Accelerating a Covid-19 vaccine

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Abstract

The World Bank estimates that Covid-19 will reduce global output by $500 bn. per month over 2020-2021. Accelerating vaccine availability would thus create huge benefits that likely far outweigh the private benefits to vaccine producers. Policy could speed vaccine development by (a) investing in capacity in parallel with testing and (b) investing in production capacity at larger scales than would be privately optimal. In this paper, we develop a model to quantify the benefits of accelerating Covid-19 vaccine delivery, and then analyze optimal vaccine investment strategy. We determine individual countries' optimal portfolios—the number of vaccine candidates and the capacity investment for each candidate. We then compute the optimal centralized investment for a global social planner and characterize financial incentives that would induce induce firms to follow that optimal plan. We find that costs can be held down by including a substantial component of "push" funding up-front, rather than relying primarily on "pull" commitments to purchase successful vaccines. We then examine incentives for countries to participate in a centralized program, and find that distributing vaccines by population may induce high-income countries to opt out. Finally, we analyze mechanisms to allocate vaccines across countries subject to incentive compatibility and equity constraints.

Introduction

The World Bank estimates that the Covid-19 crisis will reduce global economic output by $12 trillion over 2020-2021. Accelerating access to an effective vaccine by just one month would thus yield hundreds of billions in benefits—before accounting for health improvements.

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On a standard vaccine development timeline, companies wait until the end of clinical trials before installing capacity, typically taking 3-4 years from the beginning of trials until large-scale production. The massive economic benefits from a Covid-19 vaccine instead justify investing in manufacturing capacity in parallel with trials. However, private firms have insufficient incentives to make such investments: First, vaccination has significant health and economic externalities, so market prices are unlikely to reflect vaccines' full social value. Second, it is not in firms' interest to install capacity at commercial scale before they know their vaccines are safe and effective. Third, market forces mean that firms are not incentivized to install as much capacity as would be socially optimal – they would rather produce smaller quantities in lower-capacity factories, sell the initial output at high prices in high-income countries, and then, after long delays, sell at lower prices in developing countries.

We analyze the problem faced by individual countries or groups of countries considering investments to accelerate the creation of manufacturing capacity for Covid-19 vaccines. First we analyze price-taking countries. We propose a model to quantify the benefits of accelerating vaccine access, then use the model to determine individual countries' optimal portfolios—the number of vaccine candidates and the capacity investment for each candidate. Next, we analyze the optimal portfolio for a global social planner. We design financial incentives to induce firms to follow the optimal plan and analyze under what circumstances it is possible to incentivize countries to participate in such a program. Finally, national policymakers might have preferences for different vaccines. We analyze how to allocate the different vaccines in a way that is transparent and equitable that is also incentive compatible.

Because our quantitative results depend on many unknown parameters, such as success probabilities for vaccine candidates, we present results for a range of parameter values. We highlight qualitative findings that remain robust to changes in the parameters, finding that, perhaps surprisingly, many of the recommendations for country investment decisions remain close to optimal under a wide range of parameters.

Expanding manufacturing capacity for vaccines

The standard vaccine development timeline takes 3-4 years, starting with clinical trials that typically take 1-2 years. Once a vaccine is found to be safe and effective, firms install and certify manufacturing plants. With Covid-19, there are immense benefits from accelerating this process by installing and certifying manufacturing capacity during trials, so that production can begin as soon as safety and efficacy are determined.

However, installing capacity is a time-consuming and costly process. It requires many inputs that are in limited supply (e.g. bioreactors, adjuvants, glass vials), and the factories themselves must go through a lengthy regulatory process before production can start. The cost of expanding capacity will increase if existing capacity needs to be repurposed or capacity from other sectors needs to be converted. We thus model short-run supply as being relatively inelastic, in the sense that above a certain level, the marginal cost rises sharply to reflect constraints on expanding capacity. .

Given that fewer than 20% of vaccine candidates are successful, firms will require large incentives to expand capacity. The Covid-19 pandemic will also require unprecedented capacity, an especially large problem since most installed capacity will not be useful—although some of the unsuccessful capacity might be repurposed to produce a similar vaccine after some delay.

Optimal portfolio for a price-taking country

Our model assumes that countries pay upfront to finance the installation of capacity. That gives them the option to buy a certain number of courses per month for three months at the same price they would be able to buy them later without investing in capacity. We specify contracts in terms of courses per month and not simply in terms of courses because faster delivery is both critical for countries and costly for companies. Country i buys manufacturing capacity v_{ij} from each of $j = 1, .., J$ candidates at a market price p per vaccine course per month. The country's portfolio is denoted $v_i = (v_{i1}, v_{i2}, \ldots)$.

