Supplementary material

Contents

A Supplementary methods A: preparedness and response costs, and vaccine delivery **46**

- A.1 Preparedness costs 46
  - A.1.1 BPSV advance R&D 46
  - A.1.2 BPSV investigational reserve 47
  - A.1.3 SSV capacity reservation 48
  - A.1.4 Enabling activities 49
- A.2 Response cost equation 49
  - A.2.1 Risk-adjusted R&D cost per candidate calculation 50
    - A.2.1.1 SSV 50
    - A.2.1.2 BPSV 51
  - A.2.2 Procurement cost calculation 51
    - A.2.2.1 SSV 52
    - A.2.2.2 BPSV 52
  - A.2.3 Delivery Cost Equation 52
    - A.2.3.1 SSV 52
    - A.2.3.2 BPSV 53
- A.3 SSV delivery 54
  - A.3.1 Timing 55
  - A.3.2 Production 55
  - A.3.3 Allocation 57
  - A.3.4 Delivery 60
- A.4 BPSV delivery 61
  - A.4.1 Timing 61
  - A.4.2 Production 61
- A.5 Data for the cost model 61

B Supplementary methods B: modelling impacts of advance vaccine investments 69
- B.1 Framing . . . 69
- B.2 Aggregating epidemics to pandemics . . . 69
- B.3 Exceedance probabilities . . . 72
- B.4 Data for the impact model . . . 75

C Supplementary results 76
- C.1 Results for costs of preparedness and response investments . . . 76
  - C.1.1 Preparedness costs . . . 76
  - C.1.2 Cumulative preparedness costs over time . . . 76
  - C.1.3 Vaccine delivery . . . 78
  - C.1.4 Full results for preparedness and response costs . . . 82
- C.2 Impact of preparedness and response investments . . . 85
  - C.2.1 Results for the epidemic library . . . 85
    - C.2.1.1 Societal losses under alternative sector-closure policies among epidemic library candidates . . . 85
    - C.2.1.2 Societal losses under the loss-minimising sector closure policy in the epidemic library . . . 89
    - C.2.1.3 Societal losses averted by advance vaccine investments under the loss-minimising sector closure policy in the epidemic library 90
  - C.2.2 Exceedance probabilities . . . 92
  - C.2.3 Losses under business as usual . . . 94
  - C.2.4 Impact of advance investments into vaccines . . . 94
  - C.2.5 Supplementary figures for the impact model . . . 98
    - C.2.5.1 Composition of estimated impacts . . . 100

A Supplementary methods A: preparedness and response costs, and vaccine delivery

This section provides equations for the costing and delivery computations. Notation, values, distributions and data sources are summarised in Table A.5.

A.1 Preparedness costs

We can write the total preparedness cost for scenario s in year y, with discount rate r, as

$$D_{s,y}^{(\text{prep})} = \frac{1}{(1+r)^y}\left(D_s^{(\text{BP-adRD})} + D_{s,y}^{(\text{BP-sec})} + D_{s,y}^{(\text{BP-inv})} + D_s^{(\text{S-cap})} + D_{s,y}^{(\text{en})}\right)$$

where:

- $D_s^{(\text{BP-adRD})}$ is the R&D cost of BPSV prior to an outbreak; see Equation (1)
- $D_{s,y}^{(\text{BP-sec})}$ is the upfront cost of securing an investigational reserve of 100,000 BPSV doses; see Equation (2)
- $D_{s,y}^{(\text{BP-inv})}$ is the annual cost of maintaining an investigational reserve of 100,000 BPSV doses; see Equation (3)
- $D_s^{(\text{S-cap})}$ is the cost of reserved capacity for SSV; see Equation (4)
- $D_{s,y}^{(\text{en})}$ is the annual cost of enabling activities; see Equation (5).

We use $s = 0$ to denote the business as usual (BAU) scenario, and $s = 1$ for scenario S01, $s = 2$ for scenario S02, and so on.

A.1.1 BPSV advance R&D

Advance R&D for BPSVs consists of Phase 0 (which we use to denote preclinical R&D), Phase 1 and Phase 2, for which we add up costs that depend on (a) the number of candidates, (b) the cost per phase for experienced (those with licensure experience) and inexperienced developers (those without), and (c) the probability of success in each phase. The final cost, therefore, reflects the number of candidates that progressed through the developmental pipeline.

In order to achieve one successful BPSV candidate in the event of an outbreak, we assume that 14 are required to enter into preclinical R&D.[1] At present, there are seven (Table A.1). We assume that the remaining seven will come from developers without prior licensure experience.

Probabilities of success for Phase 0 and Phase 1 are $P_0^{(\mathrm{BPSV})}$ and $P_1^{(\mathrm{BPSV})}$. The probability of phase occurrence for Phase i is:

$$\hat{P}_i^{(\mathrm{BPSV})} = \begin{cases} 1 & i = 0 \\ \prod_{j=0}^{i-1} P_j^{(\mathrm{BPSV})} & i \in \{1, 2\} \end{cases}$$

The cost of each phase is T_i, a weighted average of costs of experienced ($T_i^{(e)}$) and inexperienced ($T_i^{(n)}$) manufacturers. Assuming that $N^{(\mathrm{BPSV})} = 14$ candidates start in the preclinical phase,[1] and two have prior experience with licensure (Table A.1), we take $\omega = 0.92$;

$$T_i = (1 + \pi)\left(\omega T_i^{(n)} + (1 - \omega) T_i^{(e)}\right)$$

where $\pi = 0.28$ is inflation from 2018 to 2025.[2] Then the total weighted cost for phases 0 through 2 for $N^{(\mathrm{BPSV})}$ candidates is

$$D_s^{(\text{BP-adRD})} = \begin{cases} N^{(\mathrm{BPSV})} \sum_{i=0}^{2} \hat{P}_i^{(\mathrm{BPSV})} T_i & s = 1 \\ 0 & s \neq 1 \end{cases} \tag{1}$$

Table A.1: Manufacturers working on BPSV and whether or not they have licensure experience as of February 2026.[1]

Developer	Licensure Experience
Bharat/U Syd/ExcellGene	Yes
CPI/CalTech	No
Intravacc	No
IVI consortium	No
Panacea/THSTI	No
SK Bio	Yes
VIDO	No

A.1.2 BPSV investigational reserve

Denoting the duration of Phase i as $Y_i^{(B)}$, the time taken to complete development of the BPSV up to the end of Phase 2, from which point it is manufactured to be held in an investigational reserve, is:

$$Y^{(B)} = Y_0^{(B)} + Y_1^{(B)} + Y_2^{(B)}.$$

The upfront cost of securing the investigational reserve is

$$D_{s,y}^{(\text{BP-sec})} = \begin{cases} A_4 A_5 & s = 1 \,\&\, y = Y^{(B)} + 1 \\ 0 & s \neq 1 \parallel y \neq Y^{(B)} + 1 \end{cases} \tag{2}$$

where $A_4 = 100,000$ is the size of the reserve and $A_5 = 0.113$ is the cost per dose in USD, coming from the upfront cold-chain equipment cost estimate of 138 million USD for 1.2 billion doses.[3]

The cost of goods sold (COGS) is $G = 4.68$ USD per dose. Fill/finish costs from Kis[4] of 0.29 and 0.39 USD per dose respectively for Moderna and Pfizer doses translate to 7.2% of COGS on average. Then the cost of drug substance, accounting for the fill/finish margin $M_f = 0.072$ and the profit margin $M_p = 0.2$, is $G(1 - M_f)(1 + M_p) = 5.21$ USD per dose.

The reserve is replenished every $Y_{rep} = 3$ years based on the storage characteristics for Ervebo.[5] Then the annual cost to maintain the reserve of $A_4 = 100,000$ doses is

$$D_{s,y}^{(\text{BP-inv})} = \begin{cases} \frac{A_4}{Y_{rep}} G(1 - M_f)(1 + M_p) + A_1 A_4 & s = 1 \,\&\, y > Y^{(B)} \\ 0 & s \neq 1 \parallel y \leq Y^{(B)} \end{cases} \tag{3}$$

where $A_1 = 0.01$ USD is the annual reservation cost per dose, coming from the recurring cold-chain cost estimate of 12 million USD for 1.2 billion doses.[3]

A.1.3 SSV capacity reservation

Reservation sizes, in billions, depend on scenarios. It includes the $A_3 = 0.5$ billion doses reserved for HIC (325 million for the EU,[6] and 150 million for the USA,[7] rounded up to 0.5 billion for simplicity of presentation). The cost of the EU reservation is 160 million EUR per year;[8] assuming an exchange rate of 1.08, the cost per dose per year is $A_2 = 0.53$ USD. We define the scenario-dependent total reservation size as:

$$M_{R,s} = \begin{cases} A_3 & s \in \{0,1,4,7,10\} \\ A_3 + 0.7 & s \in \{2,5,8\} \\ A_3 + 2 & s \in \{3,6,9\} \end{cases}$$

Then the total cost per year is

$$D_s^{\text{(S-cap)}} = M_{R,s} A_2 \tag{4}$$

The annual costs in billion USD are 0.27, 0.64, and 1.33, respectively.

A.1.4 Enabling activities

Denote the target "days to SSV" by ζ, so that $\zeta \in \{365, 200, 100\}$, which are the three variations we consider enabling activities might achieve. We assume that $Y^{(200)} = 5$ years are required to achieve 200 days to SSV, and $Y^{(100)} = 15$ years are required to achieve 100 days to SSV. Then annual costs, $E = 700$ million USD, accumulate depending on the year and the target:

$$D_{s,y}^{\text{(en)}} = \begin{cases} E & \zeta(s) = 200 \ \& \ y \leq Y^{(200)} \mid \zeta(s) = 100 \ \& \ y \leq Y^{(100)} \\ 0 & \zeta(s) = 365 \mid y > Y^{(100)} \mid \zeta(s) = 200 \ \& \ y \ > \ Y^{(200)} \end{cases} \tag{5}$$

We use $\zeta(s)$ to denote the mapping from our scenario definitions to their respective ζ values as follows:

$$\zeta(s) = \begin{cases} 365 & s \in \{0,1,2,3,10\} \\ 200 & s \in \{4,5,6\} \\ 100 & s \in \{7,8,9\} \end{cases}$$

A.2 Response cost equation

We write total response costs as

$$D_{s,y}^{\text{(res)}} = \frac{1}{(1+r)^y} \left(D_s^{\text{(S-RD)}} + D_s^{\text{(BP-resRD)}} + D_{s,y}^{\text{(S-proc)}} + D_s^{\text{(BP-proc)}} + D_{s,y}^{\text{(S-del)}} + D_{s,y}^{\text{(BP-del)}} \right)$$

where

- $D_s^{(\text{S-RD})}$ is the R&D cost for SSV; see Equation (6)
- $D_s^{(\text{BP-resRD})}$ is the R&D cost of BPSV after an outbreak; see Equation (7)
- $D_{s,y}^{(\text{S-proc})}$ is the cost of procuring SSV; see Equation (8)
- $D_s^{(\text{BP-proc})}$ is the cost of procuring BPSV; see Equation (9)
- $D_{s,y}^{(\text{S-del})}$ is the cost of delivering SSV; see Equation (10)
- $D_{s,y}^{(\text{BP-del})}$ is the cost of delivering BPSV; see Equation (11)

We present computation for this cost with reference to the beginning of the outbreak. Therefore, indices y in this section do not correspond to the same index in the previous section, where y indexed years of investment pre-pandemic.

A.2.1 Risk-adjusted R&D cost per candidate calculation

A.2.1.1 SSV Trial costs are adjusted for the duration of the trial, which depend on the R&D enabling investment, denoted $\zeta \in \{365, 200, 100\}$:

$$T_{\zeta,i}^{(e)} = (1+\pi)\frac{W_i^{(\zeta)}}{52Y_i^{(B)}}T_i^{(e)}$$

where $\pi = 0.28$ is inflation from 2018 to 2025, $T_i^{(e)}$ is the cost per Phase i of experienced developers (i.e. we assume only experienced manufacturers undertake reactive R&D), $Y_i^{(B)}$ is the usual phase duration in normal times in years, and $W_i^{(\zeta)}$ is its expected duration in weeks given enabling investments made prior to the outbreak.

The probability of success of each phase comes from COVID-19 data:[9]

$$P_i^{(\text{SSV})} \sim \text{Beta}\left(\sum_{j=i+1}^{4} X_j + 1, X_i + 1\right)$$

for $i \in \{0,1,2,3\}$ where X_i is the number of candidates that failed in phase i, $\sum_{j=i+1}^{4} X_j$ the number that failed after phase i (and therefore succeeded in phase i), and X_4 the number that succeeded to licensure.

The probabilities of phase occurrence are:

$$\hat{P}_i^{(\text{SSV})} = \begin{cases} 1 & i = 0 \\ \prod_{j=0}^{i-1} P_j^{(\text{SSV})} & i \in \{1,2,3,4\} \end{cases}$$

Then the total cost is

$$D_s^{(\text{S-RD})} = N^{(\text{SSV})} \left(\sum_{i=0}^{3} \hat{P}_i^{(\text{SSV})} \cdot T_{\zeta(s),i}^{(e)} + \hat{P}_4^{(\text{SSV})} T_4 \right) \tag{6}$$

where T_4 is the cost of licensure. We multiply by the number of candidates, $N^{(\text{SSV})}$, to get the total cost from the weighted average per candidate, where

$$N^{(\text{SSV})} = n^{(\text{SSV})} + F_{NegBin}^{-1} \left(Q^{(\text{SSV})}; n^{(\text{SSV})}, \hat{P}_4^{(\text{SSV})} \right)$$

is chosen to secure at least $n^{(\text{SSV})} = 5$ successful candidates with probability $Q^{(\text{SSV})} = 90\%$. Here, $F_{NegBin}^{-1}(q; n, p)$ is the cumulative density of a negative binomial distribution with parameters n and p evaluated at quantile q.

