaccine efficacy, the reproduction rate of the virus, and prior infections suggest that vaccinating 45-60% of the world's population could be enough to achieve herd immunity. However, this rate of vaccination must be achieved in every country, or else the virus may persist and mutate in populations that are not covered. Based on this calculation, we argue that vaccinating 60% of the population in each country by March 2022 (i.e., the upper bound of the range) could serve as a short-term feasible target for public health authorities. Achieving such a target would correspond to vaccinating about 5% of each population each month starting now, and would end the acute phase of the pandemic within two years after it was declared. This rate of vaccine delivery has already been achieved by COVID-19 vaccine rollouts in some countries and in historical vaccination campaigns against other diseases in low-income countries.

Second, using available data on existing vaccine pre-purchase contracts, we demonstrate that only another 350 million vaccine courses are needed to achieve 60% vaccination coverage of the populations in 91 low- and middle-income countries (LMICs) that have been identified by the COVAX AMC, the multilateral procurement facility, as needing financial assistance to vaccinate their populations. This group of countries is known as AMC91, with a combined population of about 2.5 billion.[1] The 350 million course gap in AMC91 countries corresponds to only about 25% of their need to vaccinate 60% of their populations by March 2022. Moreover, available production capacity for vaccines does not appear to be the binding constraint in procuring these

[1]Overall, the LMICs have a population of 6.5 billion. Of this about 3 billion people live in China, India, and Russia, which have domestic vaccine manufacturing capacity available to address domestic needs. The remaining population is split between 2.5 billion people in a group of 91 countries (AMC91) that have access to the COVAX AMC facility, which provides access to subsidized courses, and 1 billion people in other middle-income countries that are not eligible to access subsidized vaccines, under the assumption that they have the ability to pre-purchase vaccines at market prices. India also has access to the subsidized vaccines through the COVAX AMC, though this access is reduced given its large population relative to the population of AMC91 countries. Owing to these considerations, it is useful to focus on achieving sufficient minimum vaccine coverage in the AMC91 countries in pursuit of the goal of worldwide herd immunity.

additional vaccines, as uncontracted production capacity reported by vaccine developers far exceeds the 350 million course gap, even once allowing for potential inflated reports and production delays. Overall, these results suggest that global vaccine procurement efforts are on the right track, and that worldwide herd immunity could be achievable by next year.

Third, we quantify that $4 billion more in grant funding for the COVAX AMC (in addition to the existing donor commitment of $6.3 billion) would be sufficient to close the pre-purchase gap of 350 million vaccine courses in the AMC91 countries. The near-term aspiration of the COVAX AMC is to provide minimum vaccine coverage of 20% of the population in AMC91 countries. The additional $4 billion would allow the COVAX AMC to raise its minimum vaccine coverage to about 30% of the population of these countries. As per our calculation, most AMC91 countries already have pre-purchased sufficient vaccines to achieve population coverage of 30% or more through existing direct or regional procurement efforts like that of the African Union. Thus, providing additional donor funding to COVAX AMC may be the most effective way to achieve 60% vaccine coverage and worldwide herd immunity by March 2022. In this context, the United States has already offered to provide an additional $2 billion in grant funding to the COVAX AMC, or half the funds required for this proposal, though this will be released only when other donors have fulfilled their pledges.

While an upfront grant of $4 billion to the COVAX AMC would be the simplest way for donors to execute this proposal, we provide two additional options to address the funding gap that rely on the existing institutional framework. One reduces donors' upfront commitment by relying on the International Finance Facility for Immunisation (IFFIm) to issue Vaccine Bonds against a long-term donor commitment. Another relies on in-kind donations to equalize the distribution of vaccine pre-purchases across countries. The gap in LMICs exists despite high-income countries already having pre-purchased vaccine courses exceeding 100% of their population. High-income countries could close the 350 million course gap in AMC91 countries by donating in-kind their pre-purchases in excess of their population, which by our estimate are 740 million courses.[2] Grant funding for immediate pre-purchases by the COVAX AMC to close the gap would have the added benefit of giving producers the certainty needed to activate reported available production capacity and place orders with input suppliers. In turn, more pre-purchases could help in the discovery and resolution of production bottlenecks, which has been identified as the key challenge facing market

[2]However, high-income countries may retain strategic reserves of the vaccine over 100% of the population, in which case grant funding would be required to substitute for in-kind donations.

participants (Chatham House, 2021).[3]

We also discuss four additional challenges that could delay the path to herd immunity—under-investment in production capacity, shortages and export restrictions on raw materials and finished vaccines, scaling up mass rapid vaccination drives, and addressing mutation. We identify policy priorities in each area, while emphasizing that urgent action on vaccine pre-purchases (of 350 million courses or possibly more as buffer) will partly help resolve these challenges.

Thus far, research and development of vaccines for COVID-19 has been an unprecedented success, with active government subsidies allowing clinical trials to far exceed what would be expected based on market size (Agarwal and Gaulé, 2021). Many LMICs have weathered the first phase of the pandemic relatively better than high income countries (Goldberg and Reed, 2020; Deaton, 2021), but the second phase of the pandemic could impose an unequal burden on them if inequality in vaccine access persists. Multilateral action could avoid that outcome. In addition, given spillover risks, it is in the interest of high-income countries to have worldwide herd immunity as fast as possible (Çakmaklı et al., 2021). The benefit of achieving herd immunity one month earlier is valued at approximately 1% of world GDP (Castillo et al., 2021), which is tremendous compared to the relatively low cost of the $4 billion grant proposed. From this perspective, additional investment in pre-purchases to activate existing production capacity today is likely one of the highest-return investments countries can make.

While the world will eventually need enough vaccines for all adults (and possibly children), our paper focuses on the more urgent challenge of ensuring vaccine coverage of at least 60% of the population in all countries by March 2022—which could end the acute phase of the pandemic, allowing potentially for a return to normal life worldwide. Even if the emergence of more contagious variants or other factors pushes the vaccination threshold required for herd immunity higher, a target of vaccinating 60% of every population worldwide lays the foundation to achieve herd immunity faster in those adverse scenarios.

Beyond the near-term, the world will eventually need enough vaccines for all adults (and possibly children), and also prepare for future pandemics. Further, it is also possible that unexpected problems with the supply chain may arise, safety concerns about some vaccines may emerge, or that an escape variant means some capacity needs to be re-purposed. To insure against such

[3]This effect may be non-negligible as 350 million courses represents about 8% of the total vaccines needed to achieve the target of vaccinating 60% of the population in each country.

scenarios and to prepare for future pandemics, further coordinated global action will be needed. In this context, the demand-side action of additional donor financing for vaccine pre-purchases to activate existing capacity is complementary to supply-side actions to reduce fragility in the vaccine supply chain and expand overall manufacturing capacity.

2 The Vaccination Path to Herd Immunity

In this section, we calculate the vaccination needs to reach herd immunity and then compare that to the potential aggregate vaccine supply. First, we first provide a calculation showing 45-60% of every population needs to be vaccinated in order to achieve herd immunity by March 2022. The upper-range of this calculation informs our proposed target of 60% vaccination in each country by March 2022, which translates to 4.75 billion courses needed by March 2022. Second, we compare the vaccine needs to stated production capacity of vaccine developers, which is indicative of available aggregate supply.

Note that the 60% of the population vaccination target derived in this section should be seen as a short-term target, as the world may eventually need to vaccinate everyone. LMICs will need more help achieving that goal. Even once the herd immunity threshold is reached in each country, it is still possible to have large outbreaks if vaccination rates are uneven within countries. Nonetheless, achieving 60% vaccination coverage in each country would likely bring an end the acute phase of the global pandemic, allowing authorities to turn their attention to suppressing outbreaks in specific populations.

2.1 The Vaccination Threshold for Herd Immunity

We follow the standard approach to model herd immunity.[4] Consider a simple model of the population such that:

$$\begin{aligned} N_t &= (1-f) \cdot Infected_t \\ V_t &= E \cdot Vaccinated_t \\ B_t &= N_t + V_t \end{aligned} \tag{1}$$

where

- N_t is the fraction of population that has natural immunity due to previous infection with SARS-CoV-2. This equals the percent of non-vaccinated population already infected ($Infected_t$) times 1 minus the average susceptibility rate of re-infection (f).[5]
- V_t refers to the fraction of population that has vaccine-induced immunity, which depends on the percent of population already vaccinated ($Vaccinated_t$), the average effectiveness of the vaccines (E).
- B_t is base immunity in month t, which refers to the fraction of individuals immune to the virus at a given moment in time, either from acquired infection or vaccination. Then, $B_t = N_t + V_t$.

The base immunity needed to achieve herd immunity (B_t^*) is given by:

$$B_t^* \equiv HerdImmunity = 1 - \frac{1}{R_0} \tag{2}$$

[4]Our approach is in line with the public health and epidemiology literature (Fine et al., 2011; Delamater et al., 2019), which differentiates between two concepts of disease transmissibility. The basic reproduction number, R_0, represents the transmission *potential* of a disease, and measures the average number of secondary infections produced by a typical case of an infection when everyone in the population is susceptible. By contrast, R_t represents the effective reproduction number, and can be estimated as the product of the basic reproductive number, R_0, and the fraction of the host population that is susceptible at that time, $1 - B_t$. That is, $R_t = (1 - B_t) \cdot R_0$. Here B_t represents the base prevalence of immunity at a given time, given by the fraction of individuals immune to the virus, either from acquired infection or vaccination. Herd immunity occurs when a significant proportion of the population have been vaccinated or have gained natural immunity by prior infections. When this occurs, the effective reproduction number reaches one: $R_t = 1$. Thus, the threshold for herd immunity, B_t^*, can be found by plugging $R_t = 1$ and re-rearranging the equation such that $B_t^* = 1 - 1/R_0$. This is the approach we follow below to quantify the vaccination threshold.

[5]Note that in some adverse mutation scenarios the re-infection rate could increase. Mutations can also lead to more infectious variants that would correspond to a higher R_0, or be associated with reduced vaccine efficacy. We discuss these considerations in more detail in Section 4.4.

where R_0 is the basic reproduction number, or the average number of susceptible individuals that are infected by a single infected individual. For example, an R_0 of 3 means one individual infected with SARS-CoV-2 is likely to infect three other people. This is best measured in the early phase of the outbreak, before control measures have had time to take effect, and when most of the population is susceptible.

The vaccination threshold for herd immunity ($Vaccinated_t^*$), is the fraction of population that needs to be vaccinated to reach herd immunity on a given date t. This is given by setting $B_t = B_t^*$ in (1), substituting the value of B_t^* from (2) in (1), and solving for $Vaccinated_t^*$, such that:

$$Vaccinated_t^* = \frac{1 - \frac{1}{R_0} - (1 - f) \cdot Infected_t}{E}. \tag{3}$$

Using (3), the vaccination threshold for herd immunity, $Vaccinated_t^*$, can be found by plugging values of R_0, $Infected_t$, f, and E. To end the pandemic by March 2022, we are interested achieving $Vaccinated_t^*$ by t = March 2022. Below we discuss the parameter choices for equation (3) corresponding to this choice of t.

R_0: While initial reviews found relatively higher values of R_0, recent studies have estimates appear to be stabilizing between 2 and 3 (Omer et al., 2020; Hilton and Keeling, 2020). We evaluate $Vaccinated_t^*$ in the middle of this range of outcomes $R_0 \in [2.25, 2.75]$. That is, we exclude the bottom end of the $2 - 3$ range to be conservative, while at the same time exclude the top end of the range to take into account that even with full re-opening of the economy there are likely to be some persistent socio-behavioral changes (e.g., masking, border screening) making a post-herd-immunity environment somewhat different from that of early-2020.

Infected$_t$: The next parameter of interest is $Infected_t$. This parameter is already difficult to measure presently without representative population surveys, and to evaluate it at t = March 2022 further requires taking a view of how infection will evolve. Today, SARS-CoV-2 seroprevalence surveys (see `serotracker.com`) provide the best estimates of the prior infection rate across countries. India is one of the few LMIC countries to have conducted a recent national serosurvey, with an estimated seroprevalence of 21.5% in a sample of 28,000 individuals across 700 villages.[6]

[6]The full report has not been published yet. According to the official press release for the third national serosurvey conducted by the Indian Council of Medical Research, about 21.5 percent of India's total population showed presence of antibodies for COVID-19. The results are based on a survey of 28,000 individuals across 700 villages in 21 states between Dec. 17, 2020 and Jan. 8, 2021.

