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Supplementary Materials for

Market design to accelerate COVID-19 vaccine supply

Juan Camilo Castillo, Amrita Ahuja, Susan Athey, Arthur Baker, Eric Budish, Tasneem Chipty, Rachel Glennerster, Scott Duke Kominers, Michael Kremer, Greg Larson, Jean Lee, Canice Prendergast, Christopher M. Snyder, Alex Tabarrok, Brandon Joel Tan, Witold Więcek.

Correspondence to Michael Kremer, kremermr@uchicago.edu

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Materials and Methods

Appendix A: Estimating Pandemic Losses

As reported in Gopinath *(2),* the International Monetary Fund (IMF) estimated in April 2020 that "the cumulative output loss to the global economy across 2021 and 2022 from the pandemic crisis will be over $12 trillion" based on gross domestic product (GDP) losses alone. This translates into a monthly global GDP loss of $500 billion. Other sources and methods give larger costs. The Organization for Economic Cooperation and Development (OECD) estimates losses to global GDP of $4–$11 trillion over 2021 *(1),* with a central case of a $7 trillion loss over that one year, which translates into a $583 billion monthly GDP loss globally.

These estimates consider just short-run GDP losses. A more comprehensive measure includes health losses (both morbidity and mortality), education losses, declines in utility from restriction of ordinary activities, and longer-run harm to GDP resulting from business closures, long-term unemployment, and harm to human capital. Cutler and Summers' *(3)* estimate of more comprehensive losses from COVID-19, which includes health and longer-run economic harms, is $16 trillion in the United States alone over a 20-month pandemic. Assuming comprehensive harms are proportional to economic harms we derived from the IMF methodology, projecting the Cutler and Summers *(3)* estimate for the United States to the rest of the world yields an estimate of global losses of $70 trillion, or about $3.5 trillion per month. This projection may overestimate comprehensive harm in lower-income countries if the value of a statistical life increases more than proportionately with income. Other factors may lead it to be an underestimate. In high-income countries, access to finance might protect business from collapsing, school can be taught over Zoom, and the healthcare system remains able to provide at least basic services. The absence of this infrastructure in poorer countries would push the ratio of long-term effects to immediate GDP impacts to be higher for them than high-income countries.

Mulligan *(13)* calculates a total welfare loss for the United States of $7 trillion "per year of shutdown of nonessential businesses." This includes both market production and non-market production (such as leisure time and school time) but excludes health costs. Assuming that, without access to a vaccine, non-essential business would be shut down and that welfare loss is proportional to economic harms that we derived from the IMF methodology, projecting the Mulligan *(13)* results to the world yields an estimate of $31 trillion per year, or $2.6 trillion per month.

In our analysis, we compute the benefits from vaccination under two scenarios. In the first scenario, we treat economic harm from the pandemic as $500 billion per month, which is in line with the short-run GDP losses estimated by the IMF. In the second scenario, we use $1 trillion per month as a measure of the comprehensive harm of the pandemic, inclusive of other factors aside from GDP as described above. Losses in this second scenario are still conservative compared to estimates in Cutler and Summers *(3)* and Mulligan *(13)*, which speaks to the scale of the harm caused by the pandemic.

Appendix B: Vaccine Capacity Data

This appendix provides background behind the baseline numbers used in our analysis for vaccine capacity in place. Table S1 reviews capacity plans for 2021 for manufacturers with vaccine candidates that have been approved or are likely to be approved soon. For all candidates, we report a capacity range. The lower bound corresponds to the minimum capacity needed to fulfill the deals that have been signed and finalized between producers and buyers. The upper bound corresponds to announced production plans that we identified from published reports. Note that many announcements to date have turned out to be overoptimistic *(14,15)*. Indeed, even the lower bound exceeds the run-rate of vaccine production in January and February 2021.

Three candidates—AstraZeneca/Oxford, Pfizer/BioNTech, and Moderna—have been approved by stringent regulators according to the World Health Organization (WHO) definition *(16)*. The three candidates, which have started being used in mass vaccination, have a combined capacity for 2021 of between 2.05 and 3.00 billion courses. Two other candidates—Sputnik V and Sinovac—have started being used in mass vaccination without having applied for approval by a stringent regulator. These two candidates, with a combined capacity between 0.37 and 1.70 billion courses, only account for a small share of the courses in bilateral deals signed by high-income countries but account for a substantial share of the bilateral deals signed by middle-income countries *(17)*. Finally, two candidates—Janssen/Johnson & Johnson and Novavax—have recently completed phase-3 clinical trials and applied for approval from a stringent regulator. These candidates have a combined capacity of between 1.18 and 2.20 billion courses.