We model the total expected health and economic benefits country i obtains if it invests in portfolio vi, which we denote by $B_i(v_i)$, in two steps (see Appendix B for full details). First, given the country's portfolio v_i, we model the distribution of total effective capacity: the number of safe and effective vaccine courses the portfolio delivers per month, based on the sum of capacity bought from candidates that successfully develop a safe and effective vaccine. We set up a model of candidate success that allows for the possibility of correlated success or failure:candidates can fail because of a general problem that precludes the success of all candidates, or because of problems by platform, subcategory, or individual candidate. We estimate the likelihood that different vaccine candidates succeed or fail based on their current trial stages; platform-level success estimates depend on whether the platform has already been licensed for human use.

Given our estimates of the effective capacity implied by a country's portfolio, we estimate health and economic benefits as follows: We compute the monthly harm caused by Covid-19 based on country-specific estimates of GDP losses from the World Bank and from mortality figures. We assume that the upfront capacity investment leads to vaccine distribution $T = 3$ months before the time the country would receive vaccines with no early investment. At every point in time, benefits—the fraction of harm that is mitigated by vaccination—depend on the share of the population that has been vaccinated. Our model assumes that the vaccine is first given to the elderly and health workers, which mitigates more harm than vaccinating other populations. We aggregate monthly benefits over time to obtain the total benefit as a function of effective capacity. Finally, we discount benefits by 50% to account for the possibility of imperfect vaccines or the possibility that a treatment or other mitigation strategy will alleviate Covid-19 before a vaccine is available.

Since country i purchases capacity at price p, it solves the following problem:

$$\max_{v_i} B_i(v_i) - p \sum_j v_{ij} \tag{1}$$

The key force at play when choosing a portfolio is the fact that benefits have diminishing returns, both in the number of candidates and the capacity per candidate. In an optimally designed portfolio, the first candidate a country chooses should be the most promising; additional candidates may be redundant in scenarios in which the first candidate succeeds. Doubling capacity reduces the expected time to vaccinate a given population by one half; doubling it again is twice as expensive (because the capacity is now twice as big) but yields only half the overall acceleration benefit (because the time has already been halved once).

Country	GDP per Capita ($)	Population (mn.)	Mean Number of Candidates	Total Capacity (mn. courses / mth)	Expected Effective Capacity (mn. courses / mth)	Total Capacity (courses / mth per cap.)	Expected Effective Capacity (mn. courses / mth per cap.)	Expected Effective Capacity / Total Capacity	Expected Benefits (bn. $)	Total Cost (bn. $)
Panel A: Price = $4										
World	10.72	7523.14	33.21	5258.89	573.17	0.70	0.08	0.11	1449.26	252.43
High Income	42.73	1185.11	50.00	2769.59	269.23	2.34	0.23	0.10	1075.46	132.94
LMIC	4.74	6338.03	24.75	2489.31	303.94	0.39	0.05	0.12	373.79	119.49
IDA	1.08	1064.07	8.88	70.88	11.15	0.07	0.01	0.16	6.50	3.40
IBRD	5.59	5328.06	37.65	2493.35	300.48	0.47	0.06	0.12	384.65	119.68
North America	58.41	363.76	50.00	981.00	94.48	2.70	0.26	0.10	423.11	47.09
East Asia & Pacific	10.27	2278.78	31.74	1529.79	175.07	0.67	0.08	0.11	305.52	73.43
Europe & Central Asia	23.53	917.65	43.38	1463.49	146.54	1.59	0.16	0.10	499.02	70.25
Latin America & Caribbean	9.42	641.29	44.67	636.47	68.43	0.99	0.11	0.11	128.37	30.55
Middle East & North Africa	7.55	432.01	38.90	269.42	30.75	0.62	0.07	0.11	56.83	12.93
Sub-Saharan Africa	1.60	1074.85	12.30	121.03	16.91	0.11	0.02	0.14	13.36	5.81
Panel B: Price = $10										
World	10.72	7523.14	26.83	2558.79	299.69	0.34	0.04	0.12	1246.87	307.06
High Income	42.73	1185.11	48.85	1617.12	165.31	1.36	0.14	0.10	987.87	194.05
LMIC	4.74	6338.03	15.74	941.67	134.38	0.15	0.02	0.14	259.00	113.00
IDA	1.08	1064.07	4.96	13.61	2.19	0.01	0.00	0.16	2.48	1.63
IBRD	5.59	5328.06	26.32	968.42	136.56	0.18	0.03	0.14	270.80	116.21
North America	58.41	363.76	50.00	581.90	58.33	1.60	0.16	0.10	392.77	69.83
East Asia & Pacific	10.27	2278.78	25.82	646.10	87.11	0.28	0.04	0.13	240.01	77.53
Europe & Central Asia	23.53	917.65	38.32	814.82	86.96	0.89	0.09	0.11	449.60	97.78
Latin America & Caribbean	9.42	641.29	35.03	310.13	38.19	0.48	0.06	0.12	103.54	37.22
Middle East & North Africa	7.55	432.01	31.60	120.29	15.41	0.28	0.04	0.13	45.90	14.44
Sub-Saharan Africa	1.60	1074.85	7.40	31.02	4.69	0.03	0.00	0.15	7.06	3.72
Panel C: Price = $20										
World	10.72	7523.14	25.49	1406.26	172.81	0.19	0.02	0.12	1052.67	337.50
High Income	42.73	1185.11	47.38	1014.17	111.34	0.86	0.09	0.11	884.20	243.40
LMIC	4.74	6338.03	14.46	392.09	61.47	0.06	0.01	0.16	168.47	94.10
IDA	1.08	1064.07	4.49	1.36	0.18	0.00	0.00	0.13	0.54	0.33
IBRD	5.59	5328.06	24.65	409.71	64.05	0.08	0.01	0.16	178.86	98.33
North America	58.41	363.76	50.00	376.00	39.97	1.03	0.11	0.11	357.70	90.24
East Asia & Pacific	10.27	2278.78	24.91	332.03	45.66	0.15	0.02	0.14	186.48	79.69
Europe & Central Asia	23.53	917.65	37.70	483.24	56.12	0.53	0.06	0.12	394.03	115.98
Latin America & Caribbean	9.42	641.29	30.90	143.56	21.47	0.22	0.03	0.15	75.48	34.45
Middle East & North Africa	7.55	432.01	31.40	58.72	7.63	0.14	0.02	0.13	34.35	14.09
Sub-Saharan Africa	1.60	1074.85	6.60	9.92	1.53	0.01	0.00	0.15	3.81	2.38