Urban serosurveys in India and various LMICs often find higher seroprevalence. Outside of India, some estimates suggest that in November 2020 cumulative COVID-19 prevalence was 20% or higher in several LMICs, much more than reported in official case statistics (Louca, 2020). Projected seroprevalence at the end of 2021 is likely to be significantly higher than current estimates based on past data, given continued transmission. To be conservative, we evaluate the range $Infected_t \in [15\%, 20\%]$ reflecting high uncertainty and possible cross-country variation in this estimate.[7] This range of values implies that 15-20% of the non-vaccinated population will have prior infection by March 2022.

E and **f:** For the vaccine efficacy parameter, we set $E = 82.5\%$, reflecting the average of 10 vaccine candidates for which developers have reported Phase 3 trial results in environments with the dominant strain of the virus (prior to the global spread of the UK variant). Since re-infection rates with respect to the dominant strain of COVID-19 are estimated to be low with prior infection providing about 83% protection against new infections (Mahase, 2021), we set $f = 17\%$.

With values (i.e., R_0, $Infected_t$, f, and E) in these ranges, we find $Vaccinated_t^*$, or the vaccination threshold for herd immunity to be approximately between 45-60%.

In alternative scenarios a faster pace of vaccination may be needed to reach the goal of herd immunity by end-2021. Even in worse scenarios that push the vaccination threshold higher (e.g., due to mutations), reaching this vaccination target of 60% of the population in every country by March 2022 (i.e., the upper bound of our vaccination threshold) will provide the world with a strong foundation from which it can mitigate the adverse impact of those scenarios. Appendix A discusses how the vaccination threshold calculation could vary if being undertaken for a specific country, and the implications for the vaccination threshold under different scenarios (such as mutations).

Overall, based on this analysis we focus on the target of vaccinating 60% of the world by March 2022—i.e., by the second anniversary of the pandemic. The 60% target by March 2022 is of course an ambitious goal, and in sections 3, 4, and 5 we examine the key obstacles in the way of this goal. But before turning to those complications, Section 2.2 compares the vaccine needs computed

[7] To arrive at this number, we start with a range $[12\%, 20\%]$ of seroprevalence at end-2020 when no vaccinations had occurred. Then we assume that infections grow by about 1% per week (which is significantly lower than the weekly growth reported infections in 2021 as per the WHO tracker (`covid19.who.int`)). Finally, we assume that about 40% of those with prior infections will be vaccinated by March 2022 (which is a conservative estimate given that a non-negligible fraction of infected are children who will not be vaccinated). These assumptions together give us a range of approximately $[15\%, 20\%]$ for the share of non-vaccinated population that is infected at t = March 2022.

in this sub-section to the aggregate manufacturing capacity for vaccines as stated by the vaccine developers.

2.2 Comparing Vaccine Needs To Aggregate Manufacturing Capacity

Vaccinating 60% of the world by March 2022 requires about 4.75 billion vaccine courses. How does that compare to stated manufacturing capacity of effective vaccines?

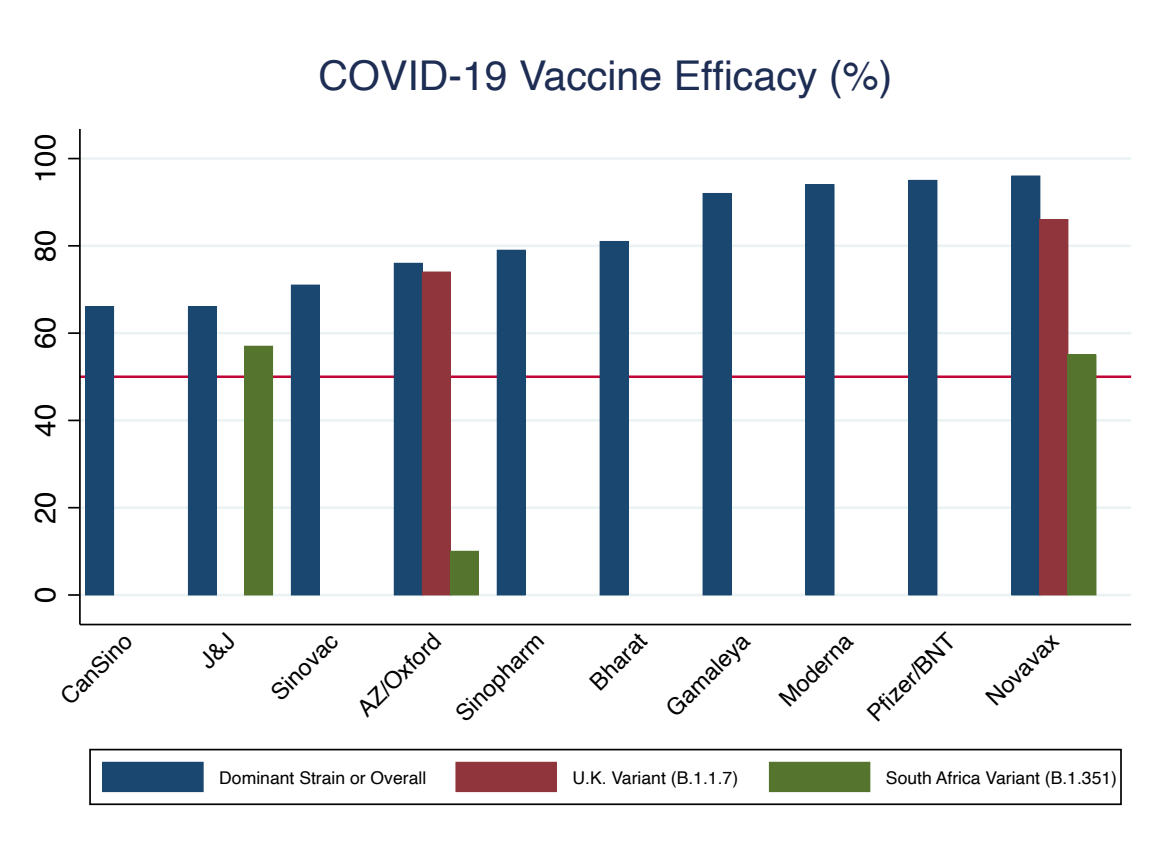
Overall, vaccine research and development efforts have been highly successful, thanks to a large market and government subsidies and incentives (Agarwal and Gaulé, 2021). There are at least 10 vaccines with some publicly available data supporting an efficacy of greater than 50% against COVID-19 (Figure 1).[8] At this level of overall efficacy, vaccines are near fully effective against hospitalization and death, and as a result are already being adopted by many countries. For example, though the AstraZeneca and Janssen (J&J) vaccines are relatively less effective, at 76% and 66%, both have been authorized for emergency use by the European Union. The recent temporary pause in delivery of these vaccines by some authorities reflected a concern about potential side-effects (i.e., blood clots) rather than efficacy. Taking available data at face value, these 10 vaccines appear sufficiently effective to suppress the virus if deployed globally.[9] In addition, each of the 10 vaccines have already been approved for use in multiple countries/jurisdiction (see `https://covid19.trackvaccines.org/vaccines/`), highlighting the growing global reach of these vaccines.

Developers of these 10 vaccines (or 'companies') report potential production capacity sufficient

[8]This 50% efficacy threshold corresponds to the guidance conveyed by the U.S. Federal Drug Administration (FDA) on June 30, 2020. The FDA guidance expects that a COVID-19 vaccine would prevent disease or decrease its severity in at least 50% of people who are vaccinated. See `https://www.fda.gov/media/139638/download`.

[9]The ten vaccines employ three different technologies. In the first-generation vaccines, the virus is either weakened (attenuated) by growing it in another species, or inactivated by heat or chemicals. There are two first-generation producers: (1) Sinovac (called Coronavac) and (2) Sinopharm. The second-generation vaccines take advantage of molecular biology advances to include specific viral proteins or protein fragments in the vaccine instead of a whole virus. There are five second-generation vaccine producers: (3) Novavax, (4) Oxford/AstraZeneca vaccine (called Covidshield when produced in India), (5) Gamaleya Research Institute (called Sputnik V), (6) Janssen (J&J), and (7) CanSino. The third-generation vaccines aim to vaccinate a patient with genetic material—RNA—that encodes for the desired viral protein target. In the case of SARS-CoV-2, the target that researchers have decided is the most promising is the spike protein, a protein on the surface of the virus that enables it to invade host cells. There are three third-generation vaccine producers: (8) Pfizer-BioNTech, (9) Moderna, and (10) Bharat Biotech (called Covaxin).

Figure 1: Company reported data suggest at least 10 vaccines are effective against the dominant strain of SARS-Cov-2.



Sources: Abdool Karim and de Oliveira (2021) and authors' calculations.

Notes: The red line indicates the 50% efficacy threshold of the US FDA. For Sinovac, the bar represents the mean of a reported range between 51-90%. See Appendix Table C.3 for further details.

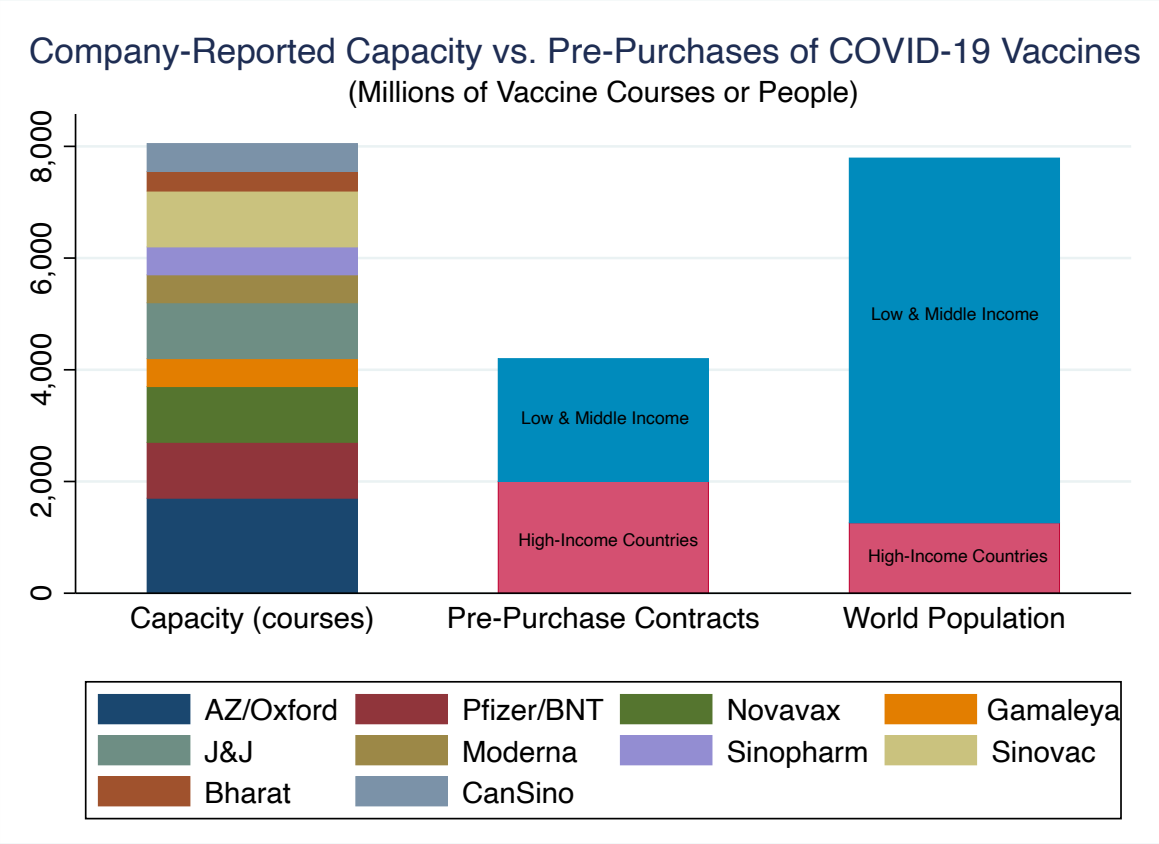
to cover of the world's population in 2021 (Figure 2). Realizing the production capacity will require rapidly bringing the reported-capacity online, and also that suppliers of vaccine inputs scale their production capacity as well. To give a sense of the scale of the challenge, producing enough doses of COVID-19 vaccines for the entire world requires producing about three to four times the pre-COVID-19 annual global supply for all vaccines (Chatham House, 2021). The increase in capacity required will be challenging due to the complexity of vaccine manufacturing processes and specificity of technical know-how and equipment. Nonetheless, just as research and development has been completed at unprecedented speed, companies have today put in place ambitious production targets. While this production capacity may not be immediately available, companies have targeted being able to bring it online this year. However, purchase contracts have not been made for much of that capacity.