A.2.1.2 BPSV One BPSV candidate that has passed through phases 0 to 2 prior to the outbreak goes through Phase 3 during the response. The duration is $W_3^{(365)} = 18$ weeks. Thus we write the BPSV R&D response cost

$$D_s^{(\text{BP-resRD})} = \begin{cases} \left((1+\pi) \frac{W_3^{(365)}}{52 Y_3^{(B)}} T_3^{(e)} + T_4 \right) & s = 1 \\ 0 & s \neq 1 \end{cases} \tag{7}$$

A.2.2 Procurement cost calculation

The cost per dose comes from the cost of goods sold (COGS), $G = 4.68$ USD, adjusted for a profit margin ($M_p = 0.2$) and transportation margin ($M_t = 0.1$). The 20% profit margin is at the top of range in U.S. Government Accountability Office,[10] and thus acts as a conservative estimate on profit margins sought by pharmaceutical companies. The 10% estimate for transportation from manufacturer to country isolates the transportation cost from the process of vaccination.[11]

$S_R = G(1 + M_p)(1 + M_t)$ evaluates to 6.18 USD.

This cost is used both for SSV doses procured via reserved capacity, and all newly manufactured BPSV doses.

A.2.2.1 SSV

A.2.2.1 SSV We denote $A_{x,s,y}$ to be the number of doses (in billions) produced from channel x in year y and scenario s, where $x \in \{R, E, B\}$, corresponding to reserved, existing (and unreserved), and reactively built capacity, respectively. $A_{x,s,y}$ comes from Equation (12). Then the total cost, in billion USD, is:

$$D_{s,y}^{(\text{S-proc})} = A_{R,s,y} S_R + \sum_{x \in \{E,B\}} A_{x,s,y} S_U \tag{8}$$

Here, $S_R = 6.18$ is the cost per reserved dose and $S_U = 18.94$ the cost per unreserved dose in USD.

A.2.2.2 BPSV The cost of BPSV doses is the sum of new doses supplied, $A_{BPSV,s}$, at the reserved-capacity cost per dose, and the doses held in the investigational reserve, for which fill/finish, transport and profit margin costs are due.

$$D_s^{(\text{BP-proc})} = \begin{cases} A_{BPSV,s} \cdot S_R + A_4(M_f + M_t)(1 + M_p)G & s = 1 \\ 0 & s \neq 1 \end{cases} \tag{9}$$

For a world population aged 65 and over of 0.85 billion, a coverage of 80% (accounting for wastage of 10%), and a cost per dose of $S_R = 6.18$ USD (the same as for SSV via reserved capacity), the procurement cost for BPSV is 4.67 billion USD.

A.2.3 Delivery Cost Equation

A.2.3.1 SSV For populations aged 15 and above, $N_i^{(15)}$ for income group i, we write

$$L_i = 2 \cdot \lambda \cdot N_i^{(15)} / (1 - \delta)$$

as the total demand for first-schedule doses for income group $i \in \{\text{LIC, LMIC, UMIC, HIC}\}$, representing two doses each for $\lambda = 80\%$ of the population and $\delta = 10\%$ wastage.

We write the delivery cost $H_{s,i,w}$ for $h_{s,i,w}$ doses given in week w and income group i as follows. There are three cost tiers, the first of which, $V_{i;0}$, is applied to the first 10% of L_i (the "start up" cost); the second ($V_{i;11}$) to the subsequent 20% (the "ramp up" cost); and the third ($V_{i;31}$) to all doses thereafter (the "at scale" cost). The same costing schedule applies both to the first-schedule plus booster SSV doses and the BPSV rollout.

$$H_{s,i,w} = \begin{cases} V_{i;0} h_{s,i,w} & \sum_{j=1}^{w-1} h_{s,i,w} \leq \frac{1}{10} L_i \\ V_{i;10} h_{s,i,w} & \frac{1}{10} L_i < \sum_{j=1}^{w-1} h_{s,i,w} \leq \frac{3}{10} L_i \\ V_{i;30} h_{s,i,w} & \frac{3}{10} L_i < \sum_{j=1}^{w-1} h_{s,i,w} \end{cases}$$

Then the delivery cost in year y and scenario s is

$$D_{s,y}^{(\text{S-del})} = \sum_{w \in y} \sum_{i} H_{s,i,w} \tag{10}$$

A.2.3.2 BPSV For the BPSV, which goes only to people aged 65 or older, with populations $N_i^{(65)}$, coverage is reached earlier in the process, so the cost is weighted more heavily towards start up and ramp up:

$$D_s^{(\text{BP-del})} = \begin{cases} \sum_i D_{\text{BPSV},i} & s = 1 \\ 0 & s \neq 1 \end{cases} \tag{11}$$

$$D_{\text{BPSV},i} = \begin{cases} N_i^{(65)} V_{i;0} & N_i^{(65)} \leq \frac{1}{10} N_i^{(15)} \\ \frac{N_i^{(15)}}{10} V_{i;0} + \left(N_i^{(65)} - \frac{N_i^{(15)}}{10} \right) V_{i;11} & \frac{1}{10} N_i^{(15)} < N_i^{(65)} \leq \frac{3}{10} N_i^{(15)} \\ \frac{N_i^{(15)}}{10} V_{i;0} + \frac{2}{10} N_i^{(15)} V_{i;11} + \left(N_i^{(65)} - \frac{3}{10} N_i^{(15)} \right) V_{i;31} & N_i^{(65)} > \frac{3}{10} N_i^{(15)} \end{cases}$$

The logic of this is as follows:

- The increments in cost correspond to numbers of eligible people in the whole population, namely those aged 15 and above.
- If the number of people eligible for the BPSV is less than 10% of the population aged 15 and over, then all doses cost the "start up" amount.
- If the number of people eligible for the BPSV is more than 10% and less than 30% of the 15+ population, then the cost of the first doses, a number equal to 10% of the 15+

population, is the "start up" amount. All remaining doses cost the "ramp up" amount.

- If the number of people eligible for the BPSV is more than 30% of the 15+ population, then the cost of the first doses, a number equal to 10% of the 15+ population, is the "start up" amount. The cost of the second tranche of doses, a number equal to 20% of the 15+ population, is the "ramp up" amount. All remaining doses cost the "at scale" amount.

Table A.2: Literature review of global and country-specific delivery costs

Country	Country status	Study type	Financial cost per dose (USD)	Source
WHO, Gavi, and UNICEF AMC Estimate	AMC	Top down	1.66	Griffiths et al.[3]
UNICEF Global Estimate	All	Model	0.73	Oyatoye[12]
DRC	LIC	Bottom up	1.91	Moi et al.[13]
Malawi	LIC	Bottom up	4.55	Ruisch et al.[14]
Mozambique	LIC	Bottom up	0.5	Namalela et al.[15]
Uganda	LIC	Bottom up	0.79	Tumusiime et al.[16]
Bangladesh	LMIC	Bottom up	0.29	Yesmin et al.[17]
Cote d'Ivoire	LMIC	Bottom up	0.67	Vaughan et al.[18]
Nigeria	LMIC	Bottom up	0.84	Noh et al.[19]
Philippines	LMIC	Bottom up	2.16	Banks et al.[20]
Vietnam	LMIC	Bottom up	1.73	Nguyen et al.[21]
Ghana	LMIC	CVIC tool	2.2–2.3	Nonvignon et al.[22]
Lao PDR	LMIC	CVIC tool	0.79–0.81	Yeung et al.[23]
Kenya	LMIC	Top down	3.29–4.28	Orangi et al.[24]
Botswana	UMIC	Mixed	19	Vaughan et al.[25]
South Africa	UMIC	Top down	3.84	Edoka et al.[26]

A.3 SSV delivery

Table A.3: Manufacturing response timeline assumptions

Category	Reserved capacity	Private response (existing capacity)	Private response (built capacity)
Annual manufacturing volume	By scenario (0.5–2.5B)	9B minus reserved volume	6B
Facility transition start	7 weeks before vaccine approval	7 weeks before vaccine approval	7 weeks before vaccine approval

Category	Reserved capacity	Private response (existing capacity)	Private response (built capacity)
Weeks to initial manufacturing	12	12 (BPSV) or 30 (no BPSV)	48
Scale-up weeks to full capacity	10	16	16

A.3.1 Timing

We assume that manufacturers will begin producing at risk once they have confidence in vaccine approval. Thus, facility transition (the reorganising of manufacturing facilities in preparation for SSV dose production) begins $I_0 = 7$ weeks before vaccine approval, which in turn depends on R&D investments. We have three levels in our scenarios, corresponding to SSVs available in 100 days, 200 days, and 365 days. The total weeks taken for vaccine approval can be written as follows:

$$W^{(\zeta)} = \sum_{i=0}^{3} W_i^{(\zeta)}$$

for $\zeta \in \{365, 200, 100\}$. These work out as 52, 28, and 14 weeks, respectively. Thus "week 0" for manufacturing occurs 45, 21, and 7 weeks, respectively, after the new pathogen has been sequenced. We denote this variable $w_s^{(0)}$:

$$w_s^{(0)} = W^{(\zeta(s))} - I_0 = \begin{cases} 45 & s \in \{0, 1, 2, 3, 10\} \\ 22 & s \in \{4, 5, 6\} \\ 7 & s \in \{7, 8, 9\} \end{cases}$$

A.3.2 Production

We estimate total global manufacturing potential to be $M_G = 15$ billion doses per year, and the amount currently in operation to be $M_C = 9$. The volume that is reserved, in billion doses, including the HIC-specific reservation of $A_3 = 0.5$ billion doses, depends on the scenarios as follows:

$$M_{R,s} = \begin{cases} A_3 & s \in \{0,1,4,7,10\} \\ A_3 + 0.7 & s \in \{2,5,8\} \\ A_3 + 2 & s \in \{3,6,9\} \end{cases}$$

where $s = 0$ denotes the BAU scenario. By definition, $M_{E,s} = M_C - M_{R,s}$ (existing unreserved capacity (“E”) equals the total currently existing (“C”) minus reserved capacity (“R”)), and $M_B = M_G - M_C$ (newly built manufacturing (“B”) equals the global total (“G”) minus the existing capacity).

Then the number of doses, in billions, that are made from capacity $x \in \{R, E, B\}$ in week w of scenario s is:

$$Z_{x,s,w} = \begin{cases} 0 & w - w_s^{(0)} \leq I_x \\ \frac{1}{52} \frac{w - w_s^{(0)} - I_x}{C_x} M_{x,s} & w - w_s^{(0)} \in (I_x, I_x + C_x] \\ \frac{1}{52} M_{x,s} & w - w_s^{(0)} > I_x + C_x \end{cases}$$

Here, $I_R = 12$ is the number of weeks to initial manufacturing for reserved capacity, assuming streamlined technology transfer and process set up (around 2 months) and facility process validation (around 1 month).[27] $C_R = 10$ is its number of weeks to scale up to full capacity, taking the lower end of the mRNA range assumed readiness from reserved capacity in Vaccines Europe.[28] $I_B = 48$ is the number of weeks to initial manufacturing for newly built capacity. This assumes early planning phase (around 2 months), longer facility improvement to build new infrastructure (around 5 months), tech transfer (around 2 months), and facility/process setup (around 2 months).[27] This also aligns with realistic estimate from manufacturing stakeholder interviews.[29] $C_B = 16$ is its number of weeks to scale up to full capacity, taking the middle of the range from Vaccines Europe.[28]

$$I_E = \begin{cases} I_{E,1} & s = 1 \\ I_{E,0} & s \neq 1 \end{cases}$$

where $I_{E,0} = 30$ and $I_{E,1} = 12$ are the number of weeks to initial manufacturing for existing and unreserved capacity (i.e. manufacturing conversion for SSVs is faster in the presence of

BPSVs as we assume that they are manufactured using the same platform). In the absence of BPSV, we assume early planning phase (around 2 months), streamlined facility improvement because using existing infrastructure (around 1 month), tech transfer (around 2 months), and facility/process set up (around 2 months).[27] $C_E = 16$ is its number of weeks to scale up to full capacity, assumed to be the same as C_B. These timelines are shown in Table A.4.

Table A.4: Vaccine Production Timeline when there is no BPSV. When BPSV is also modelled, Existing Private Capacity scales from 0 to 100 in weeks 12–21.

Weeks from transition start	Reserved Capacity (%)	Existing Private Capacity (%)	Response Private Capacity (%)
0–11			
12–21	Scales from 0 to 100		
22–29	100		
30–45	100	Scales from 0 to 100	
46–47	100	100	
48–63	100	100	Scales from 0 to 100
64+	100	100	100

A.3.3 Allocation

Denote the weekly allocated doses at week w from capacity x to income level i $k_{s,x,i,w}$, and the cumulative number $K_{s,i,w}$, such that

$$K_{s,i,w} = \sum_{x\in\{R,E,B\}} \sum_{j=0}^{w} k_{s,x,i,j}.$$

$$k_{s,R,i,w} = \begin{cases} \left(\frac{A_3}{M_{R,s}} + \frac{M_{R,s}-A_3}{M_{R,s}}\frac{N_{HIC}}{N_T}\right) Z_{R,s,w} & K_{s,\mathrm{HIC},w} < L_{\mathrm{HIC}} \;\&\; i = \mathrm{HIC} \\ \frac{M_{R,s}-A_3}{M_{R,s}}\frac{N_i}{N_T} Z_{R,s,w} & K_{s,\mathrm{HIC},w} < L_{\mathrm{HIC}} \;\&\; i \neq \mathrm{HIC} \\ 0 & K_{s,\mathrm{HIC},w} \geq L_{\mathrm{HIC}} \;\&\; i = \mathrm{HIC} \\ \frac{N_i}{N_{UMIC}+N_{LMIC}+N_{LIC}} Z_{R,s,w} & K_{s,\mathrm{HIC},w} \geq L_{\mathrm{HIC}} \;\&\; K_{s,\mathrm{UMIC},w} < L_{\mathrm{UMIC}} \;\&\; i \neq \mathrm{HIC} \\ 0 & K_{s,\mathrm{UMIC},w} \geq L_{\mathrm{UMIC}} \;\&\; i = \mathrm{UMIC} \\ \frac{N_i}{N_{LMIC}+N_{LIC}} Z_{R,s,w} & K_{s,\mathrm{UMIC},w} \geq L_{\mathrm{UMIC}} \;\&\; K_{s,\mathrm{LMIC},w} < L_{\mathrm{LMIC}} \;\&\; i \notin \{\mathrm{HIC}, \mathrm{UMIC}\} \\ 0 & K_{s,\mathrm{LMIC},w} \geq L_{\mathrm{LMIC}} \;\&\; i = \mathrm{LMIC} \\ Z_{R,s,w} & K_{s,\mathrm{LMIC},w} \geq L_{\mathrm{LMIC}} \;\&\; K_{s,\mathrm{LIC},w} < L_{\mathrm{LIC}} \;\&\; i = \mathrm{LIC} \\ 0 & K_{s,\mathrm{LIC},w} \geq L_{\mathrm{LIC}} \end{cases}$$

where $N_T = \sum_{i \in \{\mathrm{HIC},\mathrm{UMIC},\mathrm{LMIC},\mathrm{LIC}\}} N_i$.