Table 1: Optimal portfolios

Note: This table shows characteristics of the optimal portfolios for all the countries of the world and for specific group of countries. LMIC are low- and middle-income countries; IDA and IBRD are the World Bank's lending groups for the world's poorest countries and middle-income countries, respectively.

In Table 1, we show the optimal vaccine portfolio for each country over a range of prices. Overall, it is optimal to invest in large, diversified portfolios. This is especially true for high-income countries (HICs); a higher GDP per capita implies larger benefits from vaccination. Middle-income countries (MICs) should also make substantial investments. Even some low-income countries (LICs) should invest, given the high returns to the initial doses from the first few candidates. Countries may be reluctant or unable to spend the large sums required for these programs, but the benefits of having at least some early doses are huge: spending half the ideal budget produces about 75% of the benefits.

International equilibrium

Countries' optimal portfolio varies with prices, but it is unclear what the price will be. By considering an international market for early manufacturing capacity, we can assess various possible scenarios. First, we compute a global demand curve which, for a given price, gives the total capacity demanded by all countries across all candidates when choosing their optimal portfolios. Second, we compute a global supply curve. We assume an elasticity of 1/3, given the challenges of expanding capacity.

In our model, the market clearing price is around $45 per course / year. At this price, low cost suppliers would get large profits and lower-middle-income countries (LMICs) would be priced out of the market. In practice, deals have been signed sequentially, and the prices observed to date are substantially lower than $45. This may be because producers are currently utilizing only readily available manufacturing capacity, or because ethical or political constraints that prevent profiteering. In either case, we would assume each firm is selling at cost until they run out of available capacity, at which point the marginal costs of expanding capacity will drive up prices over time. These market dynamics would generate a race among buyers to lock in the low prices. The first movers—HICs, most likely— would be able to buy at lower prices, whereas countries that wait will face higher prices. While the installation of additional capacity will be available for the rest of the world in the long run, it is difficult to predict whether adequate capacity can be installed to accelerate global vaccination before the marginal costs of expanding capacity begin to increase rapidly.

Global social planning problem

We analyze how countries could cooperate in a centralized program, which could offer a variety of benefits. A centralized program can use its bargaining power to hold down prices. It can provide access to a diversified portfolio for countries lacking resources to make their own bilateral deals. It might allow for an insurance mechanism that directs vaccines to the most severe outbreaks at the time vaccines become available. It may also limit the HIC demand to hold down prices.

We consider a global social planner that chooses a portfolio $v^G = (v_1^G, v_2^G, \ldots)$, similar to how individual countries choose their portfolio but with two differences (see full details in Appendix C). First, benefits for the social planner $B^G(v^G)$ are a function that aggregates individual countries' benefits. This depends on how vaccines are allocated across countries; we consider allocation proportional to population size and other allocation rules that favor countries that contribute more to the program. The second difference is that, instead of paying the same price to each firm, the social

planner sets up a procurement scheme that firms may decide to participate in. That procurement scheme uses the centralized program's bargaining power to, lower the overall costs of the program.