The values for the potential production capacity are reported by Wouters et al. (2021), and we have confirmed and updated the values using a Google search for press releases of vaccine manufacturers. Values are reported in Appendix Table C.1. In total, companies report available capacity to produce 8.05 billion courses—more than enough for the world's 7.79 billion people, including children. Those that can be deployed most rapidly are those which: (i) can be stored in a refrigerator, rather than a freezer (or with dry ice); and (ii) have available production capacity not already pre-purchased by high income countries.

Some have worried that high-income countries have purchased most available vaccine production capacity. This is not true. Appendix Table C.1 shows that once accounting for pre-purchases by high income countries, the remaining available production capacity is 6.05 billion courses for 6.53 people in LMICs, enough to immunize 93% of the population. Even allowing for potentially inflated production targets and likely supply chain bottlenecks, trade restrictions, and cold-chain equipment investment needed to scale up delivery (discussed in more detail in Section 4), it appears that across these 10 vaccines there may be sufficient aggregate production capacity of vaccines to meet the target of vaccinating 60% of the world population by March 2022.[10]

[10]However, the supply of effective vaccines could potentially be reduced if the virus mutates. This risk is apparent in Figure 1, which reports efficacy of COVID-19 vaccines against the dominant strain, and, where data are available, the two main variants: the U.K. variant (B.1.1.7 or 501Y.V1) and the South Africa variant (B.1.351 or 501Y.V2). While the vaccines appear similarly effective against the U.K. variant as against the dominant strain, they are less effective against the South African variant. Two vaccines, Novavax and J&J, have substantially reduced efficacy against this variant, though still greater than the 50% threshold, while the AstraZeneca vaccine is ineffective against

Figure 2: Unequal Distribution of Vaccine Pre-Purchases (2021)



Sources: Bharat Biotech, CanSino, Duke Global Health Innovation Center, UN Population Prospects, Wouters et al. (2021), World Bank Income Classifications.

Notes: This figure is based on data as of end-March 2021, and only includes information for 10 vaccines that have demonstrated efficacy of greater than 50% against COVID-19 based on publicly available data. The production capacity corresponds to stated production capacity for the year 2021. See Appendix Table C.1 for further details.

In sum, sufficient aggregate supply may exist to cover the world's population. However, contracted pre-purchases to activate the existing capacity and efforts to mitigate systemic supply chain risks along the way are still needed for companies to achieve their realize the production capacity. Pre-purchases are important because manufacturing lines require lead time to prepare, and may also facilitate in capital-raising efforts by vaccine developers. Even if high-income countries have pre-purchased more than they need, this does not imply that manufacturing lines will already be prepared for LMICs, since exports to these countries may have different product requirements (e.g., less reliance on mRNA technology) and regulatory certification requirements.

The next section quantifies the pre-purchase vaccine gap for LMICs.

3 The COVID-19 Vaccine Pre-Purchase Gap

Though high-income countries have pre-purchased more than enough vaccines to cover their populations, there is still a significant gap between the amount pre-purchased and the amount needed to achieve 60% vaccination coverage in each country by March 2022.[11] A committed pre-purchase is an important first step in ensuring timely delivery. The gap is primarily in low- and middle-income countries. We arrive at this gap by comparing 60% of the population to the number of pre-purchases contracts countries have already made, based on available data. Our computation is based on the following steps.

First, we start from the publicly-available data on vaccine procurement compiled on the Launch and Scale Speedometer site by the Duke Global Health Innovation Center—updated as of April 2nd, 2021.

Second, for the COVAX AMC pre-purchases we use the available funding of $6.3 billion[12] as of March 2021 to quantify the number of courses for the AMC92 countries, which are the AMC91 countries plus India. The COVAX AMC takes a tailored approach to India, given that India accounts for 17% of the world population (35% of the total AMC92 countries' population) and

the South Africa variant. As a result, South Africa has halted delivery of AstraZeneca and is pursuing more supply of J&J. We discuss these issues further in Section 4.

[11] Thus far the vaccines have been authorized for use only for individuals aged 16 and above. The effective vaccination rate of adults achieved would differ by country, depending on the share of the population that is an adult (i.e., 16+). In regions with a large share of the population that under 16 (e.g., Africa, at about 40%), achieving herd immunity will require vaccinating a larger fraction of the adult population.

[12] See `www.gavi.org/sites/default/files/covid/covax/COVAX-AMC-Donors-Table.pdf`

the vaccine allocation to India as a share of the population will therefore have a large effect on the residual supply available to AMC91 countries. The Gavi Board, which oversees the COVAX AMC, decided that India would receive 20% of AMC donor-funded doses.[13] Using the unit price of $12 per course we allocate $6.3 billion / $12 = 525 million courses across the AMC92 countries, following this allocation rule, which gives 105 million vaccine courses to India, and 420 million vaccine courses to the AMC91 countries, equivalent to a coverage of 8% of India's population and 16% of the AMC91 population. Our assumption on vaccine prices are in line with Gavi's own estimates, which assumes that a vaccine course will cost them between $10-14 (i.e. $5-7 per dose for a two-dose vaccine) with $12 per course being the mid-point of this range.

Third, we have accounted for about 43 million vaccine doses that the COVAX provided to 51 countries in its first round of allocation (between Feb to May 2021). These are self-financed purchases (typically by higher-income countries) outside the subsidized AMC facility.[14]

Fourth, we assume that pre-purchases by regional organizations like the African Union and the European Union are allocated in proportion to population to members that have not already covered their population through direct procurement. Similarly, Mexico and Argentina have an agreement with AstraZeneca to produce the vaccine for the eventual distribution of 250 million doses to Latin America (excluding Brazil). Accordingly, we distribute these vaccine doses to the Latin American countries in proportion of their population.

Fifth, the Duke data do not cover vaccines provided as donations. Comprehensive data on vaccine donations is available for India, which as of April 6th, 2021, has made donations of 10 million doses to about 44 countries.[15] We include these in our computation (which are non-negligible for small countries like Bhutan, Maldives, etc.).

Sixth, while the Duke data are fairly comprehensive, there are several deals not recorded. The most notable are the missing data on some Sputnik V (Gamaleya Institute) deals and some deals in the oil exporters of the MENA region that are not available in the public domain. While we were unable to systematically track down these missing contracts, we were able to include a deal for Pakistan with Cansino, which allows for bulk vaccine imports by mid-April from Cansino

[13] For further details on the tailored approach for India see: `www.gavi.org/sites/default/files/board/minutes/2020/15-dec/10%20-%20COVAX%20AMC%20support%20to%20India.pdf`

[14] See `https://cdn.who.int/media/docs/default-source/3rd-edl-submissions/covax-first-round-allocation-of-az-and-sii-az---overview-tablev2.pdf`

[15] See `https://www.mea.gov.in/vaccine-supply.htm`

amounting to 3 million doses disclosed in end-March. Overall, given that some deals remain private the resulting estimate is a lower-bound for what has been pre-purchased.

Finally, we assume that uncontracted production capacity of vaccines licensed to be produced in China, India and Russia are allocated to these countries. This accounts for the fact that though these countries may not have pre-purchased vaccines for their populations, they nonetheless retain the option to requisition local supply, as India for example initially waited to grant commercial license to export the locally-manufactured AstraZeneca vaccines (by the Serum Institute of India (SII)) after it was authorized for use. Note, however, it will still be important for these countries with large domestic manufacturing capacity to immediately execute pre-purchases to meet their domestic needs (as it will reduce demand uncertainty and provide transparency about potential supply-chain bottlenecks), and to also consider investment in expanding their manufacturing capacity to handle adverse scenarios (as discussed in Section 5).

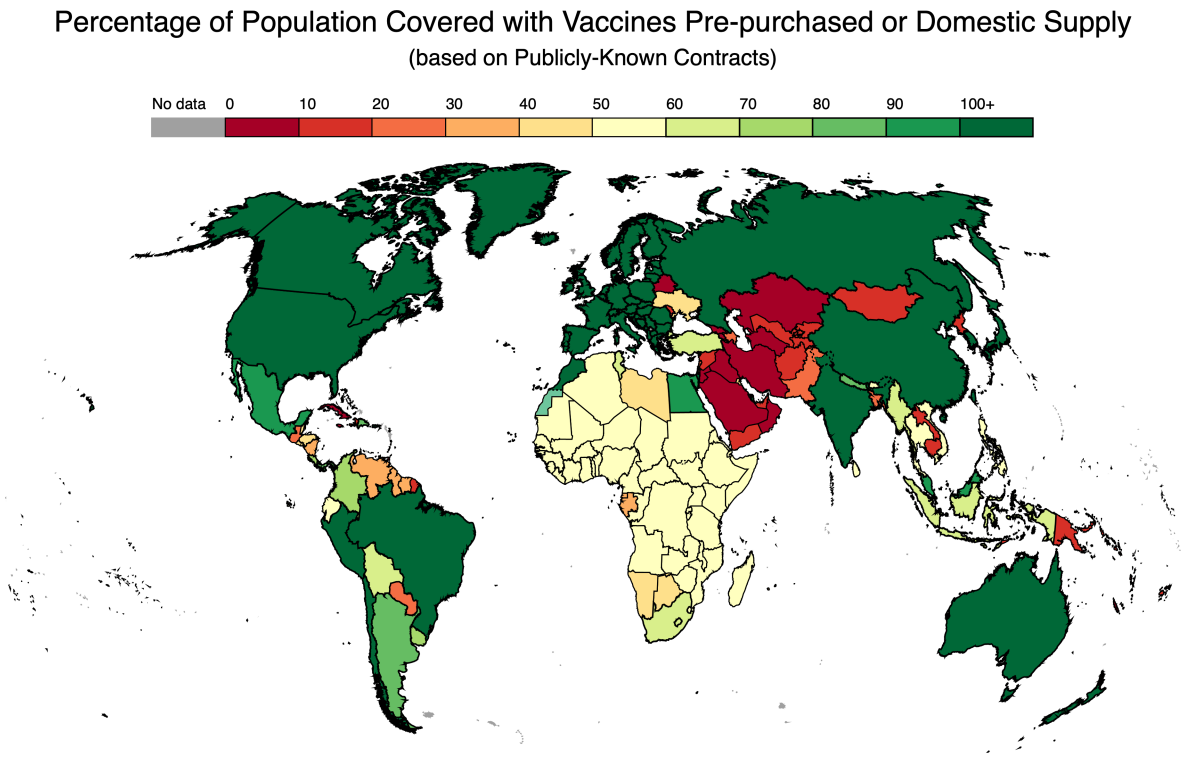
Figure 3 reports the results of this exercise in a map. A conclusion from inspecting this map is that the gap to achieve 60% coverage is not large in most countries, assuming companies delivery on existing purchase orders in a timely fashion. For instance, most countries in Africa have already pre-purchased enough to cover at least 50% of their population once accounting for orders through the COVAX and the African Union. This is cause for optimism, suggesting that closing the remaining gap to achieve 60% vaccination by March 2022 is not insurmountable.

Appendix Table B reports the gap for the 92 countries eligible for subsidized vaccine purchases under the COVAX AMC. In the AMC91 countries, which do not include India, the gap to achieve 60% coverage is about 350 million courses. Once accounting for existing coverage of 8% of its population by the COVAX and other pre-purchases, India faces a gap of about 500 million courses to achieve 60% coverage. This calculation illustrates how once separating India from the calculation, the gap in the AMC91 countries is not especially large. While India will also need to fill its pre-purchase gap, there is uncontracted domestic capacity available to meet its needs.