As these numbers show, there is substantial uncertainty in the number of vaccine courses that will be available in 2021. For that reason, we present our main results for a variety of scenarios with different production capacities. We focus on a central capacity of 3 billion courses, with half coming online in January 2021 and the remaining half coming online in April 2021. This scenario is optimistic relative to capacity run-rates during January and February 2021, which have been on the order of 0.5–0.7 billion courses on an annual basis *(18)* but lower than the best-case capacity scenarios indicated in the table. In general, the more capacity there is, and the faster it comes online, the larger are the gains from that capacity as indicated in Table 1, and the lower are the gains from adding additional capacity as analyzed in Table 2.

Appendix C: Assumptions Behind Calculation of Vaccination Benefits

In this section we explain how we compute vaccination benefits. Appendix E describes the sources of the data used as inputs to our model.

Within a country, we take vaccination benefit to be a concave function of the fraction of the population vaccinated. Although our specific quantitative results depend on the form assumed for this concave function, the qualitative nature of our results is not sensitive to alternative specifications. The functional form we use implies that 40%–60% of total country harm is alleviated by vaccinating the first quarter of the population, depending on demographics. All harm is relieved once 70% of the population has been vaccinated.

To provide further details, our analysis partitions countries into four income groups—high income, higher middle income, lower middle income, and low income—indexed by i. Countries in group i obtain vaccination benefits per unit of time that depend on the fraction $\lambda_i(t)$ of the group's population vaccinated by date t. Let h_i be the monthly harm caused by the pandemic to countries in group i. Global economic harm from the pandemic ($500 billion per month in the first column of results in Tables 1 and 2) is divided across the four income groups according to proportion of world GDP. The vaccination benefit for group i at time t equals the product of h_i and $f_i\,(\lambda_i(t))$, the fraction of the potential benefits that are obtained, satisfying $f_i\,(0) = 0$ (no benefit is obtained if no one is vaccinated) and $f_i\,(1) = 1$ (all economic harms are relieved if all are successfully immunized). Indeed, we will specify threshold λ''' such that all harms are relieved upon achieving that threshold coverage: i.e., $f_i\,(\lambda_i(t)) = 1$ for all $\lambda_i(t) \in [\lambda''', 1]$.

Countries will likely first distribute doses to high-priority populations (especially elderly) since this results in the greatest reduction in mortality for a limited vaccine supply, as can be shown by using simple epidemiological models *(19)*. However, other epidemiological models predict that the strategy of distributing to high-priority people first reduces infections roughly linearly in the proportion vaccinated until the threshold level of vaccination needed for herd immunity *(20)*. Furthermore, it is unknown whether reductions in economic losses from COVID-19 will more closely track reductions in mortality or reductions in infections and whether the efficacy in preventing severe infection translates into efficacy in preventing transmission. To accommodate this uncertainty, we specify $f_i(\cdot) = \rho\, f_i^{\,l}(\cdot) + (1-\rho) f_i^{\,d}(\cdot)$, a weighted mean of two functions: $f_i^{\,l}(\cdot)$, which is a simple linear function of $\lambda_i(t)$, and $f_i^{\,d}(\cdot)$, which is a nonlinear function capturing averted mortality. The weight ρ can take on any value in the unit interval. For our main analysis we set $\rho = 0.5$.