The global social planner's objective function involves social costs $C^G(v^G)$, which account for the cost of installing production capacity—the integral under the marginal cost curve—and for the fact that 30% of unsuccessful capacity can be repurposed. The social planner solves the following problem:

$$\max_{v^G} B^G(v^G) - C^G(v^G) \tag{2}$$

In order to obtain some portfolio v^G, the social planner's procurement scheme satisfies firms' participation constraint: revenue must be greater than cost plus a premium, which compensates for investment risk.

We consider schemes that involve two types of funding. Push funding agrees to pay a fraction of manufacturing costs to every candidate. Pull funding commits to purchase effective vaccines at certain prices as long as they satisfy certain quality standards and are delivered quickly. The planner pays a higher price for the first doses to optimize dynamic efficiency (speed) and a lower price for subsequent doses to optimize static efficiency (allocation).

Pull funding is more expensive than push funding. At a given price, candidates with a high probability of success have higher expected earnings, producing higher rents for firms. However, some pull funding is desirable to incentivize speed, and to weed out manufacturers with private information that their candidate is unlikely to succeed. As a heuristic, we consider a procurement scheme with push funding set to 85% of costs and calculate the amount of pull funding needed to induce the marginal firm to satisfy its participation constraint.

If vaccines are distributed efficiently, the global social planner invests in a program with total social cost of $90 bn and social benefit of $938 bn. The total program cost is $115 bn, of which an expected $77 bn is pull funding.

International incentives

We consider whether it is in the best interest of countries (or country coalitions) to participate in a centralized program, or whether they would be better off developing their own programs. While HICs, in particular, have incentives to create their own program to avoid sharing capacity with LICs, they could lose access to vaccines produced by the centralized program.

We compare five scenarios for every coalition (Table 2). The first three are global programs funded in proportion to GDP under different allocation rules: in proportion to population size, with priority to vulnerable populations, or in proportion to contributions. The fourth is a program under autarchy, in which participants don't have access to vaccines produced outside the coalition. Fifth, a coalition program with free trade where coalitions can contract with any outside vaccine producer. We assume countries are selfish: they only care about vaccinating their populations and do not account for economic spillover effects.

Our model suggests that HICs can obtain greater welfare benefits from making their own bilateral deals than from participating in a centralized program that allocates in proportion to population size or with priority to vulnerable populations. However, their welfare with allocation in proportion to contributions is almost as good as with their own program. Thus, global programs seeking to

	Welfare under different scenarios (bn $)					
	World program				Own program	
	By population	Priority	By contribution	Full barg. power	Autarky	Free trade
US	114.2	179.4	280.4	286.2	266.2	303.6
EU	109.2	179.2	222.3	226.5	221.6	260.5
All high-income	313.2	500.7	708.1	722.8	748.6	797.4
BRIC	103	103	61.7	67.2	78.2	90.3
Rest	105.4	82.2	48.9	52.5	41.3	—

Table 2: Welfare for different coalitions under different scenarios

Note: This table shows the welfare (benefit minus cost) for different country coalitions under different scenarios. The first four columns show the outcome of the optimal worldwide program using different allocation rules. The last two columns represent autarky, in which coalitions can only use vaccines produced within their borders. BRIC refers to Brazil, Russia, India, and China, which are the only countries that have vaccine production capability and are not high-income countries.

redistribute vaccines to LICs might end up hurting those countries if low HIC investment results in a more modest program.

Allocation

This section will include work in progress on the allocation of vaccines across countries. We will try to tackle two main points:

- If multiple vaccines are approved, allocation of different vaccines to countries could be determined by an exchange mechanism based on country preferences. While trading could occur bilaterally between countries, it would be complicated and untransparent. A better approach would be to establish a centralized exchange where countries input their preferences on candidates, speed vs quantity of doses, and price.
- While countries will make their own decisions on how to distribute and prioritize their allocated doses to their population, it may make sense to use weighted lotteries, which balance ethical and policy priorities

Conclusions

Given the enormous benefits of accelerating vaccine availability, it is worth investing in vaccine capacity in parallel with testing. Our work quantifies the benefit of accelerating access to vaccines, and provides several recommendations for the design of investments in early manufacturing capacity:

1. The optimal policy involves large-scale investment in a diversified pool of candidates.
2. In a decentralized market, it is in the interest of high- and middle-income countries, and even some low-income countries, to make substantial investments in capacity.

3. A global program could be desirable because of lower prices, easy diversification, and insurance.

4. Centralized programs should involve up-front payments to lower costs, as well as a pay-for-success component to incentivize speed and success.

5. Aiming for too much redistribution might not satisfy high-income countries' participation constraints and could result in programs that are not ambitious enough.

Appendix A Background

A.1 The vaccine landscape

We use WHO data[1] on all the efforts around the world to develop a Covid-19 vaccine. The data includes the company or companies involved, the vaccine platform, further details about the type of vaccine, and the current stage of clinical trials.