The logic of this reads as follows:

- $A_3 = 0.5$ billion doses per year from reserved capacity go exclusively to HIC, which is expressed as a fraction of the total reservation, $M_{R,s}$
- Any remaining reserved capacity doses are allocated according to population
- Once HIC reach their total demand, doses from reserved capacity are split proportional to population between UMIC, LMIC and LIC, and so on

For $x \in \{E, B\}$,

$$k_{s,x,i,w} = \begin{cases} Z_{x,s,w} & K_{s,\text{HIC},w} < L_{\text{HIC}} \;\&\; i = \text{HIC} \\ 0 & K_{s,\text{HIC},w} < L_{\text{HIC}} \;\&\; i \neq \text{HIC} \\ Z_{x,s,w} & K_{s,\text{HIC},w} \geq L_{\text{HIC}} \;\&\; K_{s,\text{UMIC},w} < L_{\text{UMIC}} \;\&\; i = \text{UMIC} \\ 0 & K_{s,\text{HIC},w} \geq L_{\text{HIC}} \;\&\; K_{s,\text{UMIC},w} < L_{\text{UMIC}} \;\&\; i \neq \text{UMIC} \\ Z_{x,s,w} & K_{s,\text{UMIC},w} \geq L_{\text{UMIC}} \;\&\; K_{s,\text{LMIC},w} < L_{\text{LMIC}} \;\&\; i = \text{LMIC} \\ 0 & K_{s,\text{UMIC},w} \geq L_{\text{UMIC}} \;\&\; K_{s,\text{LMIC},w} < L_{\text{LMIC}} \;\&\; i \neq \text{LMIC} \\ Z_{x,s,w} & K_{s,\text{LMIC},w} \geq L_{\text{LMIC}} \;\&\; i = \text{LIC} \\ 0 & K_{s,\text{LMIC},w} \geq L_{\text{LMIC}} \;\&\; i \neq \text{LIC} \end{cases}$$

The logic of this reads as follows:

- Until HIC demand is reached, all doses from unreserved capacity go to HIC. None go to UMIC, LMIC or LIC.
- Once HIC demand has been met and until UMIC demand is reached, all doses from unreserved capacity go to UMIC. None go to HIC, LMIC or LIC.
- Once HIC and UMIC demand have been met and until LMIC demand is reached, all doses from unreserved capacity go to LMIC. None go to HIC, UMIC or LIC.
- Once HIC, UMIC and LMIC demand have been met, all remaining doses from unreserved capacity go to LIC. None go to LMIC, UMIC or HIC.

Total supply of first-schedule doses in each year period is

$$A^{(1)}_{x,s,y} = \sum_i \sum_{w \in y} k_{s,x,i,w}.$$

We assume, for every second dose of SSV, a booster will be given one year later for $N^{(\text{boost})} = 2$ years.

Thus

$$A^{(2)}_{s,y} = \begin{cases} \frac{1}{2} \sum_x A^{(1)}_{x,s,y-1} & y = 2 \\ \frac{1}{2} \sum_x \left(A^{(1)}_{x,s,y-1} + A^{(1)}_{x,s,y-2} \right) & y > 2 \end{cases}$$

and

$$A^{(2)}_{x,s,y} = \min(A^{(2)}_{s,y}, M_R - A^{(1)}_{R,s,y})$$

for $x = R$ and

$$A^{(2)}_{x,s,y} = \max(A^{(2)}_{s,y} - A^{(2)}_{R,s,y}, 0)$$

for $x \in \{E, B\}$.

Then

$$A_{x,s,y} = A^{(1)}_{x,s,y} + A^{(2)}_{x,s,y}. \tag{12}$$

A.3.4 Delivery

Delivery is written as $h^{(j)}_{s,i,w}$ doses delivered in scenario s, income group i and week w for schedule j, which is $j = 1$ for first-dose SSV, $j = 2$ for second-dose SSV, and $j = 2 + k$ for $k = \{1, ..., N^{(boost)}\}$.

The second dose is prioritised over the first, and follows the first by four weeks, so

$$h^{(2)}_{s,i,w} = h^{(1)}_{s,i,w-4}.$$

Available doses are $K_{s,i,w}$, the cumulative doses allocated to income group i by week w, minus doses given so far. First doses stop being given once $L_i/2$ is reached.

$$h^{(1)}_{s,i,w} = \max\left(0, \min\left(K_{s,i,w} - h^{(2)}_{s,i,w} - \sum_{j=1}^{2}\sum_{k=1}^{w-1} h^{(j)}_{s,i,k}, L_i/2 - \sum_{k=1}^{w-1} h^{(1)}_{s,i,k}\right)\right)$$

Booster doses are given for $j = 2 + k$ for $k = \{1, ..., N^{(boost)}\}$:

$$h^{(2+k)}_{s,i,w} = h^{(2)}_{s,i,w-52k}.$$

Total doses are therefore

$$h_{s,i,w} = \sum_{j=1}^{2+N^{(boost)}} h^{(j)}_{s,i,w}.$$

The input to the impact model is $h^{(2)}_{s,i,w}$, i.e. doses delivered per week, per scenario, per income level. The weekly value is transformed to a daily value by dividing by 7, i.e. every day in a given week sees the same number of doses distributed. The impact model combines LIC and LMIC into a single category, LLMIC. For this, a population-weighted average is taken of $h^{(2)}_{s,\mathrm{LIC},w}$ and $h^{(2)}_{s,\mathrm{LMIC},w}$. The same applies to BPSV delivery.

A.4 BPSV delivery

A.4.1 Timing

The duration of the Phase 3 trial is $W_3^{(365)} = 18$ weeks. The time to manufacturing transition is $I_R = 12$ weeks, and the time to manufacturing scale-up $C_R = 10$ weeks; these are the same as the reserved-capacity times for SSV.

Facility transition occurs in week 1. Thus manufacturing begins in week $1 + I_R = 13$ and dose distribution begins in week $1 + W_3^{(365)} = 19$.

A.4.2 Production

The number of doses, in billions, that are made in week w is:

$$Z_w = \begin{cases} 0 & w < I_R \\ \frac{1}{52}\frac{w-I_x+1}{C_x}M_{x,s} & w \in [I_R, I_R + C_R) \\ \frac{1}{52}M_{x,s} & w - 1 \geq I_R + C_xR \end{cases}$$

Doses are all allocated in proportion to eligible populations.

A.5 Data for the cost model

Data sources for the costing model are given in Table A.5.

Table A.5: **Notation, parametric assumptions and data sources for inputs to the costing model.** Parameters are used as follows: uniform distributions go from Parameter 1 to Parameter 2. Triangular distributions go from Parameter 1 to Parameter 3 with a peak at Parameter 2. Multinomial distributions have equally probable values listed individually. Exponential distributions have as a mean Parameter 1. Inverse Gaussian distributions have as a mean Parameter 1, and as a shape Parameter 2. Log normal distributions have as a mean Parameter 1, and as a standard deviation Parameter 2. PearsonV distributions have shape Parameter 1, scale Parameter 2, and location 0.

Math notation	Description	Distribution	Parameters	Source
BPSV R&D				
$N^{(\mathrm{BPSV})}$	Total number of BPSV candidates in pipeline	Constant	14	See Section A.1.1
$P_0^{(\mathrm{BPSV})}$	Probability of success; preclinical	Multinomial	0.40, 0.41, 0.41, 0.42, 0.48, 0.57	Gouglas et al.[30]
$P_1^{(\mathrm{BPSV})}$	Probability of success; Phase 1	Multinomial	0.33, 0.40, 0.50, 0.68, 0.70, 0.72, 0.74, 0.77, 0.81, 0.90	Gouglas et al.[30]
$P_2^{(\mathrm{BPSV})}$	Probability of success; Phase 2	Multinomial	0.22, 0.31, 0.33, 0.43, 0.46, 0.54, 0.58, 0.58, 0.74, 0.79	Gouglas et al.[30]
$P_3^{(\mathrm{BPSV})}$	Probability of success; Phase 3	Uniform	0.4, 0.8	Lo et al.[31]
$Y_0^{(B)}$	Ordinary preclinical duration; years	Multinomial	1, 2	CEPI[32]
$Y_1^{(B)}$	Ordinary Phase 1 duration; years	Multinomial	1, 2	CEPI[32]
$Y_2^{(B)}$	Ordinary Phase 2 duration; years	Constant	2	CEPI[32]
$Y_3^{(B)}$	Ordinary Phase 3 duration; years	Multinomial	3, 4	CEPI[32]
SSV R&D				
$Q^{(\mathrm{SSV})}$	Probability of N or more SSV successes	Constant	0.9	Model choice
$n^{(\mathrm{SSV})}$	Number of SSV successes	Constant	5	Model choice
X_0	COVID-19 candidates failed at preclinical	Constant	33	Linksbridge SPC[9]

Math notation	Description	Distribution	Parameters	Source
X_1	COVID-19 candidates failed at Phase 1	Constant	20	Linksbridge SPC[9]
X_2	COVID-19 candidates failed at Phase 2	Constant	8	Linksbridge SPC[9]
X_3	COVID-19 candidates failed at Phase 3	Constant	8	Linksbridge SPC[9]
X_4	COVID-19 candidates successful	Constant	27	Linksbridge SPC[9]
$Y^{(200)}$	Years of R&D to 200-day readiness	Constant	5	Model choice
$Y^{(100)}$	Years of R&D to 100-day readiness	Constant	15	Model choice
E	Enabling activities; million USD per year	Constant	700	CEPI[33]
$W_0^{(365)}$	Reactive preclinical duration (365); weeks	Constant	14	CEPI[32]
$W_0^{(200)}$	Reactive preclinical duration (200 days); weeks	Constant	5	CEPI[32]
$W_0^{(100)}$	Reactive preclinical duration (100 days); weeks	Constant	5	CEPI[32]
$W_1^{(365)}$	Reactive Phase 1 duration (365); weeks	Constant	0	CEPI[32]
$W_1^{(200)}$	Reactive Phase 1 duration (200 days); weeks	Constant	0	CEPI[32]
$W_1^{(100)}$	Reactive Phase 1 duration (100 days); weeks	Constant	0	CEPI[32]
$W_2^{(365)}$	Reactive Phase 2 duration (365); weeks	Constant	19	CEPI[32]
$W_2^{(200)}$	Reactive Phase 2 duration (200 days); weeks	Constant	7	CEPI[32]
$W_2^{(100)}$	Reactive Phase 2 duration (100 days); weeks	Constant	0	CEPI[32]

Math notation	Description	Distribution	Parameters	Source
$W_3^{(365)}$	Reactive Phase 3 duration (365); weeks	Constant	18	CEPI[32]
$W_3^{(200)}$	Reactive Phase 3 duration (200 days); weeks	Constant	15	CEPI[32]
$W_3^{(100)}$	Reactive Phase 3 duration (100 days); weeks	Constant	8	CEPI[32]
R&D costs				
$T_0^{(e)}$	R&D cost, preclinical, experienced manufacturer; USD	Exponential	Mean: 24,213,683	Gouglas et al.[30]
$T_0^{(n)}$	R&D cost, preclinical, inexperienced manufacturer; USD	Inverse Gaussian	Mean: 7,882,792, Shape: 13,455,907	Gouglas et al.[30]
$T_1^{(e)}$	R&D cost, Phase 1, experienced manufacturer; USD	Inverse Gaussian	Mean: 15,339,198, Shape: 8,076,755	Gouglas et al.[30]
$T_1^{(n)}$	R&D cost, Phase 1, inexperienced manufacturer; USD	PearsonV	Shape: 2.2774, Scale: 9,799,081	Gouglas et al.[30]
$T_2^{(e)}$	R&D cost, Phase 2, experienced manufacturer; USD	Log normal	Mean: 28,297,339, Standard deviation: 24,061,641	Gouglas et al.[30]
$T_2^{(n)}$	R&D cost, Phase 2, inexperienced manufacturer; USD	Inverse Gaussian	Mean: 17,124,622, Shape: 35,918,793	Gouglas et al.[30]
$T_3^{(e)}$	R&D cost, Phase 3, experienced manufacturer; USD	PearsonV	Shape: 1.3147, Scale: 51,397,313	Gouglas et al.[30]
T_4	Licensure cost, 2018; USD	Constant	287750	Gouglas et al.[30]
π	Inflation (2018 t0 2025)	Constant	0.28	U.S. BLS[2]
ω	Share of manufacturers that are inexperienced	Constant	0.923076923076923	See Table A.1
r	Discount rate	Uniform	0.02, 0.06	Glennerster et al.[34]
Reservation costs				