The function $f_i^{\,d}(\cdot)$ that captures averted mortality embeds the assumption that a country uses its initial vaccines for its high-priority population. This provides θ_i times the benefit of vaccinating a non-priority person, where $\theta_i \in [5,10]$ is a scale factor that is proportional to the per-capita GDP in country group i, varying between $\theta_{\text{low}} = 5$ for low-income countries and $\theta_{\text{high}} = 10$ for high-income countries. We set the value of $\theta_{\text{high}} = 10$ based on epidemiological models of mortality reduction, which suggest that over 80% of mortality reductions are obtained from vaccinating the first 20% of the population (see Figure 1D of *(20)*), consistent with empirical data on age-specific mortality rates in developed countries. The lower value $\theta_{\text{low}} = 5$ for countries in the low-income category reflects the fact that the gradient of mortality with respect to age is less steep in these countries by as much as a factor of three *(21)*. This fact alone would call for setting θ_{low} to about a third of θ_{high}, i.e., $\theta_{\text{low}} = 3.3$. However, the current situation in many low-income countries, with lower overall prevalence levels, may lead the optimal policy to reduce mortality to depart from first vaccinating elderly to first vaccinating working-age adults *(19)*. To reflect the possibility that moving from a policy that is optimal for high-income countries (targeting the elderly) to one generating bigger benefits for initial doses rolled out in low-income countries (targeting high transmission risk groups), we set $\theta_{\text{low}} = 5$.

The function $f_i^{\,d}(\cdot)$ has a kink at the threshold λ' at which all high-priority people have been vaccinated and the vaccine begins to be distributed to others. Define two higher kink points:

$\lambda'' = 0.4$, and $\lambda''' = 0.7$. At λ'', the slope of $f_i\,(\cdot)$ falls in half. Between λ'' and λ''', $f_i\,(\cdot)$ increases linearly at the lower rate until the threshold for herd immunity, λ''', is reached. All harm is averted at this threshold and higher levels of vaccination: i.e., $f_i\,(\lambda_i(t)) = 1$ for all $\lambda > \lambda'''$. Of course the slope of $f_i\,(\cdot)$equals zero above threshold λ'''.

We include two kink points λ'' and λ''' to account for uncertainty in the threshold for herd immunity. A simple epidemiological model puts the threshold at 60% when $R_0 = 2.5$. However, several factors suggest that the full benefit may be obtained above or below this theoretical threshold. Factors pushing the threshold down include the following: (a) pre-existing immunity or lower susceptibility in younger individuals, obviating a need for them to be vaccinated *(22);* (b) high levels of acquired immunity, especially in high-income countries; (c) heterogeneity in spread, leading herd immunity to be reached earlier than a simple epidemiological model with homogeneous agents would predict *(23).* Factors pushing the threshold up include the following: (a) countries may wish to vaccinate beyond the threshold for herd immunity to reduce the infection rate more rapidly in short run; (b) countries may err on the side of over-vaccinating their populations rather than risk reopening their economies too early; (c) vaccines are less than 100% effective; (d) vaccines may not be as effective in breaking transmission as in preventing severe disease; (e) wastage and other logistical frictions; (f) vaccines might be less effective against new COVID variants.

Figure S1 shows the benefits function $f_i(\cdot)$ for the four groups of countries. The four groups differ in the fraction of high-priority population and in parameter θ_i, which determines the relative slopes before and after the first kink (the fraction of high-priority population).

We assume vaccines are distributed according to a schedule matched to proportions in reported deals *(17)*. Initially, 1/3 of vaccines are distributed to high-income countries, 1/3 to higher-middle income countries, and 1/4 to lower-middle-income countries. The remaining 1/12 are delivered through the COVAX facility and are delivered across the world according to population. Once high-income countries vaccinate 70% of their population, capacity originally delivered to them is distributed evenly across the rest of the world by population. Later, once upper-middle-income countries vaccinate 70% of their population, the capacity dedicated to them is distributed evenly across lower-middle-income and low-income countries by population. Finally, low-income countries get all vaccines once lower-middle-income countries vaccinate 70% of their population.

This allocation rule determines the number of vaccines $v_i(t)$ that country group i receives by time t. Letting P_i denote the population summed across countries in group i, the fraction of the population the group has vaccinated at time t is $\lambda_i(t) = v_i(t) \,/\, P_i$. The total benefits from vaccination are then given by

$$\int_0^T \left[\sum_i h_i\, f_i\,(\lambda_i(t))\right] dt.$$

We only consider benefits for the first $T = 24$ months, i.e., until the end of 2022.