There are several types of vaccines. The most important characteristic is the platform, which might be one of the traditional technologies used in vaccines for a long time (live-attenuated virus, inactivated virus, and viral vector) or one among some newer technologies (protein subunits, DNA, and RNA). Within each platform there are also several differences between vaccines that might determine their feasibility.

Research and development takes places in four stages. The first one are pre-clinical trials, in which vaccines are not tested yet in humans. The next stages are phases 1-3 of clinical trials, each one of which tests the vaccine in a larger, more diverse population. The main two goals of the whole process is to determine whether the vaccine is safe and whether it creates an immune response.

A.2 Vaccine manufacturing capacity

Installing vaccine manufacturing plants is a much more complicated process than the installation of plants to produce typical drugs, which only need to produce a simple molecule. Vaccines, instead, typically need to produce a virus, which has been attenuated or deactivated, or is a non-human virus that is simply used to carry genetic material. Newer technologies like protein subunit, RNA, and DNA avoid producing an entire virus, but they require high technology equipment.

Moving from the small-scale manufacturing to the large scale currently needed requires changing the manufacturing process. That creates challenges and delays, since every step in the new manufacturing process must be tested and certified before the use of the new vaccine in humans.

Appendix B Optimal portfolio for a price-taking country

Country i can buy early production capacity from several vaccine candidates (which we index by j) at a price p per course / month. The country chooses a portfolio of vaccines $v_i = (v_{i1}, v_{i2}, \ldots)$, where v_{ij} denotes how much production capacity it buys from candidate j. Our goal is to find the optimal portfolio for a given country.

[1] https://www.who.int/publications/m/item/draft-landscape-of-covid-19-candidate-vaccines

B.1 Benefits

We model the benefits for the country in two steps. First, we model the distribution of total effective capacity V given portfolio v_i. By total effective capacity we mean the number of safe and effective vaccine courses that the portfolio delivers. This is the ex-post quantity measured after clinical trials finish, at which point it is clear which candidates are successful. Second, we translate the effective capacity V into health and economic benefits from vaccination.

Effective capacity The effective capacity for country i depends, first of all, on the success of individual candidates. Let y_j be a dummy variable for whether candidate j is successful. This candidate belongs to a platform l and subcategory s. It is successful in developing a vaccine if all the following events happen:

- no overall problem prevents feasibility of a vaccine (denoted by $x_o = 1$, with probability q_o),
- no problem shows up at the platform level ($x_p = 1$, with probability q_l),
- no problem shows up at the subcategory level ($x_s = 1$, with probability q_s), and
- no problem shows up at the individual vaccine level ($x_j = 1$, with probability q_j).

The dummy for candidate j is then given by $y_j = x_o x_p x_s x_j$, and the probability of success for candidate j is $\Pr(y_j = 1) = q_o q_l q_s q_j$.

This model implicitly introduces correlations between different candidates. There is an overall correlation across all vaccines through x_o (overall vaccine feasibility). There is a stronger correlation between vaccines that belong to the same platform—through x_l—and an even stronger correlation between candidates in the same subcategory—through x_s.

If country i chooses some portfolio v_i, the total effective capacity it obtains is the sum of the installed capacities over all successful candidates:

$$V_i = \sum_j y_j v_{ij} \tag{3}$$

This is a random variable whose value depends on the success or failure of candidates with non-zero capacity investment.

The distribution of effective capacity depends on the probabilities q_o, q_l, q_s, and q_j. We assume q_s is the same for all candidates. We set probabilities for platforms q_l according to the track record of past vaccines. Viral vector or live attenuated vaccines, for instance, have had widespread use in the past, so we assign a higher probability to them. DNA and RNA vaccines have never been approved for human use, so we assign lower probabilities. We assign probabilities for individual candidates q_j depending on the current phase of trials the candidate is in. Candidates in phase 3 clinical trials have a higher probability than candidates in phase 1 or in pre-clinical trials.

Benefits as a function of capacity The larger the effective capacity, the larger the total benefits. We partition the benefits into the economic and health benefits, taking into account country-specific characteristics: GDP losses and mortality due to Covid-19, as well as the fraction of high-risk

population—i.e., the elderly and healthcare workers. We discount benefits for the fact that an effective treatment can be developed, that non-pharmaceutical interventions may stop the pandemic or that herd immunity might be achieved before any capacity becomes available.