Math notation	Description	Distribution	Parameters	Source
A_4	Size of BPSV investigational reserve, doses	Constant	100000	Model choice
A_1	Annual BPSV reservation cost from recurrent cold chain storage, USD per dose	Constant	0.00996360623461854	Griffiths et al.[3]
A_5	BPSV reserve upfront cost for cold chain equipment, USD per dose	Constant	0.113154621821165	Griffiths et al.[3]
Y_{rep}	Years after which BPSV doses are to be replaced	Constant	3	World Health Organization[5]
A_2	Advanced capacity reservation fee; USD per dose per year	Constant	0.531692307692308	Pfizer[6]
A_3	Reserved capacity for HIC, billions	Constant	0.5	See Section A.1.3
Procurement costs				
S_U	SSV procurement price, reactive capacity; USD per dose	Constant	18.9392	Linksbridge SPC[9]
G	Drug substance cost; USD per dose	Constant	4.68	Kazaz et al.[35]
M_p	Profit margin, fraction	Constant	0.2	U.S. Government Accountability Office[10]
M_f	Fill/finish cost, fraction of COGS	Constant	0.072	Kis[4]
M_t	Cost to transport product, fraction of COGS	Constant	0.1	Gotham et al.[11]
M_G	Global annual manufacturing volume; billion doses	Constant	15	Linksbridge SPC[9]
M_C	Current annual manufacturing volume; billion doses	Constant	9	Linksbridge SPC[9]

Math notation	Description	Distribution	Parameters	Source
λ	Final vaccine coverage, proportion of population	Constant	0.8	Model choice
δ	Fraction of vaccines expected to go to waste	Constant	0.1	Griffiths et al.[3]
$N^{(\text{boost})}$	Number of boosters given, one per year	Constant	2	Model choice
Manufacturing timelines				
I_0	Facility transition start; weeks before vaccine approval	Constant	7	Model choice
I_R	Weeks to initial manufacturing for reserved infrastructure	Constant	12	Kis et al.[27]
$I_{E,0}$	Weeks to initial manufacturing when there's no BPSV for existing and unreserved infrastructure	Constant	30	Kis et al.[27]
$I_{E,1}$	Weeks to initial manufacturing when there's BPSV for existing and unreserved infrastructure	Constant	12	Kis et al.[27]
I_B	Weeks to initial manufacturing for newly built infrastructure	Constant	48	Kis et al., Feddema et al.[27,29]
C_R	Weeks to scale up to full capacity for reserved infrastructure	Constant	10	Vaccines Europe[28]
C_E	Weeks to scale up to full capacity for unreserved existing infrastructure	Constant	16	Vaccines Europe[28]
C_B	Weeks to scale up to full capacity for newly built infrastructure	Constant	16	Vaccines Europe[28]
Delivery costs				

Math notation	Description	Distribution	Parameters	Source
$V_{L;0}$	Cost of vaccine delivery at start up (0–10%) in LIC; USD per dose	Triangular	1, 1.5, 2	See Table A.2
$V_{L;11}$	Cost of vaccine delivery during ramp up (11–30%) in LIC; USD per dose	Triangular	0.75, 1, 1.5	See Table A.2
$V_{L;31}$	Cost of vaccine delivery at scale (31% and over) in LIC; USD per dose	Triangular	1, 2, 4	See Table A.2
$V_{LM;0}$	Cost of vaccine delivery at start up (0–10%) in LMIC; USD per dose	Triangular	3, 4.5, 6	See Table A.2
$V_{LM;11}$	Cost of vaccine delivery during ramp up (11–30%) in LMIC; USD per dose	Triangular	2.25, 3, 4.5	See Table A.2
$V_{LM;31}$	Cost of vaccine delivery at scale (31% and over) in LMIC; USD per dose	Triangular	1.5, 2, 2.5	See Table A.2
$V_{UM;0}$	Cost of vaccine delivery at start up (0–10%) in UMIC; USD per dose	Triangular	6, 9, 12	See Table A.2
$V_{UM;11}$	Cost of vaccine delivery during ramp up (11–30%) in UMIC; USD per dose	Triangular	4.5, 6, 9	See Table A.2
$V_{UM;31}$	Cost of vaccine delivery at scale (31% and over) in UMIC; USD per dose	Triangular	3, 4, 5	See Table A.2
$V_{H;0}$	Cost of vaccine delivery at start up (0–10%) in HIC; USD per dose	Triangular	30, 40, 75	See Table A.2

Math notation	Description	Distribution	Parameters	Source
$V_{H;11}$	Cost of vaccine delivery during ramp up (11–30%) in HIC; USD per dose	Triangular	30, 40, 75	See Table A.2
$V_{H;31}$	Cost of vaccine delivery at scale (31% and over) in HIC; USD per dose	Triangular	30, 40, 75	See Table A.2
Population sizes				
$N^{(0)}_{HIC}$	Population, HIC (2025)	Constant	1267864200	UN[36]
$N^{(0)}_{UMIC}$	Population, UMIC (2025)	Constant	2820990900	UN[36]
$N^{(0)}_{LMIC}$	Population, LMIC (2025)	Constant	3335966100	UN[36]
$N^{(0)}_{LIC}$	Population, LIC (2025)	Constant	777211800	UN[36]
$N^{(15)}_{HIC}$	Population aged 15 and older, HIC (2025)	Constant	1073972000	UN[36]
$N^{(15)}_{UMIC}$	Population aged 15 and older, UMIC (2025)	Constant	2291421800	UN[36]
$N^{(15)}_{LMIC}$	Population aged 15 and older, LMIC (2025)	Constant	2376159400	UN[36]
$N^{(15)}_{LIC}$	Population aged 15 and older, LIC (2025)	Constant	459486400	UN[36]
$N^{(65)}_{HIC}$	Population aged 65 and older, HIC (2025)	Constant	257098750	UN[36]
$N^{(65)}_{UMIC}$	Population aged 65 and older, UMIC (2025)	Constant	358101650	UN[36]
$N^{(65)}_{LMIC}$	Population aged 65 and older, LMIC (2025)	Constant	212911560	UN[36]
$N^{(65)}_{LIC}$	Population aged 65 and older, LIC (2025)	Constant	25764820	UN[36]

B Supplementary methods B: modelling impacts of advance vaccine investments

B.1 Framing

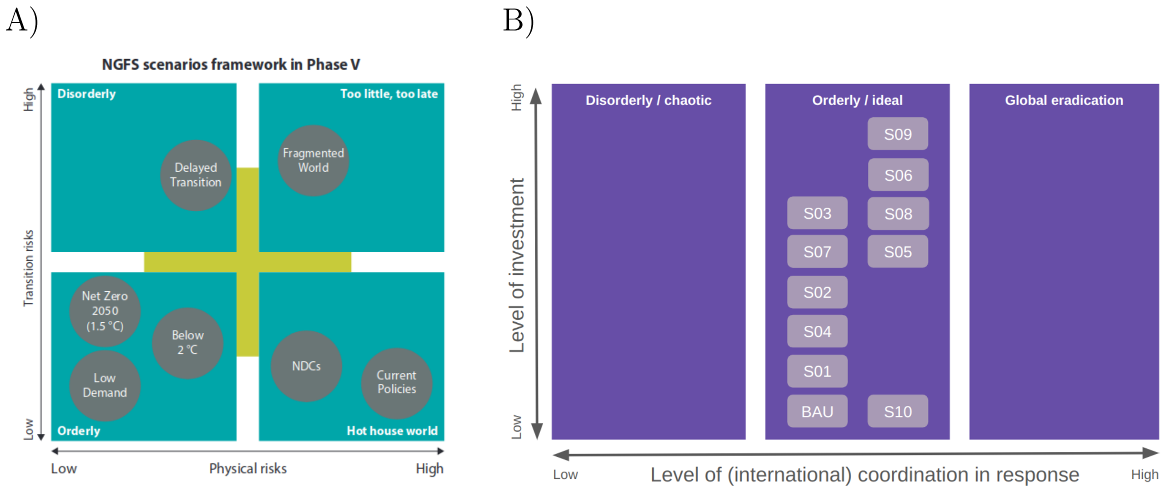

Figure B.1: **Framing scenarios by imagining futures; borrowing from the Network for Greening the Financial System (NGFS).** We borrow from NGFS to illustrate scenarios for estimating the impacts of investments. A) NGFS partition possible futures into four quadrants, with scenarios in each reflecting different levels of physical risks and transition risks.[37][d]B) In this work, we only consider "orderly" future response when we model impacts. We do not consider disorderly responses, which would likely have much higher losses and therefore investments would have a greater impact. We don't consider efforts towards global eradication, which would require global modelling. Here, the losses would be much lower, but we note that investments could facilitate the transition from "orderly" to "global eradication".

B.2 Aggregating epidemics to pandemics

We start with the "epidemic library": 2,048 pathogen samples each simulated in three synthetic country types under eleven different scenarios, from which epidemic losses averted are calculated as differences between a scenario and the BAU. We use the BAU scenario of this library to estimate the correlation between outcomes (specifically, the total societal cost as a percentage of GDP). Using this correlation, we resample outcomes, combining them to give a global loss and a global death burden.

A synthetic country–epidemic sample i in scenario s has total societal loss

---

[d] Permission received to reproduce the figure 4/8/2025.

$$\mathrm{TSL}_{i,s} = K_{1,i,s}\mathrm{VLY}_i + K_{2,i,s} + K_{3,i,s}\mathrm{VSY}_i, \tag{13}$$

where $K_{1,i,s}$ is the number of life years lost and VLY_i the value of a life year; $K_{2,i,s}$ is the lost GDP over the period due to reduced economic activity; and $K_{3,i,s}$ is the number of school years lost and VSY_i the value of one school year. Then the difference in losses for scenario s is approximated as

$$\mathrm{V}_{i,s} = \mathrm{TSL}_{i,0} - \mathrm{TSL}_{i,s}, \tag{14}$$

where $s = 0$ is BAU.

We convert each difference $\mathrm{V}_{i,s}$ from its value in dollars to its equivalent valuation in lives:

$$\tilde{V}_{i,s} = \mathrm{V}_{i,s}/\mathrm{VSL}_i. \tag{15}$$

For each scenario, we resample simulated values of $\tilde{V}_{i,s}$ to make 2,048 sets of 200 (approximating the world's total) synthetic LLMIC, UMIC and HIC with proportions { 0.52, 0.32, 0.16 }, reflecting global population distributions. We reorder each set of 2,048 samples such that the rank correlation between the 200 samples matches the median rank correlation for losses observed between synthetic countries. The median correlation between countries' losses within scenarios is 0.62.

Imagine a grid $\hat{V}$ of difference values $\hat{V}_{j,k}$, where $j = 1, ..., 2,048$ indexes the set of values for $k = 1, ..., 200$ countries. For $k = 1, ..., 104$, the sample $\hat{V}_{\cdot,k}$ is drawn from the set of values $\tilde{V}_{i,s}$ belonging to synthetic LLMIC. For $k = 105, ..., 168$ values are drawn from synthetic UMIC. For $k = 169, ..., 200$ values are drawn from synthetic HIC. Subsequent sets $\hat{V}_{\cdot,k'}$ are drawn and ordered so that the rank correlation with $\hat{V}_{\cdot,k}$ is 0.62, for all sets {k,k'}.

Our final global samples are sums across rows: $\bar{V}_j = \sum_k \hat{V}_{j,k}$.[e] Then to convert back to a dollar value, we multiply by the global VSL (for which we take the population-weighted average across all synthetic countries) to give a value in USD, or a % of global GDP.

---

[e] As the columns have been ordered, the top rows would have the most severe pandemics, where most or all countries would have high losses. The bottom rows would have the least severe pandemics, where many countries contribute losses that are nil or small. Because of the heavy-tailed nature of the loss distributions, pandemics of moderate severity would also contain many country contributions that are negligible or small.

We add up the total loss in terms of lives. This approach aligns with that taken in climate economics[38,39] as well as cost–benefit analyses in regional[40] and domestic settings.[41,42] It also has a foundation in philosophy[43] and international law.[44] Finally, it is consistent with analyses that choose not to apply valuations to lives and life years at all and therefore treat them on an equal basis. We measure in lives and not money, because it is human life that we value. We report results in monetary terms as it is more familiar as a metric for valuing but we note that money is itself of value only inasmuch as it proxies welfare.

B.3 Exceedance probabilities

To approximate the ΔLIR of investments into vaccines and vaccination capacity, we estimate the likelihood of pandemics of different severities occurring, using a generalised Pareto distribution (GPD). It has been assumed previously that these can describe the empirical exceedance frequency distribution of epidemic intensity adequately, where intensity was defined as deaths per thousand population per year.[45]

As we are interested in the total burden, we apply the same methodology to "severity", which we define as deaths per thousand population. We note that, although "severity" will likely have a different distribution from "intensity", it appears the GPD model fit is not substantially worse for the dataset of Marani et al.[45] from 1600 up to the present day (Figure B.2).

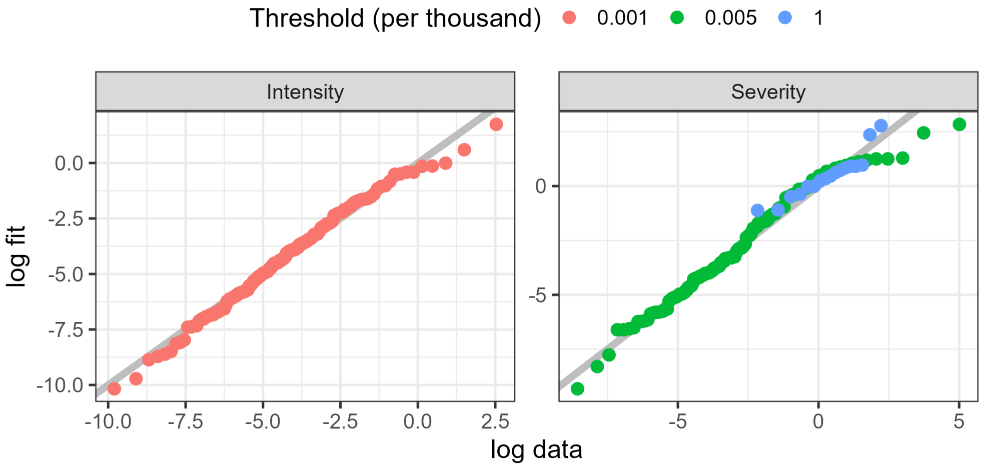

Figure B.2: **QQ plot for GPD fits** Quantile–quantile plot showing the generalised Pareto distributions' fit to the intensity (deaths per thousand population per year, left) and severity (deaths per thousand population, right) using the pandemic dataset of Marani et al.[45] up to the year 2020. The Intensity model from Marani et al.[45] assumed a threshold of 0.001. We assume the threshold to be a random variable that varies between $10^{-1 \cdot 35}$ and $10^{-0 \cdot 75}$.