4 Challenges on the Vaccination Path to Herd Immunity

As previously discussed, the research and development for vaccines against the dominant strand of COVID-19 has been an unprecedented success. Though stringent regulatory authorities take time to provide formal emergency use authorization (EUA) based on review of Phase 3 trial data,

Figure 3: Global Vaccine Coverage



Sources: The COVAX, Duke Global Health Innovation Center, World Population Prospects, news sources.

Notes: Includes only known pre-purchases of vaccines with reported efficacy greater than 50% in Phase 3 trials. Some deals for which the number of courses is not available in the public domain may not have been recorded. Orders by multilateral organizations (e.g., the COVAX AMC, European Union, African Union) are distributed to eligible members in proportion to their population. China is allocated all uncontracted production capacity of Sinovac, Sinopharm, and CanSino. Russia is allocated all uncontracted production capacity of Gamaleya, and India is allocated all uncontracted production capacity of Bharat Biologics, and the uncontracted doses of the domestically-licensed AstraZeneca/Oxford and Novavax, which are under license for production in the country by the Serum Institute of India (SII).

vaccine developers today report successful trials and enough available production capacity to cover the world's adult population in 2021. This section identifies four challenges in addition to research and development that could delay vaccine production and delivery, thereby pushing back when the world achieves herd immunity. We also discuss some actions that can be taken ahead of time to mitigate the risk of delay.

4.1 Demand Uncertainty & Under-Investment to Activate Production Capacity

A major challenge in bringing production capacity online is demand uncertainty. Without certainty that they will sell their output for at least marginal cost, manufacturers may delay investments in production lines, and placing orders for key inputs. Further, financing for the purpose of bringing capacity online may be hindered without the availability of sufficient purchase orders as collateral.

At present, significant demand uncertainty exists—both short-term (i.e., the quantity of courses demanded in 2021) and over the medium-term (e.g., if and how much demand will there be for annual booster shots in the future). As a result, input suppliers are dissuaded from making the necessary investments required to scale their own manufacturing capacity now. Immediate pre-purchases (e.g., through the COVAX AMC as we propose in Section 5) can help partly resolve this uncertainty, allowing for the discovery and resolution of supply chain bottlenecks. In this case, the price mechanism enables greater visibility and higher quality information at an aggregate level to help managers anticipate potential capacity constraints.

An immediate execution of pre-purchases helps in two regards simultaneously. First it ensures that sufficient quantities of vaccine courses are secured to reach herd immunity world-wide, in the event that high-income countries delay donating their excess purchases, or hold strategic reserves in excess of their populations. From this perspective a committed pre-purchase order is an important first step in ensuring timely delivery of vaccines in LMICs. Second, it helps to reduce demand uncertainty, provides transparency about potential supply-chain bottlenecks, and creates incentives to further scale up the production capacity along the entire supply chain in the short-term. These effects may not be small in magnitude, as 350 million vaccine courses (or equivalently about 700 million doses for 2-dose courses) represents about 8% of global needs to reach a target of 60% vaccine coverage—and constitute sizeable orders from the perspective of some companies that are likely to serve the LMICs (i.e., those that need not be stored in freezers).

In addition, the government can also play a significant role in reducing demand uncertainty and

expanding investment in manufacturing capacity through state intervention to ramp up production capacity (Cherif and Hasanov, 2020). A relevant example is the use of the Defense Production Act (DPA) by the United States to bolster vaccine production (in addition to boosting the availability of virus tests, and addressing the shortages in personnel protective equipment such as masks, shields and gloves). For instance, an Executive Order issued on January 2021 directs immediate actions to secure supplies necessary for responding to the pandemic.[16] Among other actions, the Order calls for an immediately review the availability of critical materials, treatments, and supplies needed to combat COVID-19, and taking appropriate action using all available legal authorities, including the Defense Production Act, to fill those shortfalls as soon as practicable by acquiring additional stockpiles, improving distribution systems, building market capacity, or expanding the industrial base. In addition, the Order directs the relevant agencies to provide a strategy to design, build and sustain a long-term capability to manufacture supplies for future pandemics and biological threats within 180 days.[17] Government action can also help encourage more voluntary licensing of the vaccines in LMICs (e.g. AstraZeneca and Novavax agreements with the Serum Institute of India), and can facilitate partnerships between companies to increase manufacturing capacity (such as the U.S. International Development Finance Corp. action to fund Indian manufacturer Biological E Ltd.'s efforts to manufacture at least one billion doses of J&J and other COVID-19 vaccines, or the brokered manufacturing collaboration between Merck and J&J). Overall, such concerted government action may significantly help the expansion of vaccine production capacity and addressing supply chain constraints going forward.

Investment in additional vaccine manufacturing capacity should also be considered to insure against adverse mutation scenarios of the current pandemic, and against future pandemics. In particular, at present the LMICs are relying heavily on a few vaccines such as the AstraZeneca and J&J, which have faced some concerns about safety and in the case of AstraZeneca has been shown to have low efficacy against the South Africa variant. If adverse scenarios were to materialize in which some of the existing vaccines are not effective or turn out to have non-negligible safety concerns (e.g. concerns about some adenovirus-based vaccines), then that could lead to a significant setback in the global path to herd immunity. Therefore, additional investment in manufacturing

[16] www.federalregister.gov/documents/2021/01/26/2021-01865/a-sustainable-public-health-supply-chain

[17] For further discussion see https://www.lawfareblog.com/understanding-bidens-invocation-defense-production-act

capacity in line with proposals of Castillo et al. (2021) should be considered.

4.2 Shortages of Raw Materials & Export Restrictions

In the short-term, many COVID-19 vaccine inputs such as ingredients, packaging materials, and equipment are in short supply, and constraints appear to exist in the fill and finish stage of manufacturing. Such shortages and constraints may result in several COVID-19 vaccine manufactures not being able to meet their short-term vaccine manufacturing commitments, and may also impact the industry's ability to manufacture other lifesaving vaccines.

There is a further concentration risk in terms of the locations where manufacturers of vaccines and raw materials are located. Vaccine manufacturing facilities are concentrated in a few countries/regions, especially the United States, EU, China, and India (see Appendix Figure C.1). Similarly, raw material suppliers are concentrated in the same countries. For instance, during 2017-19, vaccine producing nations sourced 88% of their key vaccine ingredients from other vaccine producing trading partners (Evenett et al., 2021). From this perspective, meeting production targets will be challenging if vaccine nationalism gives rise to export restrictions of certain raw materials or even the finished vaccines (Bown and Bollyky, 2021).

A recent example of the challenges posed by export restrictions and shortages of raw materials comes from the recent U.S. move to secure raw materials and supplies for Pfizer's COVID-19 vaccine, which could hinder manufacturers working on other shots around the globe. In March 2021, the world's largest vaccine maker by volume, Serum Institute of India, warned about bottlenecks due to a U.S. law blocking exports of certain materials needed to produce COVID-19 shots. During a World Bank panel discussion, Serum Institute of India CEO Adar Poonawalla suggested that the U.S. has obstructed exports of certain materials like bags and filters, and supply shortfalls could hinder work on Novavax's vaccine which it is licensed to manufacture in India. Similarly, WHO's chief scientist, Soumya Swaminathan, warned of shortfalls of vials, glass, plastic and stoppers.[18] The impact of such delays could significantly push back the date of worldwide herd immunity since vaccines such as Novavax are expected to be a major source of vaccine supply for the low- and middle- income countries.[19]

[18] See `https://www.livemint.com/companies/news/sii-ceo-adar-poonawalla-warns-of-delays-in-vaccine-production-as-us-prioritizes-pfizer-11614923450787.html`

[19] Notably, on March 25th, 2021, the COVAX Facility notified participating economies that deliveries of doses from the Serum Institute of India (SII) will be delayed in March and April. They noted that delays in securing supplies of

Further, as of mid-April 2021, Novavax had not filed for an emergency use authorization (EUA) in the U.K. or elsewhere despite releasing strong efficacy and safety data in early-March—possibly due to ongoing short-term constraints in the fill and finish stage of manufacturing. While Novavax has reached an agreement with GSK to get rapid support for fill and finish manufacturing capacity of up to 60 million doses as early as May 2021 (in the U.K.),[20] going forward concerted global action can help avoid such obstacles from recurring for any of the COVID-19 vaccines. In particular, such systemic supply chain risks in different stages of the vaccine manufacturing may materialize in the future threatening the speed of vaccine supplies. To mitigate or eliminate such risks, governments, multilateral agencies, and industry participants should step up global surveillance of systemic supply chain risks.

In addition, ensuring no export restrictions on raw materials and vaccines will facilitate a more efficient allocation and faster delivery of vaccines in the acute phase of the pandemic. So far many of the reported trade restrictions (or supply chain disruptions) have turned out to be relatively short-lived without fundamentally altering the critical path to herd immunity. But this could change. Going forward, the critical path can be insured against future delays by multilateral cooperation and coordination to ensure free cross-border trade of raw materials and finished vaccines.[21]

4.3 Challenges in Scaling Vaccine Delivery

Even with sufficient quantities of vaccines available, reaching herd immunity will require a rapid scaling up of vaccine delivery. Delivery of COVID-19 vaccines poses unique challenges due to the urgency of achieving population immunity—including vaccine hesitancy, storage and transportation hurdles, and coordinating a large immunization program.[22]

Deploying vaccines to cover 60% of the world's population by March 2022 will not be easy, but is achievable based on past experience. For instance, in a meningitis vaccine campaign Burkina

SII-produced COVID-19 vaccine doses were due to the increased demand for COVID-19 vaccines in India—given the constrained production schedules. Thus, we can expect that if such production constraints endure into the future, it is likely to have a direct adverse impact on the availability of vaccines for LMICs and COVAX. See `https://reliefweb.int/report/world/covax-updates-participants-delivery-delays-vaccines-serum-institute-india-sii-and`

[20] `www.gsk.com/en-gb/media/press-releases/gsk-to-support-manufacture-of-novavax-covid-19-vaccine/`

[21] See the March 2021 World Trade Organization (WTO) webinar on 'Vaccines and critical goods: production, distribution and trade policies' at `/www.wto.org/english/res_e/reser_e/economic_resilience_180321_e.htm`.

[22] For more details on vaccine delivery costs see `https://www.who.int/docs/default-source/coronaviruse/act-accelerator/covax/costs-of-covid-19-vaccine-delivery-in-92amc_08.02.21.pdf`

Faso covered its target population of 11 million individuals aged 1-29 years in just 10 days. Random surveys conducted after the vaccination campaigns show that 95.9% of eligible individuals had been vaccinated Trotter et al. (2017). Other examples of rapid vaccination efforts include the meningitis vaccine campaign in Brazil in 1974 and 1975 (Baylac-Paouly, 2019) and the 1947 smallpox vaccination campaign in New York City (Sepkowitz, 2004). Today, Colombia plans to vaccinate over 5% of its population against COVID-19 each month, reaching vaccine coverage of over 50% by end-2021 (Demombynes et al., 2021). In addition, over 10 days starting in end-March 2021, Bhutan managed to administer the first dose of the COVID-19 vaccine to about 60% of the population.

Vaccine hesitancy may be another hurdle for achieving the 60% target. Wang et al. (2020) find that even after taking into account vaccine hesitancy, age distribution, and other country-specific factors there are about 3.7 billion adults (or about 50% of total world population) who are willing to be vaccinated. While this is encouraging and not too far from the 60% target, additional vaccination campaign effort may be needed to ensure sufficient number of eligible adults are willing to be vaccinated by March 2022 in order to reach the 60% target.