Benefits vary as a function of the number of people who are vaccinated at any point in time. Let $\lambda_i(t)$ be the fraction of the population of country i that has been vaccinated at a time t. Suppose the country does not obtain any vaccines from early capacity. We assume that in that scenario no people are vaccinated before $t = \tau$, the time when vaccine production starts if there is no early capacity investment. At time T, country i starts receiving V_{NP} vaccines per month. The fraction of its population that is vaccinated is:

$$\lambda_{NP}(t) = \begin{cases} 0 & \text{if } t \leq t_0 \\ \frac{V_{NP}}{P}(t - t_0) & \text{if } t > t_0 \end{cases} \tag{4}$$

If, instead, country i obtains an effective capacity of V, it starts vaccinating V people per month at time $t = \tau - T$. T measures how much earlier is capacity available with early capacity investment. At time τ capacity ramps up to V_{NP}. Thus, the fraction of its population that is vaccinated is

$$\lambda(t; V) = \begin{cases} 0 & \text{if } t \leq t_0 - T \\ \frac{V}{P}(t - t_0 + T) & \text{if } t_0 - T < t \leq t_0 \\ \frac{V}{P}T + \frac{V_{NP}}{P}(t - t_0) & \text{if } t > t_0 - T \end{cases} \tag{5}$$

We now translate the fraction vaccinated $\lambda(t)$ into benefits per unit time. Let H_i be the monthly health and economic harm due to Covid-19 for country i. We assume that the health and economic benefits of vaccination at time t, relative to no vaccination, are given by $\delta H_i f_i(\lambda_i(t))$. $\delta \in (0, 1)$ is a factor by which we discount benefits because of the possibility that an effective treatment is developed, or that effective contact tracing avoids an important share of the benefits. The function $f_i(\cdot)$ measures the fraction of harm that is avoided. For simplicity, we assume that it is a continuous, piecewise linear function with two changepoints or "kinks". The first kink is at λ_i^{HR}, the fraction of high-risk population. Up to that point, vaccinating every additional person brings a large benefit, so f_i increases more quickly than after that point. The second kink is at $\lambda_i(t) = \lambda_i^{\text{herd}}$: at that point herd immunity is reached and there is no more harm from Covid-19.

The net benefit from effective capacity V is given by

$$b_i(V) = \delta H_i \int f_i(\lambda(t; V))\, dt - \delta H_i \int f_i(\lambda_{NP}(t))\, dt. \tag{6}$$

The left integral is the sum over time of the monthly benefits when effective capacity is V. The right integral does the same computation when there is no early investment.

The expected benefit given some portfolio v_i is the expectation of $b_i(V)$, integrating over the distribution of V induced by investment v_i:

$$B_i(v_i) = \mathbb{E}[b_i(V)|v_i] \tag{7}$$

B.2 Cost

Since the country can purchase capacity at price p per course/year, the cost of portfolio v_i is

$$C(v_i; p) = p \sum_j v_{ij} \tag{8}$$

This implicitly assumes that the countries will vaccinate the same fraction of the population with and without early capacity, and that the cost of each individual vaccine is the same in both cases. This emphasizes the point that the benefit of the portfolio is not vaccinating itself – rather, it is vaccinating *early*.

B.3 The problem for a price-taking country

Country i solves the following problem:

$$\max_{v_i} B_i(v_i) - p \sum_j v_{ij}. \tag{9}$$

We also solve for the optimal portfolio given a limited budget Y:

$$\max_{vi} B_i(v_i) - p \sum_j v_{ij} \quad \text{s.t.} \quad p \sum_j v_{ij} \leq Y. \tag{10}$$

B.4 International equilibrium with price-taking countries

Let $v_i^*(p) = \max_{vi} B_i(v_i) - p \sum_j v_{ij}$ be country i's optimal portfolio when price is p. The global demand for vaccine production capacity is

$$D(p) = \sum_{ij} v_{ij}^*(p) \tag{11}$$

To simplify our assumptions, we consider a simple global supply curve, rather than per platform, or per candidate.[2] It arises from a non-decreasing marginal cost curve $c(\bar{v})$, where $\bar{v}$ is the total early production capacity that is installed across the whole world for all vaccine candidates.

The global supply curve is given by the inverse marginal cost curve,

$$S(p) = c^{-1}(p). \tag{12}$$

The equilibrium price p^* is such that supply equals demand:

$$S(p^*) = D(p^*). \tag{13}$$

B.4.1 Alternative equilibria

There are at reasons why the world is unlikely to result in equilibrium (13). First of all, this is a market that will only clear once, which means there is no mechanism for price discovery. Equilibrium behavior would require firms to predict correctly how large demand will be in order to charge marginal costs. Additionally, there are political pressures that might induce firms to price lower than it is optimal, and countries might have limited budgets and demand less than is optimal. For that reason, we consider the following alternative scenarios:

[2] This is likely to be a strong assumption. In reality, some inputs are common (bioreactors, glass vials), some elements are specific to the vaccine, and repurposing takes time (at least 3 months).