The model described thus far assumes a 100% effective vaccine. In the paper, the subsection "Utilizing Lower-efficacy Vaccines" includes an exercise that compares the benefits of vaccines with differing efficacies, requiring the model to be extended. We use the benefit function $f_i\,(\cdot)$ for upper-middle-income countries, with $\theta_{\text{upper middle}} = 5.94$. To account for different levels of efficacy, let $e_j \in (0,1)$ denote the efficacy of vaccine j. Letting g_i denote the modified benefit function with imperfect efficacy, we specify

$$g_i(\lambda_i, e_j) = \begin{cases} e_j f(\lambda_i) & \text{if } \lambda_i < \lambda''' \\ e_j[f(\lambda''') + (\lambda_i - \lambda''')f_i'(\lambda''')] & \text{if } \lambda_i \in [\lambda''', \lambda''''] \\ 1 & \text{if } \lambda_i > \lambda'''', \end{cases}$$

where

$$\lambda'''' = \lambda''' + \frac{1/e_j - f_i(\lambda''')}{f_i'(\lambda''')}$$

.

Efficacy is introduced as a factor scaling the original total-benefits function over its initial range, i.e., $g_i(\lambda_i, e_j) = e_j f(\lambda_i)$. Instead of flattening out at λ''', where a target vaccination level is met, g_i is assumed to continue to increase linearly until 100% of harm is avoided. This specification embodies the strategy of vaccinating more of the population with a less effective vaccine to achieve a target level of immunity rather than a target level of vaccination.

Figure S2 illustrates the exercise conducted in the text, in which we compare the benefits of obtaining a 70% effective vaccine immediately and obtaining a 95% effective vaccine with a two-month lag. The area below both curves is the same, which means both vaccines are equally beneficial.

Appendix D: Additional Scenarios

In this appendix we show results analogous to the tables in the main text but for alternative scenarios.

Table S2 computes the global value of vaccine capacity, analogous to Table 1, under alternative assumptions about the schedule with which vaccine production will ramp up. The first five rows assume that the full production capacity is available in January 2021. This scenario involves greater production than what has taken place as of February 16, 2021 *(18)*, so it should be interpreted as an upper bound on the benefits for capacity in place. The last five rows assume that only half of the capacity is available in January 2021, and the full capacity is not available until July 2021.

Comparing these numbers with Table 1, we see that being able to produce at full speed three months earlier has a value of at least \$0.5 trillion in terms of GDP alone and at least \$1 trillion in terms of comprehensive losses. This is true both when the ramp-up is brought forward from July to April and from April to January. If we focus on our baseline capacity, the value of getting a full capacity of 3 billion doses per year in January instead of April results increases benefits by \$1.3 trillion (after rounding). In all cases, being able to produce at full speed 3 months earlier speeds up the vaccination of 70% of the population by 1.5 months, both for high-income countries and the world.

Table S3 computes the global value of an additional 2 billion courses per year for the same scenarios as Table 2. In all cases the additional value of capacity is substantial. In the baseline scenario, the additional capacity increases benefits by \$1.6 trillion. However, additional capacity has diminishing marginal returns: all values are between 1.5 and 1.7 times the benefits of an additional billion courses per year. The speed-up to 70% vaccination shows a similar pattern: there is a substantial speed-up from additional vaccines, but there are diminishing marginal returns.

Table S4 computes the global value of vaccine capacity, as in Table 1, but under the assumption that the benefits of vaccination are linear within each country; that is, rather than assume that early doses go to high-priority people within each country and that vaccinating high-priority is particularly economically valuable, we assume all vaccinations are equally valuable. (Formally, this means setting $\rho = 0$ or, equivalently, $\theta = 1$ and $\lambda'' = \lambda''' = 0.7$). Table S5 computes the global value of an additional 1 billion courses per year, as in Table 2, but under this assumption of linear benefits.

Observe that the numbers in Table S4 are smaller than their counterparts in Table 1 in the main text: for example, the comprehensive value of 3 billion doses is $15.6 trillion instead of $17.4 trillion. This reflects that early doses have less value in the linear-benefits scenario. At the same time, the values in Table S5, for the value of additional doses, are considerably higher than their counterparts in Table 2. For example the value of 1 billion additional courses online in April 2021, against a baseline of 3 billion, is $1.412 trillion instead of $989 billion. This reflects that incremental doses suffer less from being "too late" to serve those in highest need.

Apart from these results, we performed several sensitivity analyses by computing the benefits from vaccination under many different scenarios. The main takeaways from our analysis still hold. Some of the alternative scenarios we looked at include the following, available from the authors upon request.