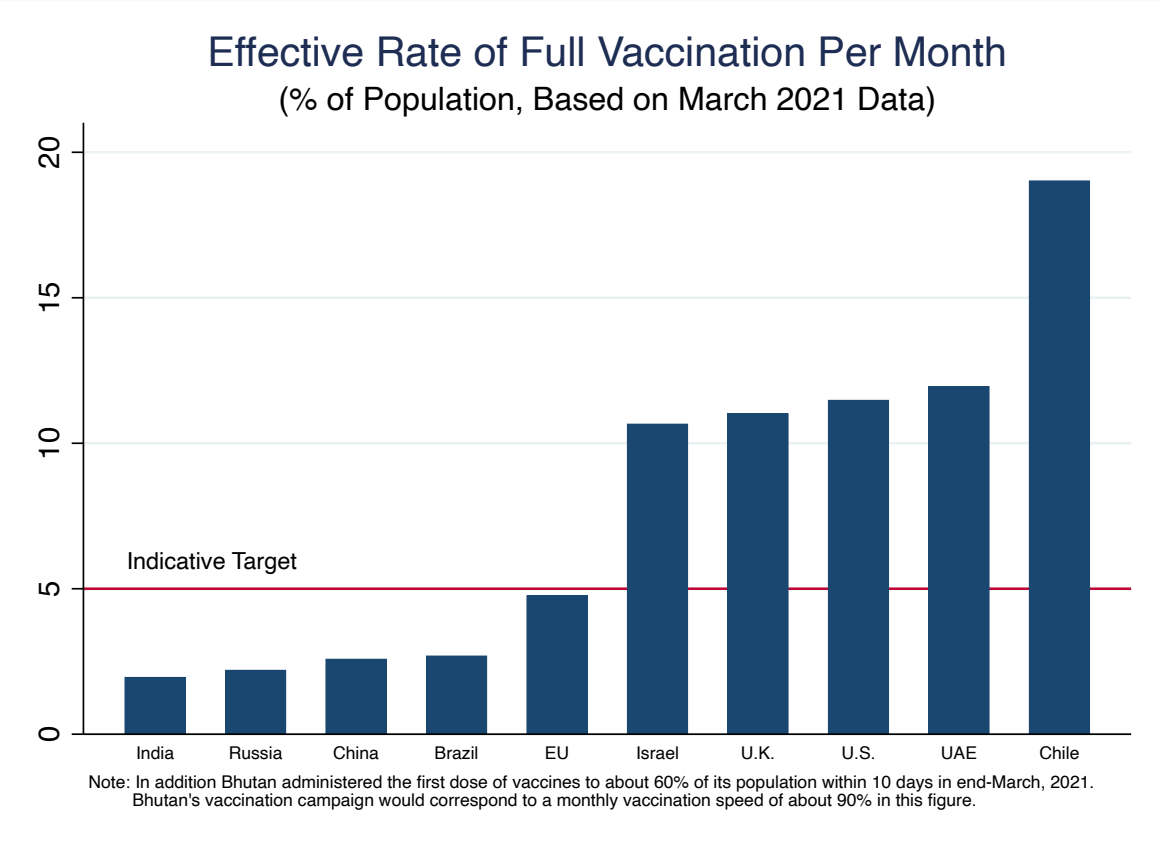
The goal of vaccinating 60% of the population may be particularly challenging for several countries in Africa, where the share of youth population is about 40%. Currently, though Pfizer and Moderna are testing their vaccines for children ages 12 and above, most COVID-19 vaccines are authorized for emergency use only for individuals age 16+, which implies that the share of adults that need to be vaccinated to reach herd immunity is likely much higher in Africa than rest of the world. One policy consideration in this context would be for regulatory authorities to evaluate the costs and benefits of lowering the minimum age of vaccines (from 16 years) by a few years to address this demographic challenge.

In terms of speed, vaccinating 60% of the world's population by March 2022 will require vaccinating approximately 5% of the population each month from April 2021 onwards. This monthly rate could serve as an indicative target for countries aspiring to achieve a minimum 60% coverage by March 2022.

As Figure 4 shows, among the group of countries with access to ample supply of vaccine doses, the 5% rate of monthly vaccination rate has been easily surpassed. However, the monthly vaccination rate so far remains relatively low in middle-income countries such as India and China.

Still, India, China, and Russia have supported the global fight to end the pandemic, by continuing exports of finished vaccines despite the relatively low vaccination rates domestically. For

Figure 4: Current Speed of SARS-Cov-2 Vaccination



Sources: Authors' calculations and Our World in Data.

Notes: The red line shows the indicative target rate of vaccination needed to achieve 60% population coverage by March 2022. Note that since steady state of vaccinations have not been reached yet (due to the 3-4 week gap in administering two vaccine doses to the same individual) in a number of countries, this calculation divides total doses by two to compute the number of courses delivered per month. This may under-state the actual vaccination speed in the steady state due to the usage of one-dose vaccines (e.g., J&J) and increased speed later after the initial phase of the vaccination campaign.

instance, as of end-March 2021, India had exported over half of its domestic production—either in the form of in-kind donations, deliveries on behalf of the COVAX through the SII, or commercial exports. From this perspective, the current slow speed of uptake of vaccines in India and China (given their large populations) may provide an ancillary benefit to other countries, as it allows for much-needed vaccine exports to other low- and middle-income countries. However, one challenge going forward will be to maintain continued exports of vaccines from India and China as their domestic vaccination rates pick up. Thus, ensuring that vaccine developers in these countries have continued access to key raw materials (as discussed above) will be critical.

In terms of policy actions to speed of vaccine delivery, countries waiting to receive vaccine deliveries could begin investing in information campaigns, setting up technology platforms, regulatory approvals, and training personnel for an efficient deployment of the vaccines. For instance, customizing the vaccine deployment based on local conditions (e.g., availability of vaccines in dense urban areas where risk of spread is high) is likely to be beneficial (Ives and Bozzuto, 2021). The logistics of deployment, especially in remote areas, will be important, and the WHO has already issued guidance on this issue.[23] High-income countries can also help with vaccine deployment by providing technical and financial assistance bases on lessons learned from their own COVID-19 vaccine campaigns, building on the experience that low-income countries already have with vaccinating against other diseases.

4.4 Addressing Mutation

Our estimate of the 45-60% vaccination threshold to achieve herd immunity is based on a baseline scenario that assumed limited further mutation of the virus. Downside scenarios of further mutation that gives rise to new variants with high re-infection rates and transmissability could increase the vaccination threshold required to achieve herd immunity, and is likely to affect our calculation in a number of ways (e.g., due to a lower E, a higher f, or a higher R_0.).

Already a number of variants have emerged that have raised concerns about increased transmissability, particularly the U.K. variant (B.1.1.7) that has grown rapidly, the South Africa variant (B.1.351) and the Brazilian Manaus variant (P.1). Further, prior infection may provide only modest protection against some of the new variants—particularly the South Africa and Manaus variants.[24]

[23] See `https://www.who.int/publications/i/item/who-2019-ncov-vaccine-deployment-logistics-2021-1`

[24] In Manaus, Brazil, a study of blood donors indicated that 76% of the population had been infected with SARS-

In addition, since mid-February we have seen a rapid rise in new cases in a number of LMICs—including India, Bangladesh, Brazil, Ethiopia, Pakistan among many others. Some have speculated that mutations may possibly explain this rapid rise, but more evidence is needed to assess the associated links. For instance, the new reported cases in India reached an all-time high of over 150,000 daily cases in early April 2021 (and rising), compared to a trough of 8,500 in the beginning of February 2021. A new lineage developing in India with the L452R and E484Q mutations coming together ('double mutant') has been suggested as a possible explanation for the rapid rise in cases. However, based on preliminary evidence, the government has thus far denied such a link.[25] Similarly, in early April it was reported that the South Africa variant had rapidly become dominant in Dhaka, Bangladesh, and could be linked to the rapid rise in cases in the country.[26]

Going forward, if some vaccines become less effective in protecting against new variants of the SARS-CoV-2, mutation may exacerbate the pressure on supply chains further, in at least two ways. First, the existing vaccine manufacturing capacity might need to be split towards each relevant strain or instead to prepare multivalent doses. Second, it takes time to adjust vaccines for new variants. While production of prior versions of the vaccine can likely continue during the majority of the adjustment process, it will take months until production capacity for vaccines effective against the new variant is brought online. In addition, more needs to be known about durability of immunity from vaccines and prior infection. If immunity is not durable, annual booster

CoV-2 by October, 2020. The estimated SARS-CoV-2 attack rate in Manaus would be above the theoretical herd immunity threshold (67%). In this context, the abrupt increase in the number of COVID-19 hospital admissions in Manaus during January, 2021 (3431 in Jan 1-19, 2021, vs 552 in Dec 1-19, 2020) has been a concerning development suggesting a resurgence in infection despite high seroprevalence (Sabino et al., 2021). Similarly, though the spread of the South Africa variant was contained thus far, it may be spreading based on recent reports. Moreover, recent clinical trial results suggest that prior infection of the original strain of COVID-19 offers only about a 50% protection against the South Africa strain. In particular, in its March 11 readout of the Phase 2b clinical trial results from South Africa, Novavax reported that: "In placebo recipients, at 90 days the illness rate was 7.9% in baseline seronegative individuals, with a rate of 4.4% in baseline seropositive participants." See https://ir.novavax.com/node/15661/pdf for further details.

[25]On March 24th, 2021 the health ministry said: "Though VOCs [variants of concern] and a new double mutant variant have been found in India, these have not been detected in numbers sufficient to either establish a direct relationship or explain the rapid increase in cases in some states." See `https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1707177`

[26]See `www.thedailystar.net/coronavirus-deadly-new-threat/news/south-african-variant-covid-19-dominant-bangladesh-icddrb-study-2073757`

shots may be required in order to achieve herd immunity.

If the current pattern of limited mutation were to continue for the rest of the year, given indications of sufficiently high efficacy of existing vaccines against the U.K. variant (Figure 1), the current portfolio of vaccines may be sufficient to end the pandemic by March 2022. However, the world remains exposed to a major downside risk of mutation that can significantly push back the time to herd immunity.[27] Even in such scenarios, a target of vaccinating 60% of every population worldwide lays the foundation to achieve herd immunity faster in those adverse scenarios.

Further, to insure against the threat of mutations it is important for vaccine developers and government agencies to start prioritizing development of booster or multivalent shots to protect against possible new variants; invest in strain sequencing and conduct trials to evaluate efficacy against new strains; have contingency plans in place to shift capacity from low efficacy candidates to more effective candidates if some vaccine prove less effective; over-invest in capacity to ensure sufficient vaccine doses will be available if booster doses are needed; and take steps to expedite vaccination speed to reduce chance of mutation.

5 Closing the Vaccine Pre-Purchase Gap in LMICs

Having identified the gap needed to achieve herd immunity by March 2022 under the baseline and having discussed the various challenges on the vaccine path to herd immunity, this section focuses on ways to close the 350 million course pre-purchase gap in AMC91 countries. While addressing the challenges described above will also be important, pre-purchasing enough vaccines to cover every country is the first step on the critical path to achieving worldwide herd immunity.[28]

First, the section discusses the current approaches taken of the international community to assist LMICs in pre-purchasing vaccines. Second, the section describes three options to close the

[27] For instance, as of end-March about 90% of the vaccines administered in India were made by AstraZeneca, which has reduced efficacy (of only about 10%) against the South Africa variant (Figure 1). If such variants are driving the rise in cases in countries like India (which have heavily relied on vaccines that may have reduced efficacy against the same variants), then there may be a significant setback in the global vaccination path to herd immunity. From this perspective an urgent priority should be to ensure an expedited review of vaccines such as Novavax that have shown efficacy of greater than 50% against the South Africa variant in clinical trials and is already licensed to be manufactured by the Serum Institute of India to supply both India and the COVAX Facility.

[28] The pre-purchase contracts should preferably include provisions that incentivize speed of delivery, for instance with penalties for delays in delivery beyond a certain date or through premiums for delivery on a priority basis.

350 million course pre-purchase gap in AMC91 countries.

5.1 Current Approaches to Assist LMICs in Procuring Vaccines

At market prices, vaccine procurement requires considerable expenditure. Two-dose vaccine courses reportedly cost between $6 for AstraZeneca/Oxford, $20 for Gamaleya, $60 for Sinovac, $62 for Moderna, and $140 for Sinopharm, the most expensive.[29] For a country with GDP per capita of $1,000, procuring a $40 per course vaccine would cost 4% of GDP, which could be prohibitively expensive.

To address this issue, the international community has taken two approaches to address countries' potential inability to pay for vaccine purchases. The first are subsidized or free vaccine doses through the COVAX AMC. The second are concessional loans through multilateral organizations such as the World Bank, which make it cheaper for countries to borrow for the purposes of vaccine procurement.