Our exceedance probability function is defined by four parameters: the location μ, the detection threshold p_b, and the GPD parameters ξ and σ. We create model uncertainty for this function by (a) sampling parameter values, and (b) resampling the Marani et al.[45] dataset so that the composition is different for each sample. We sample the threshold μ that defines where the tail begins, which we express as a power of ten with exponent varying uniformly between -1.35 and -0.75. We treat the threshold as a random variable to reflect modelling uncertainty about where the GPD tail should begin. The other three parameters are estimated for each bootstrapped dataset as in Marani et al.[45][f]: p_b is defined as the fraction of epidemics with deaths per thousand greater than μ in the resampled dataset, and ξ and σ are estimated through fitting the function to the data given the sampled value of μ using the maximum likelihood method in the R package `evir`. Maximum likelihood is consistent with the methodology of Marani et al.[45] and performs well with small samples, as we have as μ approaches 1. We account for sensitivity to the few extreme values through bootstrapping.

The bulk of the distribution is fit using a lognormal distribution, which is used to give probabilities to values to the left of the tail. We have one more parameter to complete this part of the model: p_S, which is the probability for the epidemic-causing pathogen to be a sarbecovirus. This value comes from application of a logistic function to the subset of resampled data from the last one hundred years (excluding the last instance of pneumonia, which might have been SARS). Sampled values for this parameter have a mean of 0.22 and an IQR of 0.11–0.29. Using this distribution, the probability (IQR) that at least one SARS-X pandemic triggers a pandemic response (i.e. it has the severity of a once-in-thirty-years pandemic or greater) in a seventy-five–year period is 40–44%. The expected number of such events over the period has IQR 0.52–0.57.

The global samples approximating pandemics from Section B.2 have an associated number of deaths. We use the global death burden in the BAU scenario to be the "counterfactual" pandemic death burden. We map this number onto the GPD to get an exceedance probability for each sample (illustrated in Figure C.8). As each scenario uses the same set of epidemics in the same order, the scenario has the same probability as its counterfactual counterpart, and we can build the distribution of ΔLIR as the differences between scenarios and their counterfactuals.

We also use the exceedance probability of the counterfactual to build distributions of ΔLIR for events corresponding to a particular return time, for the cases that the pandemics are caused by SARS-X, where return time is the average time expected to pass between events that exceed a specified threshold of severity. That is, we imagine there has been a pandemic that was caused by SARS-X and has a severity that we would expect to see only once per return time. These illustrations therefore do not include uncertainty from the random variable

---

[f] Note that we use all the data collated by Marani et al.[45] up to now, and add the COVID-19 pandemic.[46] Additionally, we find 1.8 thousand rather than 1.8 million deaths reported in Hashemi Shahraki et al.[47]

p_S.

B.4 Data for the impact model

Table B.6: **Data sources used in the impact model.** Some sources were accessed directly from the source that produced them; others are from publications that collated data and made them available, which we subsequently accessed.

Item	Source	Date accessed	Number of countries in source HIC	UMIC	LMIC	LIC
Demographic						
Population distribution by age	Walker et al.[48]	June 2024	64	51	55	27
Life expectancy	Doohan et al.[49]	May 2023	51	50	54	25
Economic						
GDP	Piburn[50]	April 2024	67	53	54	24
Number of workers per sector	Doohan et al.[49]	May 2023	44	36	42	19
GVA per sector	Doohan et al.[49]	May 2023	42	15	10	2
Labour share of GVA	Feenstra et al.[51]	April 2024	52	35	29	9
Fraction working from home by sector	Doohan et al.[49]	May 2023	44	36	42	19
Tourism statistics	UN Tourism[52]	April 2024	28	5	2	0
COVID-19 tourism impact	UN Tourism[53]	April 2024	42	14	8	0
Pupil–teacher ratio	Piburn[50]	September 2025	68	49	53	27
Economic configurations	Doohan et al.[49]	May 2023	2	1	0	0
Epidemiological						
Community contact matrix	Walker et al.[48]	October 2023	10	2	2	0
Workplace-related contacts	Jarvis et al.[54]	January 2024	4	0	0	0
Hospital capacity	Doohan et al.[49]	May 2023	57	50	55	26
Testing rate	Doohan et al.[49]	May 2023	55	46	44	25
Mobility	Doohan et al.[49]	May 2023	52	31	33	10
COVID-19 deaths	Doohan et al.[49]	May 2023	52	31	33	10
Policy response	Doohan et al.[49]	May 2023	52	31	33	10
Pathogen natural history parameters	Doohan et al.[49]	May 2023	NA			
Historic outbreaks	Marani et al.[45]	November 2023	NA			

C Supplementary results

C.1 Results for costs of preparedness and response investments

C.1.1 Preparedness costs

Preparedness costs are given in Table C.10. Capacity reservation costs are incurred annually. BPSV manufacturing begins after R&D completion and vaccine licensure and doses are stored in an investigational reserve. One third of the vaccine reserve is manufactured each year to replace expiring doses. For enabling activities, we assume that CEPI's 2.0 budget is required for accelerating vaccine development timelines. We assume that five years of investment are needed to achieve 200 days to SSV, and 15 years of investment are needed to achieve 100 days to SSV, costing \$700M annually for the duration of investment.[33]

C.1.2 Cumulative preparedness costs over time

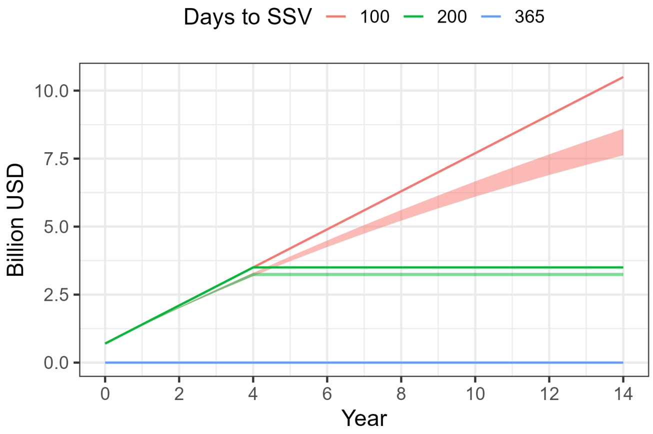

Figure C.3: Cumulative costs for R&D investments into SSV preparedness as they accumulate over a fifteen-year time horizon for three levels of investment considered: none, which would lead to 365 to SSV; five years of investments, which would lead to 200 days to SSV; and fifteen years, which would lead to 100 days to SSV. Lines show costs without discounting, and shaded areas IQRs with uncertain discount rates.

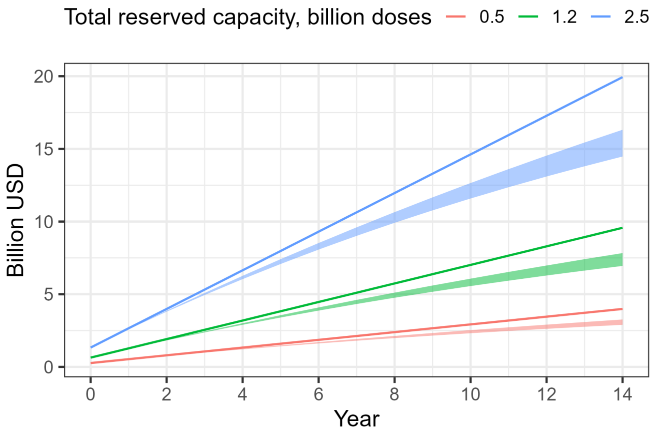

Figure C.4: Cumulative costs for capacity reservations as they accumulate over a fifteen-year time horizon for three levels of investment considered: no additional reservations beyond the 0.5bn-dose existing agreement; 0.7bn additional reserved doses; and 2bn additional doses. Lines show costs without discounting, and shaded areas IQRs with uncertain discount rates.

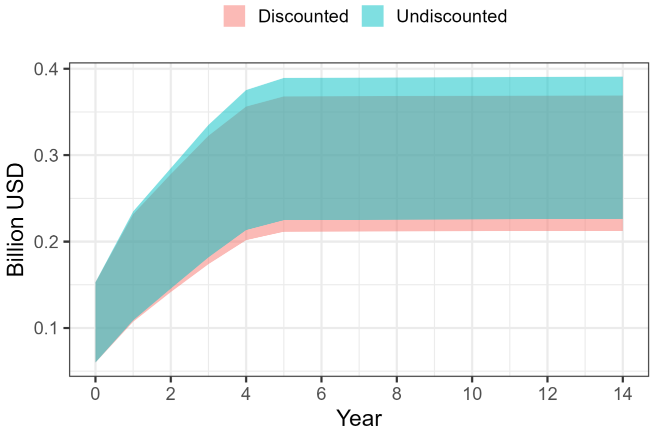

Figure C.5: Cumulative costs for BPSV investment as they accumulate over a fifteen-year time horizon (interquartile range). Red shows costs without discounting, and blue areas with uncertain discount rates.

C.1.3 Vaccine delivery

Table C.7: **Excess doses held by HIC.** The maximum number of SSV doses held idle (i.e. in excess of what they can deliver) by HIC while other countries have no doses during outbreak response.

Scenario	Doses (millions)
BAU	560
S01	641
S02	0
S03	0
S04	560
S05	0
S06	0
S07	560
S08	0
S09	0
S10	0

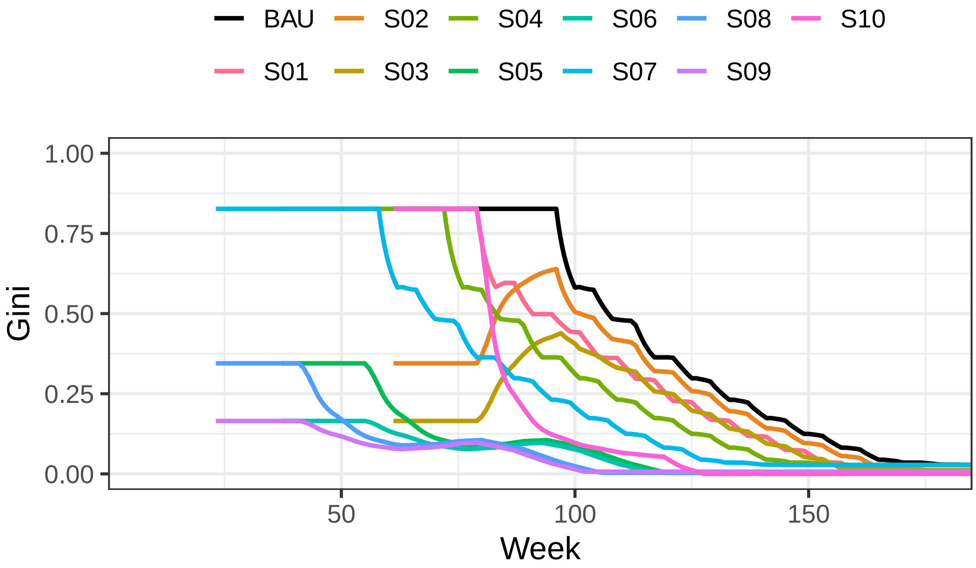

Figure C.6: **Inequality in vaccine delivery across income levels.** Shown for each scenario is the evolution of the Gini coefficient over time for SSV second doses delivered. There are three starting points corresponding to the three reservation sizes: where only HIC have capacity reserved (BAU, S01, S04, S07, S10), 17% of the world's population aged 15 and older get all the doses. The coefficient here is 0.83, close to the 0.88 reported by Tatar et al..[55] Where there is reserved capacity of 700 million doses per year also for UMIC and LLMIC (S02, S05, S08) the starting coefficient is lower, and for two billion doses (S03, S06, S09) it is lower still. Coefficients tend towards zero, at which point all income levels have 80% coverage in the target population. In scenarios in which there are additional reservations and unreserved doses go preferentially to HIC (S02, S03), there is an increase in the coefficient when those unreserved doses are produced and delivered in HIC. All scenarios whose unreserved doses go preferentially to HIC (BAU, S01, S02, S03, S04, S07) display delivery bottlenecks (which manifest as kinks in trajectories, also visible in Figure 1), wherein the countries receiving doses reach their delivery capacity and therefore have excess doses lying idle.

Table C.8: **Time to 40% vaccination coverage, by scenario and country income group, in weeks.** The timeline starts on the day the pathogen is sequenced.

Scenario	HIC	UMIC	LMIC	LIC
BAU	89	106	141	149
S01	73	90	130	139
S02	88	106	135	142
S03	88	103	128	132
S04	65	82	117	125
S05	77	85	89	86
S06	74	83	85	84
S07	51	68	103	111
S08	63	71	75	72
S09	60	69	71	70
S10	102	110	110	110

Table C.9: **Cost differences: investments vs. BAU, for different types of investment.** Values, corresponding to Figure 2, are shown to two significant figures, with interquartile ranges (IQR) in parenthesis. Response (Per pandemic) costs are discounted to the first year in which they occur (the start of the pandemic). Upfront and annual costs (Per year) are presented without discounting.

When cost is incurred	Type of cost	Investment	Cost vs. BAU, billion USD; median (IQR)
Upfront	Reservation and procurement	BPSV	0.000011
Upfront	R&D	BPSV	$0.29\ (0.22, 0.39)$
Upfront	R&D	200 days to SSV	3.5
Upfront	R&D	100 days to SSV	10
Per year	Reservation and procurement	BPSV	0.17
Per year	Reservation and procurement	0.7 billion capacity	0.37
Per year	Reservation and procurement	2 billion capacity	1.1
Per pandemic	R&D	BPSV	$0.007\ (0.0039, 0.015)$
Per pandemic	R&D	200 days to SSV	$-0.15\ (-0.25, -0.093)$
Per pandemic	R&D	100 days to SSV	$-0.23\ (-0.36, -0.15)$
Per pandemic	Reservation and procurement	BPSV	4.7
Per pandemic	Reservation and procurement	0.7 billion capacity	-34
Per pandemic	Reservation and procurement	2 billion capacity	-110
Per pandemic	Delivery	BPSV	$14\ (12, 16)$
Per pandemic	Delivery	0.7 billion capacity	$0.15\ (0.11, 0.18)$
Per pandemic	Delivery	2 billion capacity	$0.35\ (0.27, 0.43)$
Per pandemic	Delivery	Equality + Delivery	$-1.8\ (-2.3, -1.4)$

C.1.4 Full results for preparedness and response costs

Table C.10: **Preparedness and response costs.** Singular values are shown for values that don't include uncertainty. Interquartile ranges of 10,000 samples are shown for uncertain costs. All values are million USD in 2025 prices, with response costs given once discounted to the first year of response, once without discounting, and once as a percentage of total response costs. Upfront costs are discounted to the present day.