- We set the baseline capacity at 1 billion courses per year in January 2021 (which we believe is a likely scenario given the rate of production observed so far *(18)*). The capacity then ramps up to values between 2 and 5 billion courses per year at different times between March and July 2021.

- Instead of aiming to vaccinate 70% of their population, countries aim for a somewhat higher or lower proportion (e.g., reflecting different potential thresholds for herd immunity).

- The benefit function of individual countries takes a more or less concave shape, ranging from $\rho = 0$ (as in tables S4 and S5) to $\rho = 1$ (see Appendix C).

Appendix E: Data Sources for Model Parameters

Our model from Appendix C uses as inputs the population, GDP, and fraction of high-risk population (defined as people over 65 years old and healthcare workers) for the countries in each income group. We use World Bank data for the population, population over 65, GDP, and income group of every country *(24–26)*. We use WHO data for the number of healthcare workers by country *(27)*.

Fig. S1.
Share (f_i) of benefits obtained by countries in income group i as a function of the fraction of the population vaccinated (λ_i)

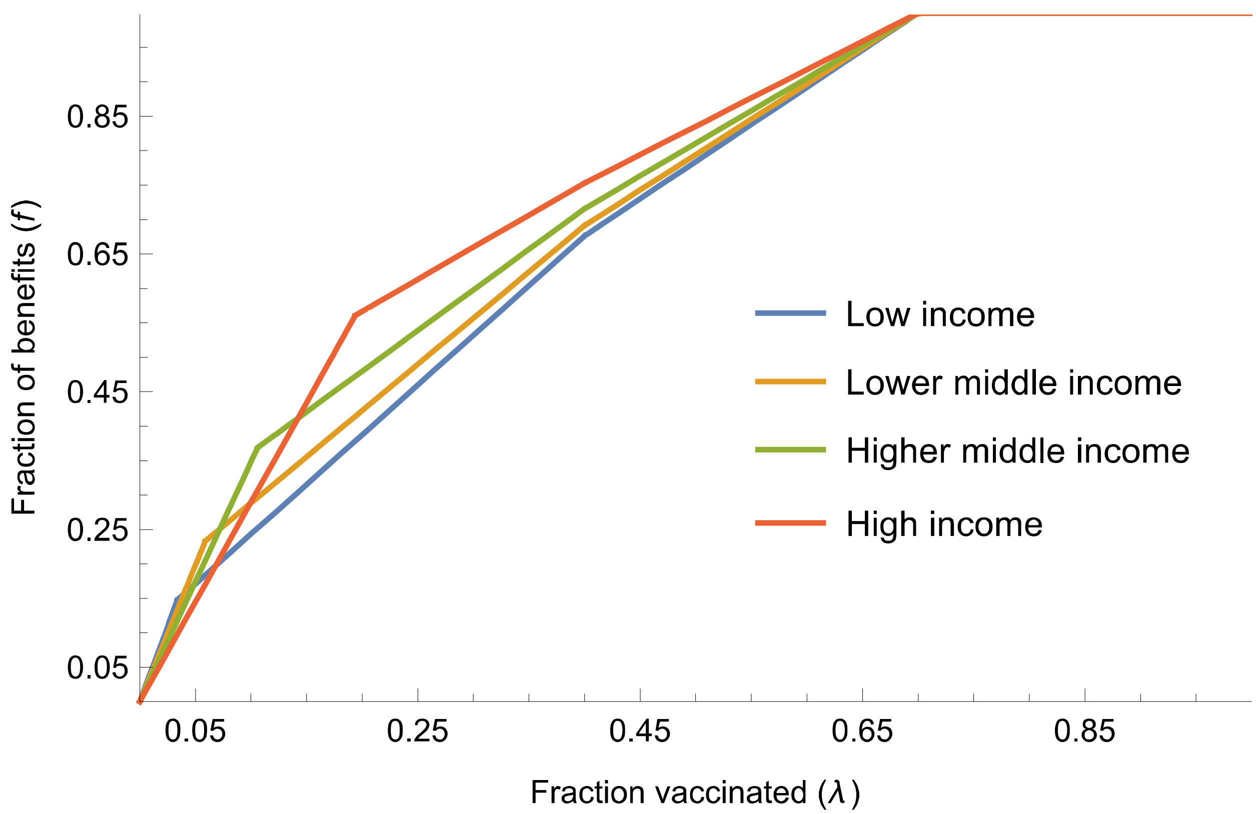

Fig. S2.