5.1.1 The COVAX AMC Facility

The COVAX AMC was created by Gavi in partnership with CEPI and the World Health Organization (WHO) with the aim of ensuring equitable access to vaccines by reducing the price that low- and middle-income countries have to pay. AMC-eligible countries have the option to purchase vaccines following a cost-sharing principle, which works as follows. First, donor-funded, fully-subsidized doses (i.e., free vaccines) are distributed across eligible countries until each country has enough to cover 20% of its population (or until donor resources are exhausted). Second, after 20% coverage is achieved, eligible countries are able to purchase vaccines for a price equal to 15% to 20% of cost (as per their cost sharing principle).[30]

Gavi estimates about $7 billion is needed to provide free vaccines for 20% of the population in the AMC91 countries (which exclude India). Given the $6.3 billion committed as of March 2021, there is a $700 million shortfall to meet its aspiration of 20% coverage. Beyond this shortfall, the COVAX AMC needs additional funding to provide vaccine coverage to LMICs above the 20%

[29] See: https://healthpolicy-watch.news/sputnik-v-vaccine-results-shore-up-prospects-of-elusive-vaccine-trio-but-chinese-results-remain-untested/

[30] See: www.gavi.org/sites/default/files/board/minutes/2020/15-dec/09%20-%20AMC%20Resource%20Mobilisation.pdf

threshold. As we show below, applying the cost sharing principle, $4 billion will be sufficient to achieve about 30% minimum coverage in each AMC91 country, and 14% coverage in India.

Donor coordination failure may partially explain the shortfall in funds available to the COVAX AMC. The potential for coordination failure arises when donors wait for other donors to pledge, leading to a low contribution equilibrium in which all countries contribute small amounts over many months, rather than making an upfront commitment.

To partially address this issue, the United States has promised to match other donors: "*The United States will [...] take a leadership role in galvanizing further global contributions to the COVAX by releasing an additional $2 billion through 2021 and 2022, of which the first $500 million will be made available when existing donor pledges are fulfilled and initial doses are delivered to AMC countries.*"[31]

The additional condition that funds are made available only once initial doses are delivered however restricts the ability of the COVAX to pre-purchase, as it waits for production capacity for existing orders to come online. The United States could help the COVAX procure vaccine courses more quickly by dropping the condition, while retaining the matching incentive.

5.1.2 Multilateral Development Bank Loans for Vaccine Purchases

Several multilateral development banks including the World Bank and Asian Development Bank have established loan facilities to address inability to borrow for the purpose of vaccine procurement and delivery. Loans under this facility offer concessional interest rates that are lower than what could be obtained on international capital markets. While these facilities make it possible for countries without enough tax revenue to buy vaccines at prevailing prices (including at subsidized prices via the COVAX AMC), these facilities do not themselves subsidize the price at which vaccines are purchased, and therefore do not address affordability issues directly.[32]

An additional consideration with these facilities are that regulators in LMICs are not allowed to determine on their own which vaccines are eligible for pre-purchase using development bank

[31] See: `www.whitehouse.gov/briefing-room/statements-releases/2021/02/18/fact-sheet-president-biden-to-take-action-on-global-health-through-support-of-covax-and-calling-for-health-security-financing`

[32] Some funds may be given by the World Bank as grants to very poor countries through the International Development Association (IDA), but the majority of funds in its vaccine lending window are given as credits that must be repaid.

financing. For instance, at the time of writing World Bank financing cannot be used to make pre-purchases of vaccines that do not satisfy stringent criteria:[33] either "*(i) approval by 3 Stringent Regulatory Authorities (SRAs) in three regions or (ii) WHO prequalification and approval by 1 SRA*" is required. The World Bank's criteria are more stringent than those of the Asian Development Bank, which requires only that the vaccine is authorized by a single SRA or the World Health Organization, not multiple organizations.[34] Requiring vaccines to be approved by certain regulators before they are pre-purchased limits the set of vaccines countries can purchase in the short-term with the intent to ensure product quality.

A challenge however is that SRAs include only certain Western countries plus Japan with government agencies deemed rigorous enough evaluate the efficacy of vaccines.[35] At present SRAs are prioritizing the approvals of vaccine candidates they intend to use for their own populations, and many have not initiated the emergency use authorization (EUA) process for all vaccine candidates that report high efficacy in Phase 3 trials (e.g. those of Novavax, or the Gamaleya Research Institute). This may explain the slow speed at which World Bank financing for vaccine purchases is being deployed. As of March 31, 2021, only $1.6 billion in projects had been approved even though an envelope of $12 billion was made available in October 2020.

One possible solution would be to broaden the list of regulatory authorities considered as SRA. The concept of an SRA was developed by the WHO and the Global Fund to Fight AIDS, Tuberculosis and Malaria to provide low- and middle-income countries with a straight-forward and transparent way to determine whether drugs are safe for use. Many LMICs fast-track approval of drugs once they are approved by an SRA. A broader list of SRAs with excess capacity to evaluate Phase 3 trial data could offer to fast-track authorization of any vaccine manufacturer that will share data, benefiting low- and middle-income countries.

[33]These are outlined in para. 42 the paper COVID-19: World Bank Group Support for Fair and Affordable Access to Vaccines by Developing Countries prepared by the by the World Bank Group for the virtual April 9, 2021 Development Committee Meeting. See: `https://www.devcommittee.org/sites/dc/files/download/Documents/2021-03/DC2021-0003%20Vaccines%20final.pdf`

[34]See `https://www.adb.org/sites/default/files/linked-documents/54171-003-sd-07.pdf`

[35]See `https://www.who.int/medicines/regulation/sras/en/`

5.2 Options to Close the Pre-Purchase Gap

As described above, existing donor funding of $6.3 billion is sufficient for the COVAX AMC to provide minimum vaccine coverage of about 16% in each AMC91 country, for free, in line with Gavi's own calculations. Here we show how an additional $4 billion is sufficient to guarantee about 30% minimum vaccination coverage in each AMC91 country. This will allow the COVAX AMC to procure 400 million courses, of which 80 million (20% by a Gavi rule described in Section 3) will be allocated to India, and 320 million will be allocated to the AMC91 countries—under existing rules. Thus, this amount would be sufficient to close much of the 350 million course pre-purchase gap to achieving 60% coverage of the population in each AMC91 country—assuming that the residual gap of 30 million will be met by existing deals and grants that are under negotiation.

To see how this calculation works, note that under the pricing and cost sharing assumptions currently used by the COVAX AMC, procuring 400 million courses would cost approximately $4 billion.[36] This amount is split into two components: (a) $0.7 billion to meet the intermediate goal of 20% coverage with free vaccines, and (b) additional $3.3 billion to achieve 28% minimum coverage under a cost-sharing arrangement wherein AMC-eligible countries pay 20% of the cost of vaccines rather than getting them for free.[37] See Appendix Table C.2 for details. Figure 5 shows population coverage and donor funding currently, under the aspiration of 20% population coverage in AMC91 countries, and under the proposed additional financing.

We now discuss three options to secure the additional $4 billion required to close the pre-purchase gap in AMC91 countries.

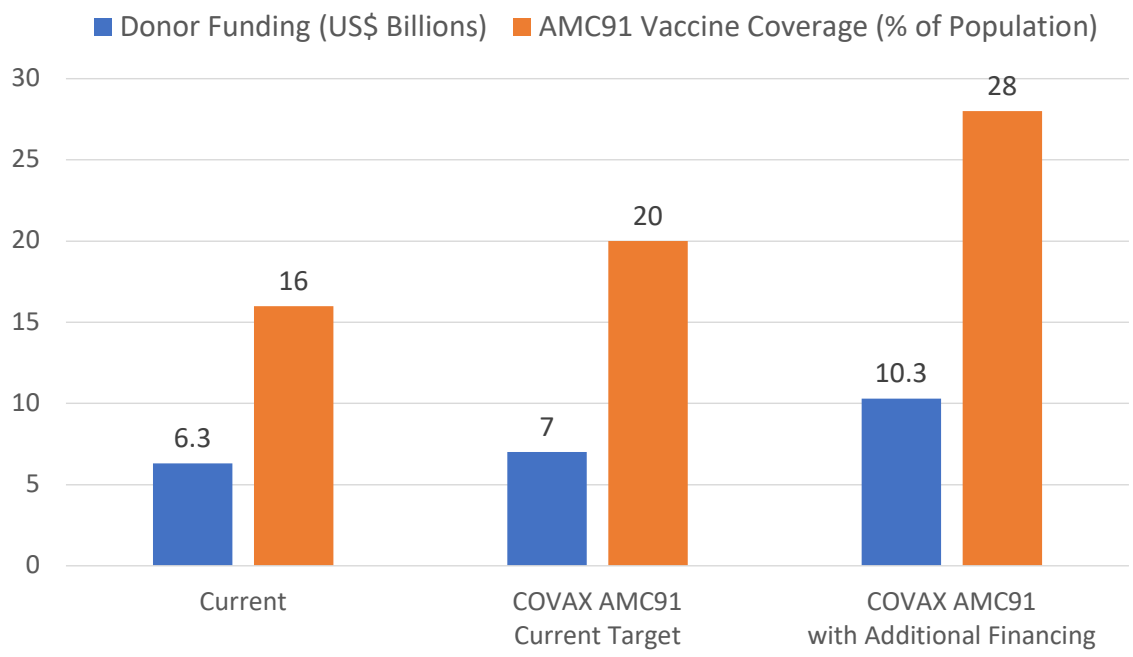
5.2.1 Option 1: Additional $4 Billion Donor Funds for the COVAX AMC

The simplest option to secure this $4 billion would be for donors to commit this funding immediately, coordinating through a multilateral body such as the G20. So far, the United States has conditionally committed $2 billion to the COVAX AMC, or half of the proposed funding requirement, so only $2 billion in additional commitments is required from other donors.

[36] Gavi estimates assume that a vaccine course will cost them between $10-14 (i.e. $5-7 per dose for a two-dose vaccine) with $12 per course being the mid-point of this range.

[37] Before countries achieve 20% coverage, the cost to the COVAX AMC is assumed to be $12 per course, and $0 to the purchasing country. Afterward 20% coverage is achieved, we apply a 20% cost sharing rule (in line with suggested cost-sharing rules of the AMC), which implies a cost of $9.6 to the AMC and $2.4 to the purchasing country. These pricing assumptions are in line with those used by Gavi.

Figure 5: The COVAX AMC under Different Financing Scenarios



Sources: Gavi, and Authors' calculations.

Notes: Donor costs with additional financing account for some cost sharing by AMC91 countries, in line with current plans for the COVAX AMC. The group of LMICs countries eligible to access the AMC includes 92 countries, and are referred to as AMC92, or as AMC91 + India. The Gavi Board takes a tailored approach to India as described in Section 3.

5.2.2 Option 2: Additional $4 Billion Donor Funds for the COVAX AMC financed by a Vaccine Bond

While the $4 billion required is a small amount of money relative to the size of high-income countries' economies, the fact that it has not been forthcoming already suggests the cost could still be perceived as too high, perhaps given domestic political constraints.

Here we describe a financing mechanism that provides $4 billion to the COVAX AMC, while reducing the requirement that donors provide upfront payment (Figure 6). The left panel depicts the status quo, in which countries have not yet made the $4 billion upfront commitment. Without cash up front, the COVAX and regional procurement initiatives do not make pre-purchases from vaccine producers, delaying investment in capacity and discovery of bottlenecks.