	BAU	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10
Upfront costs; million USD											
BPSV upfront R&D	0	210–370	0	0	0	0	0	0	0	0	0
BPSV upfront procurement	0	0.01	0	0	0	0	0	0	0	0	0
Enabling activities	0	0	0	0	3,200–3,300	3,200–3,300	3,200–3,300	7,600–8,600	7,600–8,600	7,600–8,600	0
Total upfront	0	210–370	0	0	3,200–3,300	3,200–3,300	3,200–3,300	7,600–8,600	7,600–8,600	7,600–8,600	0
Annual costs; million USD;											
Reserved capacity cost	270	270	640	1,300	270	640	1,300	270	640	1,300	270
BPSV investigational reserve	0	0.17	0	0	0	0	0	0	0	0	0
Total annual	270	270	640	1,300	270	640	1,300	270	640	1,300	270
Response costs (million USD; discounted)											
BPSV response R&D	0	3.9–15	0	0	0	0	0	0	0	0	0
BPSV response procurement	0	4,700	0	0	0	0	0	0	0	0	0
BPSV delivery	0	12,000–16,000	0	0	0	0	0	0	0	0	0
SSV R&D	200–520	200–520	200–520	200–520	100–260	100–260	100–260	52–170	52–170	52–170	200–520

	BAU	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10
SSV procurement	370,000–380,000	370,000–390,000	340,000–350,000	270,000–280,000	380,000–390,000	350,000–360,000	290,000–300,000	380,000–400,000	340,000–350,000	290,000–300,000	360,000–370,000
SSV delivery	180,000–230,000	180,000–230,000	180,000–230,000	180,000–230,000	180,000–230,000	180,000–230,000	180,000–230,000	180,000–240,000	180,000–240,000	180,000–240,000	170,000–230,000
Total response	550,000–610,000	580,000–640,000	520,000–580,000	450,000–510,000	560,000–620,000	530,000–590,000	480,000–530,000	570,000–630,000	530,000–590,000	470,000–530,000	540,000–600,000
Response costs (million USD; undiscounted)											
BPSV response R&D	0	3.9–15	0	0	0	0	0	0	0	0	0
BPSV response procurement	0	4,700	0	0	0	0	0	0	0	0	0
BPSV delivery	0	12,000–16,000	0	0	0	0	0	0	0	0	0
SSV R&D	200–520	200–520	200–520	200–520	100–260	100–260	100–260	52–170	52–170	52–170	200–520
SSV procurement	410,000	410,000	380,000	300,000	410,000	380,000	320,000	410,000	370,000	310,000	400,000
SSV delivery	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000	190,000–250,000
Total response	600,000–660,000	620,000–690,000	570,000–630,000	490,000–550,000	600,000–660,000	570,000–630,000	510,000–570,000	600,000–660,000	560,000–620,000	500,000–560,000	590,000–650,000
Response costs (% of total response)											
BPSV response R&D	0	<1	0	0	0	0	0	0	0	0	0
BPSV response procurement	0	<1	0	0	0	0	0	0	0	0	0
BPSV delivery	0	2–2.4	0	0	0	0	0	0	0	0	0
SSV R&D	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
SSV delivery	31–38	31–36	33–40	39–45	31–38	34–40	37–44	31–38	34–40	38–45	32–38
SSV procurement	62–68	61–67	60–67	55–61	62–68	60–66	56–63	62–69	60–66	55–62	62–68

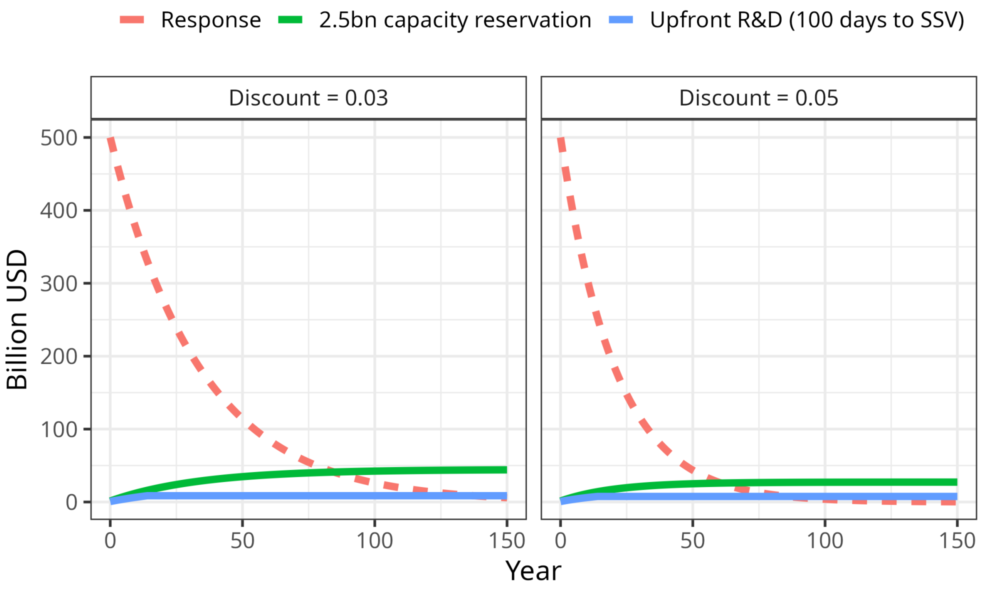

Figure C.7: **Relationships between costs, time, and discount rate.** For a representative response cost of 500 billion USD, we show how its value diminishes over time with two different rates of discounting, 3% and 5% (the IQR for the distribution used in our simulations). The y axis shows the present value of the instantaneous response cost in the event of a pandemic occurring in x years. For comparison, we show the present value of the cumulative cost over time of the most expensive upfront activity, namely 15 years of R&D to enable development of SSVs reactively in 100 days. We also show the present value of the most expensive annual cost accumulating, which is a capacity reservation of 2.5 billion doses. Present-value response costs can be expected to exceed other costs should a SARS-X pandemic occur in the next 61–85 years. Beyond this point, reservation costs continue accumulating, and response costs continue decreasing, going below the SSV R&D upfront cost 86–138 years into the future.

C.2 Impact of preparedness and response investments

C.2.1 Results for the epidemic library

C.2.1.1 Societal losses under alternative sector-closure policies among epidemic library candidates In this section we present approximations of the losses caused by epidemics from randomly generated pathogens for synthetic countries by country archetype, sector-closure policy, and vaccination scenario, for the three losses separately and summed up. Because we are varying key parameters across 2,048 epidemics in countries within a category (LLMIC, UMIC, or HIC), there is a distribution over losses, and uncertainty in the approximated range of losses is therefore very high.

Our sector-closure policies are: no closures (NC, because no closures are mandated) and reactive closures 1 to 3 (RC1 to RC3, which use different rules and stringencies to reduce infections through closures). They are defined by economic configurations and rules for moving between them. An economic configuration is a vector specifying the extent to which each sector is open, expressed as a percentage, and provides the link between the economic projection and the epidemiological model. Our economic configurations are constructed using data from three countries (Indonesia (RC1), the United Kingdom (RC2 and RC3), and Australia (RC3)), via the manifest economic impacts in the wake of the COVID-19 pandemic. We take the sectoral GVA observed during the COVID-19 pandemic expressed as a percentage of the values observed in the year before, i.e. we assume that the relative GVA reflects the degree to which sectors were open. See Johnson et al.[56] for details of this implementation, which is based on Doohan et al..[49]

Table C.11 shows the interquartile range (IQR) of total societal losses associated with epidemics by sector-closure policy, scenario and synthetic country group and expressed as % of pre-epidemic GDP. The table shows first outcomes for the BAU scenario, followed by the advance investment scenarios. The columns YLL, Education and GDP give the average percentage of the total losses coming from each type of loss.

The sector-closure policy has marked impacts on losses across the three categories. For example, the NC policy results in high YLL, but low education and GDP losses. School and economic closure policies result in lower YLL, at the expense of higher education or GDP losses, respectively. RC3 results in the highest total societal losses, with the lowest YLL of all policies, but high economic losses for UMIC and HIC.

Table C.11: **Societal losses of epidemics, by investment scenario, income country group, and sector-closure policy.** IQR of losses as % of pre-epidemic annual GDP.

Scenario	Sector-closure policy	Income group	Total losses	YLL (%)	Education (%)	GDP (%)
BAU	NC	LLMIC	9.4–107.3	89	0.6	10.4
BAU	RC1	LLMIC	87.2–243.6	24.6	62.8	12.6
BAU	RC2	LLMIC	47.6–143.4	27.3	18.5	54.1
BAU	RC3	LLMIC	101.8–224.5	18	37.8	44.1
BAU	NC	UMIC	7.8–98.2	92.3	0.4	7.3
BAU	RC1	UMIC	39.4–135.2	34.4	51	14.6
BAU	RC2	UMIC	26.5–93.9	39.4	10	50.6
BAU	RC3	UMIC	64–125.6	15.4	30.6	54
BAU	NC	HIC	8.5–99.5	92.7	0.3	7
BAU	RC1	HIC	33.6–126.9	41.4	44	14.6
BAU	RC2	HIC	24.3–88.5	43.1	9.1	47.8
BAU	RC3	HIC	56.4–104.1	15	27.8	57.2
S01	NC	LLMIC	8.6–100.9	89.4	0.6	10
S01	RC1	LLMIC	77.3–219.6	24	63.1	12.8
S01	RC2	LLMIC	43–127.7	26.7	19.4	53.9
S01	RC3	LLMIC	94.5–204.6	16.2	38.9	44.9
S01	NC	UMIC	6.8–90.9	92.4	0.4	7.2
S01	RC1	UMIC	33.5–115.6	32.9	51.9	15.2
S01	RC2	UMIC	23.7–80.2	38	10.8	51.2
S01	RC3	UMIC	55.7–103.7	13.2	31.1	55.7
S01	NC	HIC	7.2–90.3	92.5	0.3	7.1
S01	RC1	HIC	27.6–99.4	38.8	45.6	15.6
S01	RC2	HIC	20.8–72.7	41.1	9.9	49
S01	RC3	HIC	46.7–82.2	12.3	28.4	59.2
S02	NC	LLMIC	9.1–106.9	89.7	0.6	9.7
S02	RC1	LLMIC	80.2–230.4	25.4	62.2	12.4
S02	RC2	LLMIC	44.5–136.9	28.5	19.1	52.4
S02	RC3	LLMIC	97.8–216.1	18.3	37.9	43.8
S02	NC	UMIC	7.8–98	92.4	0.4	7.2
S02	RC1	UMIC	39.3–134.7	34.3	51.1	14.5
S02	RC2	UMIC	26.3–93.4	39.5	10	50.6
S02	RC3	UMIC	63.4–124.1	15.1	30.7	54.2
S02	NC	HIC	8.5–99.4	92.7	0.3	7
S02	RC1	HIC	33.5–126.8	41.4	44	14.6
S02	RC2	HIC	24.2–88.5	43.2	9.1	47.7
S02	RC3	HIC	56.3–104	15	27.8	57.1
S03	NC	LLMIC	9–106.6	90	0.6	9.4
S03	RC1	LLMIC	77–224	25.9	61.7	12.3
S03	RC2	LLMIC	42.9–132.7	28.6	19.5	51.9
S03	RC3	LLMIC	93.4–206.5	18.3	38.1	43.6
S03	NC	UMIC	7.7–98	92.4	0.4	7.2
S03	RC1	UMIC	38.9–133.7	34.4	51.1	14.5

Scenario	Sector-closure policy	Income group	Total losses	YLL (%)	Education (%)	GDP (%)
S03	RC2	UMIC	26.2–92.3	39.4	10	50.6
S03	RC3	UMIC	63.2–123.2	14.9	30.9	54.3
S03	NC	HIC	8.5–99.4	92.7	0.3	7
S03	RC1	HIC	33.4–126.7	41.4	44	14.6
S03	RC2	HIC	24.2–88.3	43.2	9.1	47.7
S03	RC3	HIC	56–103.9	15	27.8	57.1
S04	NC	LLMIC	8.9–106.9	89.8	0.6	9.6
S04	RC1	LLMIC	76.9–222.5	25.6	61.9	12.5
S04	RC2	LLMIC	43–134.1	28.2	19.5	52.3
S04	RC3	LLMIC	89.9–197	19.1	38.2	42.7
S04	NC	UMIC	7.1–97	93.6	0.4	6
S04	RC1	UMIC	33–122.4	37.4	48.6	14
S04	RC2	UMIC	22.7–84.8	41.1	11.2	47.7
S04	RC3	UMIC	52.5–105.5	16	31.2	52.8
S04	NC	HIC	7.7–97.7	93.6	0.3	6.1
S04	RC1	HIC	27.2–114.9	45.4	40.8	13.8
S04	RC2	HIC	20.4–79.3	44.9	10	45.1
S04	RC3	HIC	43.5–83.5	15.1	28.4	56.5
S05	NC	LLMIC	8.2–102.8	91.7	0.6	7.7
S05	RC1	LLMIC	60.8–186	28.1	59.9	12
S05	RC2	LLMIC	35.5–116.2	30.3	21.3	48.5
S05	RC3	LLMIC	72.7–161	18.8	39.5	41.7
S05	NC	UMIC	7.3–96.1	92.8	0.4	6.8
S05	RC1	UMIC	35.2–124	35.4	50.2	14.3
S05	RC2	UMIC	24.1–86.3	39.9	10.6	49.6
S05	RC3	UMIC	55.9–110.8	14.9	30.9	54.2
S05	NC	HIC	8–98.5	92.7	0.3	7
S05	RC1	HIC	31.5–120.9	41.5	44	14.6
S05	RC2	HIC	23.1–83.5	42.8	9.3	47.8
S05	RC3	HIC	51.7–95	14.5	27.9	57.6
S06	NC	LLMIC	8.1–101.4	91.7	0.6	7.6
S06	RC1	LLMIC	59.1–182.6	28.2	59.8	11.9
S06	RC2	LLMIC	34.9–114.6	30.2	21.5	48.3
S06	RC3	LLMIC	70.9–156.5	19.1	39.3	41.6
S06	NC	UMIC	7.1–95.8	92.8	0.4	6.8
S06	RC1	UMIC	34.5–123	35.5	50.2	14.4
S06	RC2	UMIC	23.7–85.4	39.9	10.6	49.5
S06	RC3	UMIC	54.7–108.6	14.8	30.8	54.3
S06	NC	HIC	7.9–98	92.7	0.3	7
S06	RC1	HIC	31.1–118.1	41.6	43.8	14.5
S06	RC2	HIC	22.7–82.7	42.9	9.4	47.7
S06	RC3	HIC	50.9–93.1	14.3	27.9	57.7
S07	NC	LLMIC	8.6–106.1	90.4	0.6	9
S07	RC1	LLMIC	71.5–210.7	26.4	61.3	12.4
S07	RC2	LLMIC	40.3–128	28.5	20.3	51.2
S07	RC3	LLMIC	82.7–182.8	19.2	38.8	42
S07	NC	UMIC	6.7–94.8	94.3	0.4	5.3