Fraction of benefits obtained over time with a 70% effective vaccine that is available now and with a 95% effective vaccine that is available with a two-month lag.

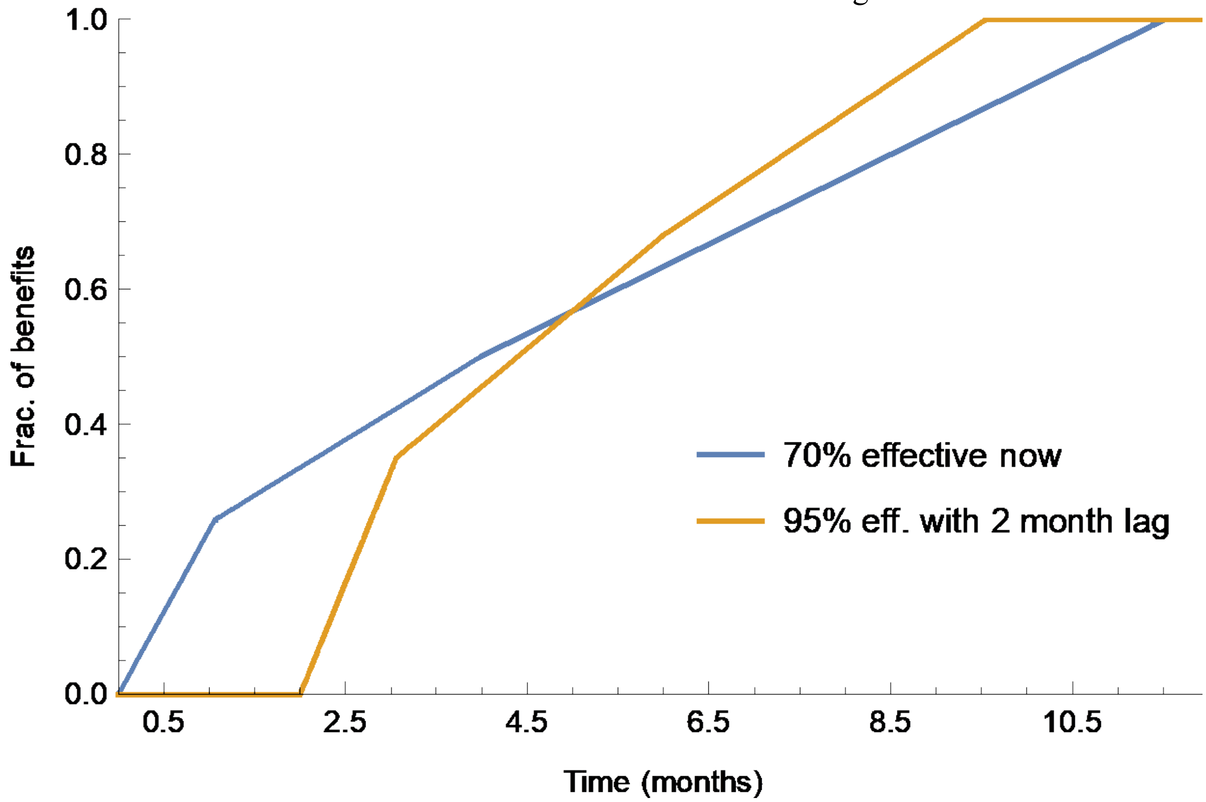

Table S1. Vaccine Production Capacity for 2021

Producer	Production over 2021 (billion courses)		Sources
	Lower bound	Upper bound	
Group 1: Started mass vaccination after authorization from a stringent regulator			
Oxford/AstraZeneca	1.15	1.50	*(17)*, *(28)*
Pfizer/BioNTech	0.60	1.00	*(17)*, *(29)*
Moderna	0.30	0.50	*(17)*, *(30)*
Group total	2.05	3.00	
Group 2: Started mass vaccination but have not applied for authorization from a stringent regulator			
Sputnik V	0.17	1.20	*(17)*, *(31)*
Sinovac	0.20	0.50	*(17)*, *(32)*
Group total	0.37	1.70	
Group 3: Awaiting authorization from a stringent regulator			
Janssen/Johnson & Johnson	1.00	1.20	*(17)*, *(33)*
Novavax	0.18	1.00	*(17)*, *(34)*
Group total	1.18	2.20	