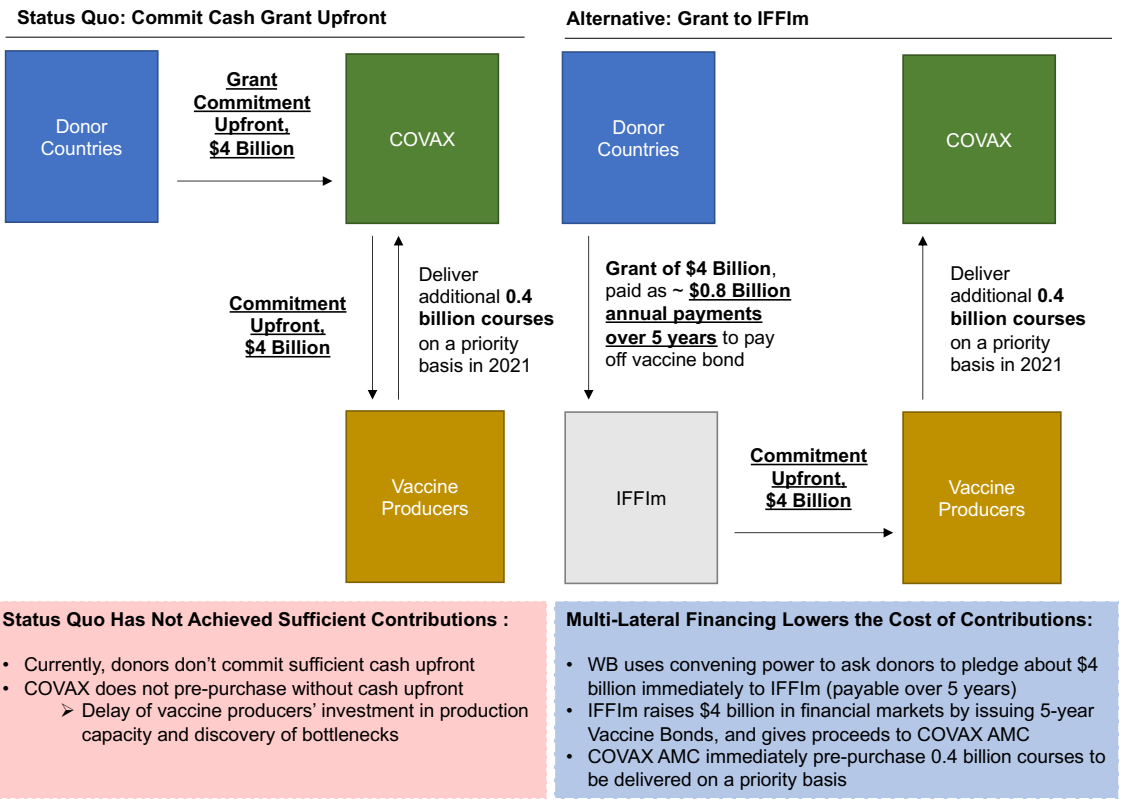
Instead, an alternative (depicted in Figure 6 right panel), is to use an existing multi-lateral financing institution—the International Finance Facility for Immunisation (IFFIm)—to meet the $4 billion shortfall. The IFFIm issues Vaccine Bonds, backed by long-term, legally binding pledges from donor governments, on international capital markets. The money raised by these bonds provides Gavi with funds upfront to deliver vaccines. IFFIm at present has 10 donors—Australia, Brazil, France, Italy, the Netherlands, Norway, South Africa, Spain, Sweden and the UK. Of these countries, Australia, Norway, Spain and the UK have already used money pledged to IFFIm to fund the COVAX AMC for COVID-19 vaccines.

In line with these actions, this option relies on simply scaling up these efforts and issue COVAX Vaccine Bonds worth $4 billion. This allows the donor countries to spread out their grants over 5 years (assuming a maturity of 5 years for the vaccine bonds) rather than paying the full amount upfront, which could be more politically palatable for domestic constituencies.[38] In effect, the IFFIm injects liquidity into the COVAX AMC up front, while recouping that investment from high income donor countries in small annual payments of $800 million over 5 years in the form of grants from the donor countries, plus interest payments. The COVAX AMC can in turn use the up front liquidity to fund pre-purchases of about 400 million courses on a priority-basis. Thus, this proposal ensures frontloading of resources, which essentially transforms long-term donor commitments into immediate cash for the COVAX AMC.

A consideration in using IFFIm to implement this financing mechanism is that IFFIm has only

[38]This may require slightly higher commitments than $4 billion since the IFFIm keeps a reserve buffer for risk mitigation.

Figure 6: Financing Options to Close the Pre-Purchase Gap



10 donors, excluding for example the United States. Using IFFIm to implement this financing mechanism may require broadening the set of donors that issue pledges to back repayment of the Vaccine Bonds. To initiate this process, the World Bank and other multi-lateral agencies could help by using their convening power to ask donors (e.g., the G20) to immediately pledge the $4 billion to IFFIm. Given the modest size of this pledge—especially when spread across 20 or more of the largest economies—and the goal of all countries to end the pandemic as soon as possible, this proposal may be feasible and within reach.

We focus on IFFIm to rely as much as possible on the existing institutional framework for funding vaccinations. However one could in principle imagine a way to execute this financing proposal through other multi-lateral institutions such as the World Bank, as such operations may be in line with their mandate for Global Public Goods (GPG) lending. In this context, Mazarei (2021) discusses other possible multi-lateral approaches to fund vaccine purchases.

5.2.3 Option 3: In-Kind Donation of Excess Vaccine Pre-Purchases

An additional option to fill the pre-purchase gap would be for countries to make in-kind donations of vaccine pre-purchases already made in excess of their populations. For instance, the United States has at least 275 million pre-purchased courses in excess of its entire population. This puts it in a unique position to help end the pandemic in 2021. If the United States gives a gift of 230 million courses, this could close two-thirds of the 350 million pre-purchase gap. Towards this option, Canada has committed to invest CAD 5 million in the development of a mechanism to equitably reallocate vaccine doses: through the COVAX, either by donation or exchange.[39]

However, high-income countries are likely to retain strategic reserves of the vaccine over 100% of the population. Even more challenging, United States procurement contracts in particular may be subject to a clause prohibiting vaccines from being used outside of the United States.[40] This clause in question is designed to ensure that manufacturers retain liability protection. It is not clear whether the clause can be abrogated, clearing the way to donate vaccines to other countries.

All this means that while in-kind donation may avoid additional donor expenditure, it will likely lead to slower delivery than a $4 billion grant upfront or financed by IFFIm. With these two options, the COVAX ensures a minimum coverage of about 30%, and in-kind donations and other initiatives are complementary, building on that minimum coverage.

6 Conclusion

Research and development of the COVID-19 vaccine has been an unprecedented success. As a result, a feasible path exists to reach worldwide herd immunity against COVID-19 through vaccination by March 2022 in which 60% of the population in each country is vaccinated by that date. As per vaccine developers' stated production capacity, there are sufficient supplies of effective vaccines to meet this target, and current and historical vaccination campaigns suggest it is feasible to deploy vaccines as fast as would be required.

However, achieving this goal requires first addressing a gap of 350 million vaccine courses in 91 low- and middle-income countries—due to the unequal distribution of pre-purchase orders across

[39] See https://www.who.int/news/item/18-12-2020-covax-announces-additional-deals-to-access-promising-covid-19-vaccine-candidates-plans-global-rollout-starting-q1-2021

[40] See https://www.vanityfair.com/news/2021/04/why-the-us-still-cant-donate-covid-19-vaccines-to-countries-in-need

countries.

The gap can be closed if the COVAX AMC sets a goal of ensuring a minimum vaccine coverage of about 30% in the AMC91 countries (vs. their current aspiration of at least 20%). Direct procurement and through regional initiatives like the African Union can provide the remaining supply allowing every country to achieve 60% vaccination coverage. Immediate donor funding of $4 billion from high-income countries will be sufficient to meet this goal. The donation can be secured in three ways: (i) direct grants to the COVAX AMC, (ii) direct grants to the COVAX AMC financed through IFFIm, or (iii) in-kind donations. Closing this gap is likely the highest-return investment the world can make to end the pandemic.

Our paper has focused on the urgent near-term challenge of ensuring vaccine coverage of at least 45-60% in all countries by 2021, which could end the acute phase of the pandemic, allowing potentially for a return to normal life worldwide. Looking beyond the near-term, the world will eventually need enough vaccines for all adults (and possibly children), and also prepare for future pandemics. Further, it is also possible that unexpected problems with the supply chain may arise, safety concerns about some vaccines may emerge, or that an escape variant means some capacity needs to be re-purposed. To insure against such scenarios and to prepare for future pandemics, further coordinated global action will be needed, including to expand global vaccine manufacturing capacity. In this context, demand-side action through additional donor financing for vaccine pre-purchases are complementary to supply-side actions—given the fragility of the vaccine supply chain and risk of mutations or future pandemics. Thus, we need additional donor financing for vaccine pre-purchases to activate existing capacity, while stepping up global surveillance of systemic supply chain risks and expanding overall vaccine manufacturing capacity.

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Appendix A: Country-Specific Considerations for the Vaccination Threshold

Country-specific considerations will change the calculation of the vaccination rate needed to reach herd immunity. Below we discuss five considerations and their implications.

First, the basic reproduction number (R_0) may differ by countries due to social, geographic, and environmental factors. Some low/middle income countries may have a lower R_0 than the range we consider (2.25 to 2.75) due to favorable population density and other environmental factors. This would make it easier to achieve the herd immunity goal.

Second, the allocation rules (e.g. allocation mechanisms under the COVAX), nature of contracts (e.g. the priority basis clauses in the contracts), and delays in scaling up manufacturing for specific vaccines (e.g. shared inputs in the supply chain being oriented towards mRNA vaccines vs. first/second generation vaccines) will affect whether a given country can get sufficient vaccines on a monthly basis to vaccinate 5% of their population in the first half of 2021. Delays on this front, will require a more back-loaded vaccination strategy requiring higher monthly vaccination rates in the second half of 2021 to reach herd immunity in these countries by the end of the year.

Third, certain low/middle income countries may have have a greater seroprevalence of SARS-CoV-2, thus having a higher share of infected with natural immunity (i.e. higher $Infected_0$), which would make it easier to achieve herd immunity.

Fourth, some countries may end up receiving relatively less effective vaccines (i.e. lower E), which can require them to have a greater vaccination coverage to reach herd immunity.

Finally, the percentage of population below 16 differs substantially across countries. In African countries, on average the share of young (i.e. below 16) is relatively high at about 40%, relative to the average in Asia or Latin American of about 25%, and the average in Europe and North America of about 17%. Currently, the vaccines are authorized/approved for use for individuals 16+, which implies that in these certain countries (especially in Africa) a much larger share of the adult population will need to be targeted for vaccination to reach herd immunity. So, while this consideration does not directly affect the vaccination threshold calculations, it does mean that the share of adults that need to be vaccinated to reach herd immunity is likely much higher in Africa than rest of the world. One policy consideration in this context would be for regulatory authorities to consider lowering the minimum age of vaccines (from 16 years) by a few years to address this

demographic challenge. Overall, our sensitivity analysis suggests that while these considerations affects the vaccination threshold, the indicative vaccination target of 60% still works well for a large share of countries in the world under the baseline.

Note, however, our calculations have assumed limited further mutations of the virus. Downside scenarios of further mutations that give rise to new variants with high re-infection rates and infectiousness will push back the time to herd immunity, and is likely to affect our calculation in a number of ways (i.e., through a lower E, a higher f, or a higher R_0.).