Scenario	Sector-closure policy	Income group	Total losses	YLL (%)	Education (%)	GDP (%)
S07	RC1	UMIC	29.1–114.8	39.8	46.5	13.7
S07	RC2	UMIC	20.5–79.7	42.4	11.7	45.9
S07	RC3	UMIC	45.1–93	16.3	31.5	52.1
S07	NC	HIC	6.9–95.3	94.3	0.3	5.4
S07	RC1	HIC	22.7–102.4	47.3	39	13.6
S07	RC2	HIC	17.5–70.7	45.5	10.7	43.8
S07	RC3	HIC	35.7–69.5	15.3	28.4	56.3
S08	NC	LLMIC	7.8–97.5	92.1	0.6	7.3
S08	RC1	LLMIC	54.1–170.8	28.8	59.4	11.8
S08	RC2	LLMIC	32.4–108.1	30.4	22.1	47.5
S08	RC3	LLMIC	64.5–142.2	18.8	39.6	41.6
S08	NC	UMIC	6.7–93.2	93.5	0.4	6.1
S08	RC1	UMIC	31.2–115.9	37	48.9	14.1
S08	RC2	UMIC	21.8–80.5	40.9	11.1	48
S08	RC3	UMIC	48.8–98.3	15.5	31.1	53.4
S08	NC	HIC	7.5–96.2	93.2	0.3	6.5
S08	RC1	HIC	27.3–107	42.9	42.7	14.4
S08	RC2	HIC	20.2–76.4	43.4	9.8	46.7
S08	RC3	HIC	44.2–81.9	14	28.2	57.7
S09	NC	LLMIC	7.6–96.1	92.2	0.7	7.2
S09	RC1	LLMIC	52.5–165.2	28.9	59.3	11.8
S09	RC2	LLMIC	31.6–104.4	30.2	22.3	47.6
S09	RC3	LLMIC	62.6–137.9	18.3	39.8	41.8
S09	NC	UMIC	6.6–92.4	93.5	0.4	6
S09	RC1	UMIC	30.6–114.3	36.9	49	14.2
S09	RC2	UMIC	21.2–79.1	40.7	11.2	48.1
S09	RC3	UMIC	47.8–95	15.2	31.1	53.7
S09	NC	HIC	7.3–95.5	93.2	0.3	6.5
S09	RC1	HIC	26.8–106.5	42.9	42.7	14.4
S09	RC2	HIC	19.8–75	43.3	9.9	46.8
S09	RC3	HIC	43–80.3	13.9	28.3	57.7
S10	NC	LLMIC	8.6–105.7	91.6	0.6	7.8
S10	RC1	LLMIC	65.3–199.1	27.9	60.1	12
S10	RC2	LLMIC	38.2–124.9	30.7	20.9	48.5
S10	RC3	LLMIC	82–181.9	19.6	39.1	41.4
S10	NC	UMIC	7.8–98.3	91.8	0.4	7.8
S10	RC1	UMIC	42.1–139.8	32.8	52.4	14.8
S10	RC2	UMIC	28.3–95.5	38.1	9.6	52.2
S10	RC3	UMIC	68.2–132	14.8	30.3	54.9
S10	NC	HIC	8.8–100.3	91.9	0.3	7.8
S10	RC1	HIC	38.4–131.8	38.3	46.5	15.2
S10	RC2	HIC	27.2–93.4	41.4	8.5	50.1
S10	RC3	HIC	64.6–115.5	14.3	27.3	58.4

Some distributions, notably those for GDP losses under the RC3 strategy, are bimodal. This means that samples group into two distinct types, those with higher losses and those with lower losses, with few samples having losses that fall in between. This is due to the construction of the closure policies, which each consist of two economic configurations, one of which is more stringent than the other. The higher-loss projections likely correspond to epidemics that result in heavy closures for the whole duration, based on the closure rules, while the lower-loss projections correspond to epidemics that result in heavy closures for a short period only. Outbreaks are either easily controlled with just a short closure, or they require stringent interventions.

C.2.1.2 Societal losses under the loss-minimising sector closure policy in the epidemic library

From among the four sector-closure policy options considered in Section C.2.1.1 for each scenario–country combination, we select the loss-minimising option for each epidemic and retain it for inclusion in a library of epidemics. Results analogous to those of Section C.2.1.1 are shown in Table C.12.

Among epidemics that are least severe, NC is most often the loss-minimising policy. In contrast, among severe epidemics, closures are more often chosen as they reduce overall societal losses, which means that, in this space, YLL can be decreased at the expense of higher economic and educational losses with a net societal benefit overall.

Table C.12: **Losses (IQR) for all investment scenarios and country types,** taking the loss-minimising epidemic from the four sector closure policy options in Table C.11.

Scenario	Income group	Total losses	YLL (%)	Education (%)	GDP (%)
BAU	LLMIC	9.4–97.5	85.4	1.3	13.2
BAU	UMIC	7.8–77.2	83	2.8	14.2
BAU	HIC	8.5–72.2	79	4.2	16.8
S01	LLMIC	8.6–89.8	84.6	1.9	13.5
S01	UMIC	6.8–65.6	81.3	3.5	15.2
S01	HIC	7.1–57.2	76	5.3	18.7
S02	LLMIC	9.1–95.4	85.4	1.6	13
S02	UMIC	7.7–76.1	82.9	2.9	14.2
S02	HIC	8.5–71.8	78.8	4.4	16.8
S03	LLMIC	9–92.8	85.1	1.7	13.1
S03	UMIC	7.7–75.6	82.9	2.8	14.3
S03	HIC	8.5–71.8	78.8	4.4	16.8
S04	LLMIC	8.9–92.7	85.1	1.7	13.2
S04	UMIC	7.1–69.2	81.3	4	14.8
S04	HIC	7.6–61.2	75.4	5.7	18.9
S05	LLMIC	8.2–84	84.7	2.6	12.7

Scenario	Income group	Total losses	YLL (%)	Education (%)	GDP (%)
S05	UMIC	7.3–70.2	81.6	3.3	15.1
S05	HIC	8–66.5	77.6	4.7	17.6
S06	LLMIC	8.1–82.5	84.6	2.6	12.7
S06	UMIC	7.1–69.3	81.4	3.3	15.2
S06	HIC	7.9–65.7	77.1	4.9	18
S07	LLMIC	8.6–90.4	84.9	2	13.1
S07	UMIC	6.7–63.8	80.3	4.6	15.1
S07	HIC	6.9–53.3	73.6	6.6	19.8
S08	LLMIC	7.8–79.6	83.7	3.1	13.2
S08	UMIC	6.7–65.1	80.9	3.9	15.2
S08	HIC	7.4–59.4	75.9	5.4	18.6
S09	LLMIC	7.6–77.6	83.4	3.3	13.3
S09	UMIC	6.6–63.9	80.8	4	15.2
S09	HIC	7.3–58.4	75.5	5.7	18.8
S10	LLMIC	8.6–89.3	85.8	2.1	12.1
S10	UMIC	7.8–78	83.2	2.5	14.4
S10	HIC	8.8–76.6	79.8	3.7	16.5

C.2.1.3 Societal losses averted by advance vaccine investments under the loss-minimising sector closure policy in the epidemic library

We approximate the losses averted by advance vaccine investments under the loss-minimising sector closure policy in the epidemic library as the difference in losses between a scenario and BAU, where in each case the loss is the least it can be given the sector-closure options considered. The IQR of losses averted with the investment scenarios for the library of epidemics are tabulated in Table C.13. As with the epidemic losses shown in Table C.12, there is high variability in losses averted in the epidemic library (Table C.13), with high density close to zero and some extreme losses averted.

Table C.13: **Epidemic losses averted by advance vaccine investments.** IQR, % of annual pre-epidemic GDP. Epidemic losses averted by advance vaccine investments, having selected the loss-minimising sector closure policy in the epidemic library, expressed as a percent of annual pre-epidemic GDP; shown is the IQR of 2,048 samples, rounded to two significant figures; shown are the ΔLIR of all scenarios when compared against BAU.

Scenario	Income group	Epidemic library losses averted (% of GDP)
S01	LLMIC	0.21–4.9
S02	LLMIC	0.035–0.75
S03	LLMIC	0.09–1.8

Scenario	Income group	Epidemic library losses averted (% of GDP)
S04	LLMIC	0.1–1.5
S05	LLMIC	0.33–5.5
S06	LLMIC	0.36–6.3
S07	LLMIC	0.17–2.6
S08	LLMIC	0.48–8.2
S09	LLMIC	0.52–9.8
S10	LLMIC	0.24–3.3
S01	UMIC	0.29–6.5
S02	UMIC	0.0031–0.14
S03	UMIC	0.012–0.36
S04	UMIC	0.17–3.5
S05	UMIC	0.13–2.7
S06	UMIC	0.16–3.2
S07	UMIC	0.28–6
S08	UMIC	0.28–5.5
S09	UMIC	0.33–6.5
S10	UMIC	-0.57–-0.022
S01	HIC	0.44–8.8
S02	HIC	0.0033–0.061
S03	HIC	0.0081–0.16
S04	HIC	0.29–4.9
S05	HIC	0.097–2.2
S06	HIC	0.12–2.7
S07	HIC	0.56–9.8
S08	HIC	0.34–6.5
S09	HIC	0.38–7.4
S10	HIC	-2.4–-0.13

C.2.2 Exceedance probabilities

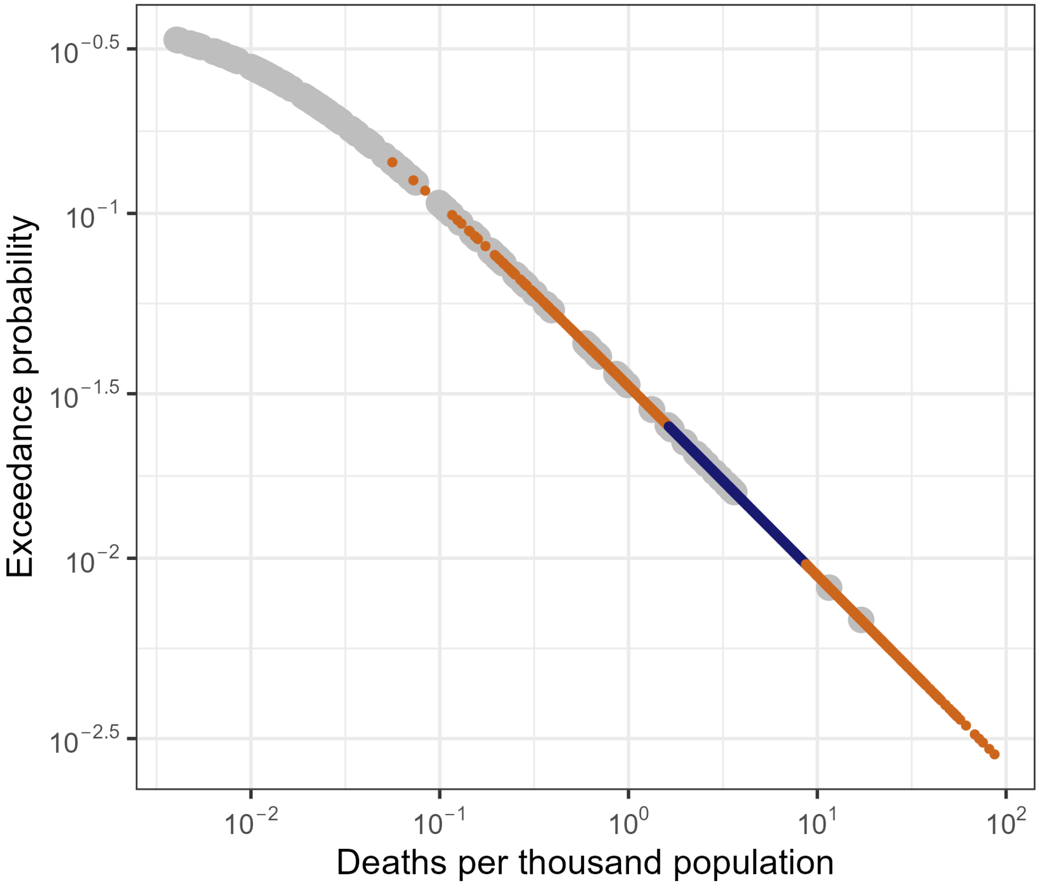

Figure C.8: **Exceedance probabilities of pandemics as a function of severity.** We map pandemic outcomes (deaths per thousand population) onto exceedance probabilities using a generalised Pareto distribution fitted to the data in Marani et al..[45] In grey are the numbers of deaths per thousand population in the data shown against the corresponding exceedance probability. In orange and blue the numbers of deaths per thousand of our synthetic pandemics and the corresponding exceedance probabilities using the function fit to the historical data. Blue points are those lying within the interquartile range.