Notes: Capacities are measured in courses. All candidates plan courses involving two full doses except for Janssen/Johnson & Johnson, which is planning to offer one-dose courses. AstraZeneca plans a two-dose course, but one of those could be a half dose, raising the possibility that their capacity is up to 33% higher. The lower endpoint refers to the total capacity from deals signed and finalized for 2021; note that much of this production is not currently running as of February 2021, so even this level is not guaranteed to materialize. The upper endpoint refers to the highest announced capacity plan that we could identify. Stringent regulatory authorities are defined by WHO *(17)*. Data sources *(17,28–34)*.

Table S2: Global Value of Vaccine Capacity with Alternative Ramp-up Schedules

Scenario					
Ramp-up completed by	Global capacity (billion courses)	Global benefit (trillion $)		Time to 70% vaccination (months)	
		GDP alone	Comprehensive	High-income countries	World
Jan. 2021	1	5.8	11.5	30.0	64.5
"	2	8.1	16.3	15.0	32.2
"	3	9.4	18.8	10.0	21.5
"	4	10.0	20.1	7.5	16.1
"	5	10.4	20.9	6.0	12.9
Jul. 2021	1	4.8	9.6	33.0	67.5
"	2	7.0	14.0	18.0	35.2
"	3	8.3	16.5	13.0	24.5
"	4	9.0	18.0	10.5	19.1
"	5	9.5	19.0	9.0	15.9

Notes: This table is identical to Table 1 in the main text but with alternative ramp-up schedules. Table 1 in the main text assumes that half of global capacity is available in January 2021 and the full capacity is available in April 2021. In this table, the first five rows assume that the full capacity is available in January 2021. The last five rows assume that half of the global capacity is available in January 2021 and the full capacity is available in July 2021. All other model details are identical to those in the main text.

Table S3: Global Value of Additional 2 Billion Annual Courses of Capacity

Scenario					
Additional capacity online	Baseline capacity (billion courses)	Additional global benefit (billion $)		Speed-up to 70% vaccination (months)	
		GDP alone	Comprehensive	High-Income countries	World
Apr. 2021	2	1,514	3,028	6.7	15.4
"	3	792	1,583	3.4	8.0
"	4	450	901	2.0	4.9
Jul. 2021	2	1,014	2,027	5.2	13.9
"	3	461	922	2.2	6.8
"	4	215	429	1.0	3.9

Notes: This table is identical to Table 2 in the main text but considers the value of an additional two billion courses of capacity per year, whereas Table 2 in the main text considers an additional one billion courses of capacity per year. All other model details are identical to those in the main text.

Table S4: Global Value of Vaccine Capacity under Linear Benefit Function.

Global capacity (billion courses)	Global benefit (trillion $)		Time to 70% vaccination (months)	
	GDP alone	Comprehensive	High-income countries	World
1	3.3	6.7	31.5	66.0
2	6.2	12.3	16.5	33.7
3	7.8	15.6	11.5	23.0
4	8.7	17.3	9.0	17.6
5	9.2	18.4	7.5	14.4

Notes: This table is identical to Table 1 in the main text but with a linear benefit function, whereas the analysis in the main text assumes that early doses have higher value than later doses within a country. All other model details are identical to those in the main text.

Table S5: Value of Additional 1 Billion Annual Courses of Capacity under Linear Benefit Function.

Scenario		Additional global benefit (billion $)		Speed-up to 70% vaccination (months)	
Additional capacity online	Baseline capacity (billion courses)	GDP alone	Comprehensive	High-income countries	World
Apr. 2021	2	1,358	2,717	4.5	10.2
"	3	706	1,412	2.1	5.0
"	4	391	782	1.2	2.9
Jul. 2021	2	937	1,875	3.5	9.2
"	3	420	839	1.4	4.3
"	4	186	372	0.6	2.3

Notes: This table is identical to Table 2 in the main text but with a linear benefit function, whereas the analysis in the main text assumes that early doses have higher value than later doses within a country. All other model details are identical to those in the main text.

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