Appendix B: Vaccine supply gap in COVAX AMC-eligible countries

Country	Population	Vaccine courses pre-purchased directly	+	Vaccine courses pre-purchased through the African Union and the COVAX AMC	=	Total vaccine courses secured	Gap to fill In order to cover 60% of population
	Millions	*% of population*		*% of population*		*% of population*	*Millions*
Afghanistan	38.9	1		16		17	17.9
Algeria	43.9	0		53		53	4.4
Angola	32.9	0		53		53	3.3
Bangladesh	164.7	11		16		27	54.3
Benin	12.1	0		53		53	1.2
Bhutan	0.8	36		16		52	0.1
Bolivia	11.7	35		34		69	0.0
Burkina Faso	20.9	0		53		53	2.1
Burundi	11.9	0		53		53	1.2
Cabo Verde	0.6	0		53		53	0.1
Cambodia	16.7	0		16		16	7.7
Cameroon	26.5	0		53		53	2.7
Central African Republic	4.8	0		53		53	0.5
Chad	16.4	0		53		53	1.6
Comoros	0.9	0		53		53	0.1
Congo, Dem Rep	89.6	0		53		53	9.0
Congo, Rep	5.5	0		53		53	0.6
Cote d'Ivoire	26.4	0		53		53	2.6
Djibouti	1.0	0		53		53	0.1
Dominica	0.1	0		16		16	0.0
Egypt, Arab Rep	102.3	46		53		99	0.0
El Salvador	6.5	15		34		50	0.8
Eritrea	3.5	0		53		53	0.4
Eswatini	1.2	0		53		53	0.1
Ethiopia	115.0	0		53		53	11.5
Fiji	0.9	0		16		16	0.4
Gambia, The	2.4	0		53		53	0.2
Ghana	31.1	0		53		53	3.1
Grenada	0.1	0		16		16	0.1
Guinea	13.1	0		53		53	1.3
Guinea-Bissau	2.0	0		53		53	0.2
Guyana	0.8	5		34		40	0.2
Haiti	11.4	0		16		16	5.3
Honduras	9.9	7		34		42	2.0
Indonesia	273.5	47		16		63	0.0
Kenya	53.8	0		53		53	5.4
Kiribati	0.1	0		16		16	0.1
Korea, Dem People's Rep	25.8	0		16		16	12.0
Kosovo	1.9	0		16		16	0.9
Kyrgyz Republic	6.5	0		16		16	3.0
Lao PDR	7.3	0		16		16	3.4
Lesotho	2.1	0		53		53	0.2
Liberia	5.1	0		53		53	0.5
Madagascar	27.7	0		53		53	2.8
Malawi	19.1	0		53		53	1.9
Maldives	0.5	18		16		34	0.2
Mali	20.3	0		53		53	2.0
Marshall Islands	0.1	0		16		16	0.0
Mauritania	4.6	0		53		53	0.5
Micronesia, Fed Sts	0.1	0		16		16	0.1
Moldova	4.0	0		16		16	1.9
Mongolia	3.3	2		16		18	1.5
Morocco	36.9	89		53		142	0.0

Country	Population	Vaccine courses pre-purchased directly	+	Vaccine courses pre-purchased through the African Union and the COVAX AMC	=	Total vaccine courses secured	Gap to fill In order to cover 60% of population
	Millions	*% of population*		*% of population*		*% of population*	*Millions*
Mozambique	31.3	0		53		53	3.1
Myanmar	54.4	46		16		62	0.1
Nepal	29.1	65		16		81	0.0
Nicaragua	6.6	2		34		36	1.8
Niger	24.2	0		53		53	2.4
Nigeria	206.1	0		53		53	20.6
Pakistan	220.9	14		16		30	72.0
Papua New Guinea	8.9	0		16		16	4.2
Philippines	109.6	43		16		59	3.5
Rwanda	13.0	0		53		53	1.3
Samoa	0.2	0		16		16	0.1
Sao Tome and Principe	0.2	0		53		53	0.0
Senegal	16.7	1		53		53	1.6
Sierra Leone	8.0	0		53		53	0.8
Solomon Islands	0.7	0		16		16	0.3
Somalia	15.9	0		53		53	1.6
South Sudan	11.2	0		53		53	1.1
Sri Lanka	21.4	41		16		57	1.2
St Lucia	0.2	7		16		23	0.1
St Vincent and the Grenadines	0.1	18		16		34	0.0
Sudan	43.8	0		53		53	4.4
Syrian Arab Republic	17.5	0		16		16	8.1
Tajikistan	9.5	0		16		16	4.4
Tanzania	59.7	0		53		53	6.0
Timor-Leste	1.3	0		16		16	0.6
Togo	8.3	0		53		53	0.8
Tonga	0.1	0		16		16	0.0
Tunisia	11.8	11		53		63	0.0
Tuvalu	0.0	0		16		16	0.0
Uganda	45.7	0		53		53	4.6
Ukraine	43.7	27		16		43	8.8
Uzbekistan	33.5	1		16		17	15.1
Vanuatu	0.3	0		16		16	0.1
Vietnam	97.3	41		16		57	5.3
West Bank and Gaza	5.1	20		16		36	1.4
Yemen, Rep	29.8	0		16		16	13.9
Zambia	18.4	0		53		53	1.8
Zimbabwe	14.9	3		53		55	1.1
AMC91 TOTAL	**2538.8**						**345.7**
India	1380.0	15		8		23	510.6
AMC92 TOTAL	**3918.8**						**856.3**

Notes: Includes only pre-purchases of vaccines with reported efficacy greater than 50% in Phase 3 trials. Supplies based on orders by the African Union and the COVAX AMC, in addition to the Mexico-Argentina production deal for AstraZeneca, are distributed to eligible members in proportion to their population.

Appendix C: Additional Charts and Tables

Table C.1: Company-Reported Production Capacity

Vaccine candidates with company-reported efficacy greater than 50% in Phase 3 trials	Company- reported production capacity in 2021 *Courses, Bn*	-	Pre-purchases by high-income countries *Courses, Bn*	=	Remaining production capacity in 2021 *Courses, Bn*
i) Refrigerator Storage (i.e., at 2-8 degrees Celsius)					
Oxford-AstraZeneca	1.70		0.49		1.21
Novavax	1.00		0.10		0.90
Sinovac	1.00		0.06		0.94
Janssen (J&J)	1.00		0.37		0.63
CanSino Biologics	0.50		0.00		0.50
Sinopharm	0.50		0.00		0.50
Bharat Biotech	0.35		0.01		0.34
ii) Freezer Storage (i.e., below -15 degrees Celsius)					
Pfizer-BioNTech	1.00		0.56		0.44
Gamaleya Research Institute	0.50		0.03		0.47
Moderna	0.50		0.35		0.15
TOTAL	**8.05**		**2.00**		**6.05**
Total population	**7.79**				
High-income country population			**1.26**		
Low- and middle-income country population					**6.53**
Share of population covered	*103%*		*158%*		*93%*

Sources: Bharat Biotech, CanSino, Duke Global Health Innovation Center, UN Population Prospects, Wouters et al. (2021), World Bank Income Classifications.

Notes: The population of Russia, China and India is 2.97 billion, and these are classified as middle-income countries by the World Bank.

COVAX: CURRENT AND AFTER FINANCING PROPOSAL

	COVAX under Existing Financing	Additional Financing Proposal			COVAX after Financing Proposal
		Total =	*20% Coverage Goal (with no cost sharing)* +	*Additional Coverage (with cost sharing)*	
Donor Financing as of March 2021 ($US Billion)	**6.3**	**4.0**	1.4	2.6	**10.3**
Projected Price per Vaccine Course for COVAX ($US per course)	12		12	10	
Total Number of Vaccine Courses in COVAX AMC (Millions)	525	388	117	271	913
India	105	78	23	54	183
AMC91	420	310	93	217	730
Minimum India Coverage (% of Population)	8	6	2	4	14
Minimum AMC91 Coverage (% of Population Coverage)	16	12	4	8	28

Table C.2: COVAX AMC under Different Financing Scenarios

Source: Authors' calculations.

Notes: This table provides technical details of our financing proposal and how that would change the COVAX AMC vaccine coverage. Gavi policy for the COVAX AMC works under a cost-sharing principle. The cost-sharing will work as follows. First, fully subsidized donor-funded doses (i.e. free for the countries) will be distributed across AMC92 countries to reach the 20% coverage target (or until donor resources are exhausted). Then, the AMC92 countries will have the opportunity to allocate additional funds to receive further doses, fully paid for with these cost-sharing contributions. Countries will have an opportunity to complement and build on the essential foundation built by the early, donor funded doses if they wish to achieve a higher population coverage. In its own projections Gavi has envisioned a cost-sharing share of 15-20% in the additional vaccine purchases. For our proposal we us this cost-sharing rule with a value of 20%. The 20% cost-sharing value implies that a fully loaded vaccine course costing $12 (say the J&J vaccine) would cost $9.6 to the COVAX AMC and $2.4 to the purchasing country. At that price per course, an additional $3.3 billion will allow the COVAX AMC to close the procurement gap of 0.4 billion vaccine courses to reach global herd immunity–or equivalently ensure a vaccine coverage of about 30% of the AMC91 population.

Vaccine Efficacy in Preventing Clinical Covid-19 (%)

Vaccine	Generation	Type	Sample Size (#)	Overall Efficacy or Dominant Strain	B.1.1.7 Variant. (U.K.)	B.1.351 Variant (South Africa)
Novavax	2nd	Protein Subunit	15,000	96	86	55
Pfizer/BioNtech	3rd	mRNA	34,922	95		
Moderna	3rd	mRNA	28,207	94		
Gamaleya (Sputnik V)	2nd	Viral Vector	19,866	92		
Bharat Biotech (Covaxin)	3rd	mRNA	25,800	81		
Sinopharm	1st	Inactivated	NA	79		
AstraZeneca/Oxford	2nd	Viral Vector	32,449	76	74	10
Sinovac (CoronaVac)	1st	Inactivated	19,767	71		
J&J (Janssen)	2nd	Viral Vector	43,783	66		57
CanSino	2nd	Viral Vector	40,000	66		

Table C.3: Vaccine Efficacy in Preventing Clinical COVID-19

Sources and Notes: This table is based on Abdool Karim and de Oliveira (2021), which was published as a correspondence in the New England Journal of Medicine on March 24, 2021. The efficacy for Sinovac is shown as a range reflecting reported results from trial sites in Turkey (7,371 participants with efficacy of 91%) and Brazil (12,396 participants with efficacy of 51%). We have updated the table for the AstraZeneca/Oxford vaccine to reflect the high-level primary findings of their U.S. Phase III trial based on a sample of 32,499 trial participants released on March 25, 2021. In addition, when data was available, we have updated the table to reflect the efficacy of the vaccines against the different variants. This was only possible for Novavax, J&J, and AstraZeneca/Oxford, which had clinical trial data on efficacy against some of the variants. At present, there are no findings from clinical trials available about the efficacy of the vaccines against the Manaus variant (P.1).

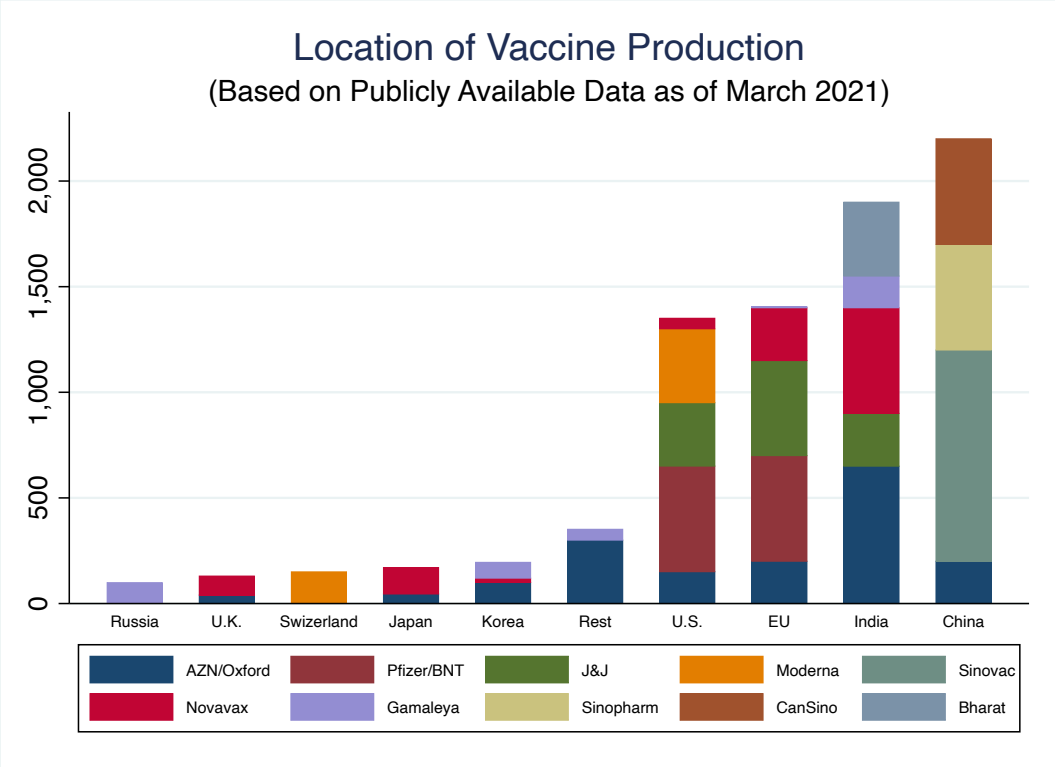

Figure C1: Location of COVID-19 Vaccine Production (millions of courses)

Source and Notes: Authors' calculations from various publicly-available sources based on data as of end-March 2021. The figure represents number of vaccine courses in millions by location of production facility.