- Countries bargain successively with firms. Firms start charging higher prices as they move up the marginal cost curve. Thus, first movers, who are likely to be the highest income countries, will be able to buy at lower prices.
- Because of political pressures, firms are willing to sell capacity at average cost plus a 20% markup. The idea is that countries understand costs, take-it-or-leave-it offer for production capacity at (average) cost.
- Not all countries are able to obtain funds to buy optimal quantity. We assume that demand is 75% lower than optimal. Though countries should demand more at that price, not all will. We can still compute what a country should do at that price. Interpretation: The advice to a given country about capacity purchases at the expected equilibrium price. Note that in practice, countries are moving up the supply curve contract by contract.

Appendix C The Global Social Planning Problem

C.1 A centralized program for procuring and distributing vaccine

We now turn to the problem of analyzing how countries could cooperate in a centralized program. Similar to an individual country's problem, we consider a global social planner that chooses a portfolio $v^G = (v_1^G, v_2^G, \ldots)$, and we want to determine what the optimal portfolio looks like. There are two main differences relative to an individual country's problem. First, benefits for the social planner are a function that depends on the way vaccines are distributed across countries. Second, instead of being a price taker, the social planner is able to set up a procurement scheme that firms may decide to participate in.

Benefits We consider two different benefit functions, which correspond to different allocation rules. In the first case, vaccines are distributed across countries in proportion to population. In other words, if the social planner chooses a portfolio $(v_1^G, v_2^G, \ldots)$, vaccines are distributed to country i at rates $\left(s_i v_1^G, s_i v_2^G, \ldots\right)$, where s_i is the share of global population in country i. Under this scenario, the global benefit function is given by

$$B^{G,P}(v^G) = \sum_i B_i(s_i v^G). \tag{14}$$

In the second scenario, we consider the efficient allocation, which maximizes the sum of benefits. This allocation rule greatly favors high income countries. The global benefit function under this scenario is

$$B^{G,E}(v^G) = \max \sum_i B_i(v_i) \quad \text{s.t.} \quad \sum_i v_i = v^G, \quad v_i \geq 0. \tag{15}$$

Cost The global social planner minimizes the social cost function, which is composed of two parts. The first one is simply the integral of the marginal cost curve. The second part accounts for the fact that there is fungibility in production. Let $\bar{v}^G = \sum_j v_j^G$ be the total production capacity investment. Suppose that the effective capacity turns out to be V. We assume that a fraction ϕ of the unsuccessful capacity $\bar{v} - V$ can be repurposed for a gain $\underline{c}$ per course/year. The social cost is therefore

$$C^G(v^G) = \int_0^{\bar{v}^G} c(x)\, dx - \phi \underline{c} \left(\bar{v}^G - \mathbb{E}[V|v^G] \right). \tag{16}$$

Optimal program Given some allocation rule $A \in \{P, E\}$, the social planner solves the following problem:

$$\max_{v^G} B^{G,A}(v^G) - C^G(v^G). \tag{17}$$

C.2 Designing incentives for firms

In order to obtain some portfolio v^G, the social planner must set up a procurement scheme that creates enough incentives for all the firms that are part of the portfolio to participate. We consider schemes that involve two types of funding. *Push funding* means paying for a fraction of the cost of installing manufacturing capacity. *Pull funding* is the commitment to purchase effective vaccines at certain prices as long as they satisfy certain quality standards and are delivered quickly enough—in other words, an advanced market commitment. The sum of push and pull funding must be larger than candidates' costs in order to incentivize participation.

Vaccine candidates incur two types of costs. First, they must pay the price of installing manufacturing capacity. We assume these costs are shared across candidates in proportion to their manufacturing capacity. In other words, the manufacturing capacity cost for candidate j is $C_i(v^G) = \frac{v_j^G}{\bar{v}^G} C^G(v^G)$. Second, they pay production costs. We assume there is a constant marginal cost of production c^{prod} per vaccine course.

Push funding takes a simple form: The planner agrees to pay a fraction μ of manufacturing costs to every candidate. For pull funding, the planner agrees to pay p^{high} for the first x^{high} vaccines that are delivered within T months after production is planned to start (i.e., before deliveries would start without early manufacturing capacity). It also agrees to pay p^{low} for the next x^{low} vaccines that are delivered, as long as they are delivered within T months after production is planned to start.

If total effective capacity is V, net revenue across all firms is given by

$$\pi(V) = \begin{cases} p^{\text{high}} VT - c^{\text{prod}} VT & \text{if } VT \leq x^{\text{high}} \\ p^{\text{high}} x^{\text{high}} + p^{\text{high}}(VT - x^{\text{high}}) - c^{\text{prod}} VT & \text{if } x^{\text{high}} < VT \leq x^{\text{high}} + x^{\text{low}} \\ p^{\text{high}} x^{\text{high}} + p^{\text{high}} x^{\text{low}} - c^{\text{prod}}(x^{\text{high}} + x^{\text{low}}) & \text{if } VT > x^{\text{high}} + x^{\text{low}} \end{cases} \tag{18}$$

We assume that net revenue is distributed in proportion to manufacturing capacity among all firms that are successful. Thus, firm j's net revenue is given by $\pi_j = \frac{v_j^G}{\bar{v}_j^G} \pi(V)$.

Incentive compatibility Firm j is willing to participate if the following participation constraint is satisfied:

$$\mathbb{E}[\pi_j | v^G] \geq \gamma(1 - \mu) C_i(v^G) \tag{19}$$

The left hand side is the firm's expected net revenue. It must be greater than the investment the firm needs to make upfront, $(1 - \mu)C_i(v^G)$, scaled up by a risk premium $\gamma > 1$ that compensates for the fact that accepting this deal is a risky investment for the firm, since its probability of success is low.

A *procurement scheme* $(v^G, \phi, p^{\text{high}}, p^{\text{low}}, x^{\text{high}}, x^{\text{low}})$ is a portfolio as well as the parameters that describe how push and pull funding takes place. We say that it is *incentive compatible* if the participation constraint is satisfied for every firm.

In practice, we fix ϕ, p^{low}, x^{high}, and x^{low}, and for a set of portfolios we find the lowest price p^{high} such that the procurement scheme is incentive compatible.

C.3 Calculating Required Pull Funding

What is the proposed price structure? The vaccine is to have a high initial price to optimize for dynamic efficiency (speed). The marginal price can be used to optimize for static efficiency (allocation). Guarantee to pay for any courses delivered during the first six months, and sell first billion courses at high price \$X and remaining at \$5/course. The high price \$X is such that the earnings of the marginal firm covers cost, plus 33%. The costs include 15% of the cost of capacity + the production cost (assume \$1/course). The solution for the global program, thus, entails that the high price is \$X = \$53, with push funding at \$77 bn. and the expected pull funding at \$38 bn. This might be higher if there are many successful candidates (a good scenario).

Appendix D Baseline parameter values

Our model involves a large number of parameters. In this section we list the values at which we set them for our baseline model. At the end of this section we also run several robustness checks to show that our main findings are robust to changes in these parameters.

Vaccine success We assume that, overall, a vaccine is feasible with probability $p_o = 0.9$. The probability that there is no problem at the platform level (p_l) is 0.8 for extensively used platforms like viral vectors, live attenuated virus, and inactivated virus. The probability is 0.6 for somewhat more experimental platforms like RNA vaccines that have been licensed for animal vaccination but not for humans, and 0.4 for unused technologies like DNA vaccines.

We assume there is no problem in each individual subcategory with probability $p_s = 0.8$. Finally, we assume that no problem prevents specific candidates from working with probability (p_j) 0.5 if the candidate is in phase 3 clinical trials, 0.32 if it is in phase 2 clinical trials, 0.23 if it is in phase 1 clinical trials, and 0.14 if it is in preclinical trials.

Benefits from vaccination H_i is the sum of total economic and health harm. We use World Bank figures for economic harm by country (cite report). Health harm is the product of (a) mortality, which we assume is 200,000 per month distributed across the world in proportion to population, (b) the value of a statistical life, which is proportional to GDP per capita and is \$7 million for the US, and (c) the fraction of one life that is lost on average due to Covid-19 deaths, $\frac{10}{71}$, which assumes that each death implies a loss of 10 years and that there is a life expectancy of 71 years.

We assume that, in expectation, a fraction $\delta = \frac{1}{2}$ of H_i will be avoided due to treatments, better social distancing, contact tracing, or, in the worst case, herd immunity by the time a vaccine is available. We assume that the form of $f_i(\cdot)$ is such that every high-priority person vaccinated brings flow benefits that are nine times the benefits of vaccinating one non-priority person. Herd immunity is achieved when a fraction $\lambda_i^{\text{herd}} = 0.7$ of the population is vaccinated.

We assume that early investment in capacity accelerates vaccine production by $T = 3$ months. In the absence of early capacity investment, global vaccine production after time t_0 will be $V_{NP} = 500$ million courses / month, which will be distributed across the world in proportion to population.

Production cost Capacity initially costs \$2 per course/year, or \$24 per course/month. After 200 million courses/month, marginal costs increase with constant elasticity of 3—or, equivalently, the

supply curve has elasticity $\frac{1}{3}$ from that point on. 30% of capacity can be recovered for a failed candidate for a gain of $\underline{c} = \$2$ per course/year.

Designing incentives The risk premium firms require to participate is $\gamma = \frac{4}{3}$. In our baseline case, we analyze a procurement scheme that pays for a fraction $\mu = 0.85$ of the cost of manufacturing capacity, that commits to buy the first $x^{\text{high}} = 1$ billion courses at some high price p^{high}, as wells the next $x^{\text{low}} = 3.5$ billion courses at a lower price of $p^{\text{high}} = 5$ per course. For different portfolios v^G, We compute the lowest value of p^{high} such that the procurement scheme is incentive compatible.