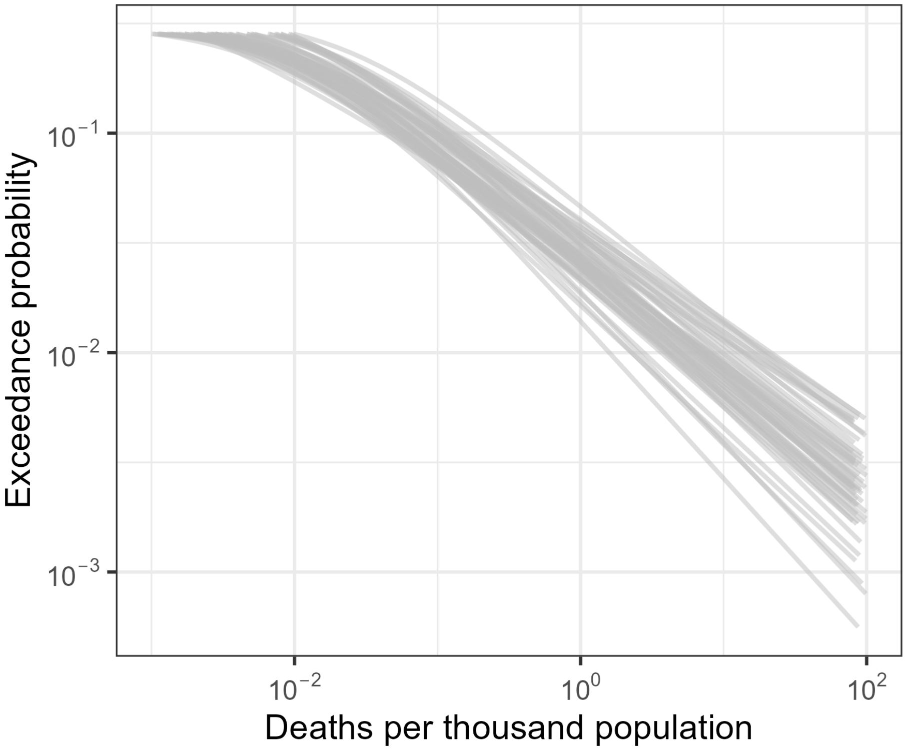

Figure C.9: **Exceedance probabilities of pandemics as a function of severity with sampled location parameters.** Lines show relationships generated by fitting generalised Pareto distributions when the location parameter is sampled and epidemics constituting the dataset are resampled with replacement.

C.2.3 Losses under business as usual

Table C.14 presents estimates of losses under ideal response (ΔLIR) for the counterfactual BAU scenario with limited advance investments into vaccines for pandemics of varying severity.

Table C.14: **Total societal losses and deaths under BAU**

	LIR, % global GDP	Deaths per thousand
Expectation	0.39–1.1	0.023–0.063
Conditional on pandemic severity and SARS-X being the causative agent		
Once in thirty years	15–21	1.1–1.5
Once in forty years	20–32	1.4–2.1
Once in fifty years	27–41	1.8–2.6
Once in sixty years	33–51	2.1–3.1
Once in seventy years	39–61	2.5–3.6
Once in eighty years	44–73	2.8–4.2
Once in ninety years	50–83	3.1–4.7
Once in one hundred years	56–92	3.3–5.3

C.2.4 Impact of advance investments into vaccines

Table 2 presents estimates of annualised differences in losses under ideal response (ΔLIR) by advance investments in vaccines for all investment scenarios compared to losses under BAU.

To illustrate the impacts of different (ac)counting assumptions on results, Table C.15 shows examples where ΔLIR is accumulated over a number of years using different temporal assumptions. Interested readers can enter their own values and generate their own results using the provided Supplementary Table (currently residing at https://docs.google.com/spreadsheets/d/1eeeCgBZlPtiZ3ziO4YKiXjAb7PA1tEmp_J6D33yikwY/edit?usp=sharing).

Table C.15: **Expected value of investments for different temporal assumptions in present-value USD; trillions (2025 prices).** All examples start with a global GDP of 113.8 trillion USD in 2025. Accumulation begins in 2040 for Examples 3 and 4, and 2050 for Examples 1 and 2. It ends in 2099 for Examples 1, 2 and 3, and 2089 for Example 4. Growth and discount rates are both 0.023 for Examples 1 and 3, and growth is 0.03 and discount 0.04 for Examples 2 and 4.

	Example 1	Example 2	Example 3	Example 4
Accumulation inputs				
Discount rate	0.023	0.04	0.023	0.04
Growth rate	0.023	0.03	0.023	0.03

	Example 1	Example 2	Example 3	Example 4
Time horizon	2050–2099	2050–2099	2040–2099	2040–2089
Results by scenario; trillion USD, 2025 prices				
S01	2.2–6.3	1.3–3.9	2.6–7.5	1.5–4.2
S02	0.22–0.63	0.14–0.39	0.27–0.75	0.15–0.42
S03	0.39–1.1	0.24–0.67	0.47–1.3	0.27–0.73
S04	0.91–2.5	0.56–1.5	1.1–3	0.62–1.7
S05	1.4–3.8	0.84–2.3	1.6–4.5	0.93–2.5
S06	1.6–4.3	0.98–2.7	1.9–5.2	1.1–2.9
S07	1.6–4.4	0.98–2.7	1.9–5.3	1.1–3
S08	2.3–6.3	1.4–3.9	2.7–7.5	1.5–4.2
S09	2.6–7.4	1.6–4.6	3.1–8.9	1.8–5
S10	0.43–1.2	0.27–0.74	0.52–1.4	0.29–0.81

Table C.16 presents the ΔLIR of advance investments in the cases that pandemics of specific severities occur, and assuming the pandemic is caused by SARS-X. Note that not all pandemics with a severity we would expect to see once in every thirty years will be caused by SARS-X. Therefore, investments will not have impact in every once-in-thirty-years pandemic, but only for the subset of pandemics caused by SARS-X with a severity we would expect to see once in every thirty years.

ΔLIR values are given in terms of % of counterfactual pandemic losses as well as percent of contemporaneous global GDP (Table C.14). Note that ΔLIR of investments decrease in terms of counterfactual pandemic losses as pandemics become more severe, but increase as a percentage of GDP. This is because overall the losses are greater for severe pandemics, so there is more to be gained in advance investments. The smaller losses of milder pandemics are more successfully averted with advance investments, compared to greater losses of more severe pandemics.

Table C.16: **ΔLIR of advance vaccine investments in pandemics of specified severities conditional on the pandemic having been caused by SARS-X** Note: Estimates are conditional on the pandemic having been caused by SARS-X

Probability	Scenario	ΔLIR, % of counterfactual	ΔLIR, % GDP
Once in thirty years	S01	8.7–10	1.3–2.1
Once in thirty years	S02	1–1.5	0.17–0.29
Once in thirty years	S03	2–2.7	0.32–0.53
Once in thirty years	S04	4.7–5.6	0.71–1.1
Once in thirty years	S05	7–8.5	1.1–1.7

Probability	Scenario	ΔLIR, % counterfactual	ΔLIR, % GDP
Once in thirty years	S06	7.9–9.5	1.2–1.9
Once in thirty years	S07	8.1–9.6	1.2–1.9
Once in thirty years	S08	11–13	1.7–2.7
Once in thirty years	S09	12–15	1.9–3
Once in thirty years	S10	1.9–2.9	0.3–0.56
Once in forty years	S01	8.9–11	1.9–3.1
Once in forty years	S02	1.1–1.5	0.24–0.43
Once in forty years	S03	2–2.7	0.44–0.75
Once in forty years	S04	4.7–5.6	1–1.6
Once in forty years	S05	6.9–8.5	1.5–2.5
Once in forty years	S06	7.9–9.5	1.7–2.8
Once in forty years	S07	8.2–9.7	1.8–2.8
Once in forty years	S08	11–13	2.4–4
Once in forty years	S09	12–15	2.7–4.4
Once in forty years	S10	1.9–2.9	0.43–0.8
Once in fifty years	S01	9–11	2.6–4.2
Once in fifty years	S02	1.1–1.5	0.31–0.58
Once in fifty years	S03	2–2.6	0.59–1
Once in fifty years	S04	4.7–5.6	1.4–2.2
Once in fifty years	S05	7–8.5	2–3.3
Once in fifty years	S06	7.9–9.6	2.3–3.7
Once in fifty years	S07	8.2–9.8	2.4–3.7
Once in fifty years	S08	11–13	3.2–5.2
Once in fifty years	S09	13–15	3.6–5.9
Once in fifty years	S10	1.9–3	0.57–1.1
Once in sixty years	S01	9.1–11	3.2–5.3
Once in sixty years	S02	1.1–1.6	0.39–0.72
Once in sixty years	S03	2–2.6	0.71–1.2
Once in sixty years	S04	4.6–5.6	1.6–2.7
Once in sixty years	S05	7–8.5	2.5–4.1
Once in sixty years	S06	7.9–9.6	2.8–4.6
Once in sixty years	S07	8.1–9.8	2.9–4.7
Once in sixty years	S08	11–14	4–6.5
Once in sixty years	S09	13–15	4.5–7.3
Once in sixty years	S10	1.9–3	0.71–1.4
Once in seventy years	S01	9.2–11	3.8–6.4
Once in seventy years	S02	1.1–1.5	0.46–0.85
Once in seventy years	S03	1.9–2.6	0.86–1.5
Once in seventy years	S04	4.6–5.6	1.9–3.2
Once in seventy years	S05	6.9–8.5	2.9–4.9
Once in seventy years	S06	7.9–9.6	3.3–5.6
Once in seventy years	S07	8.1–9.8	3.4–5.6
Once in seventy years	S08	11–14	4.7–7.9
Once in seventy years	S09	13–15	5.3–8.9
Once in seventy years	S10	1.9–2.9	0.84–1.6
Once in eighty years	S01	9.3–11	4.4–7.6
Once in eighty years	S02	1.1–1.5	0.54–0.97

Probability	Scenario	ΔLIR, % counterfactual	ΔLIR, % GDP
Once in eighty years	S03	1.9–2.6	0.99–1.7
Once in eighty years	S04	4.5–5.5	2.3–3.7
Once in eighty years	S05	6.9–8.4	3.4–5.7
Once in eighty years	S06	7.9–9.6	3.8–6.5
Once in eighty years	S07	8–9.7	3.9–6.4
Once in eighty years	S08	11–14	5.5–9.2
Once in eighty years	S09	13–15	6.2–10
Once in eighty years	S10	2–2.9	0.99–1.8
Once in ninety years	S01	9.3–11	5–8.5
Once in ninety years	S02	1–1.5	0.61–1.1
Once in ninety years	S03	1.9–2.6	1.1–1.9
Once in ninety years	S04	4.4–5.5	2.5–4.1
Once in ninety years	S05	6.8–8.4	3.8–6.5
Once in ninety years	S06	7.8–9.5	4.3–7.3
Once in ninety years	S07	7.9–9.5	4.4–7.1
Once in ninety years	S08	11–14	6.2–11
Once in ninety years	S09	13–15	7–12
Once in ninety years	S10	2–2.9	1.1–2.1
Once in one hundred years	S01	9.3–11	5.6–9.9
Once in one hundred years	S02	1–1.5	0.67–1.2
Once in one hundred years	S03	1.9–2.5	1.2–2
Once in one hundred years	S04	4.3–5.4	2.8–4.4
Once in one hundred years	S05	6.8–8.3	4.2–7
Once in one hundred years	S06	7.8–9.5	4.8–8
Once in one hundred years	S07	7.8–9.4	4.9–7.9
Once in one hundred years	S08	11–13	6.8–12
Once in one hundred years	S09	13–15	7.6–13
Once in one hundred years	S10	2–2.8	1.2–2.4

C.2.5 Supplementary figures for the impact model

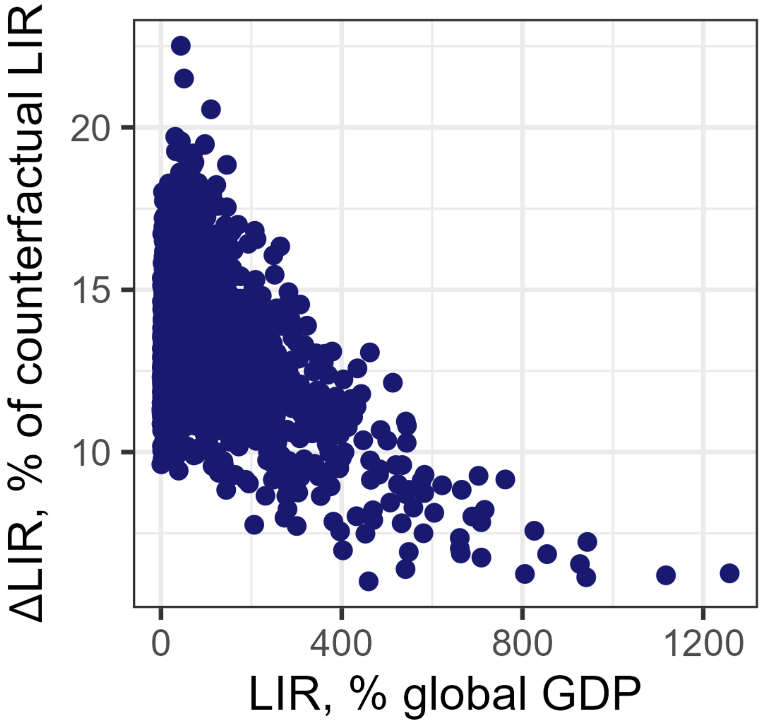

Figure C.10: **ΔLIR as % of loss vs. loss as a % of GDP for S09.** When the loss is low, as much as 20% of losses can be averted with investment. For high losses, however, only 5% might be expected to be averted.

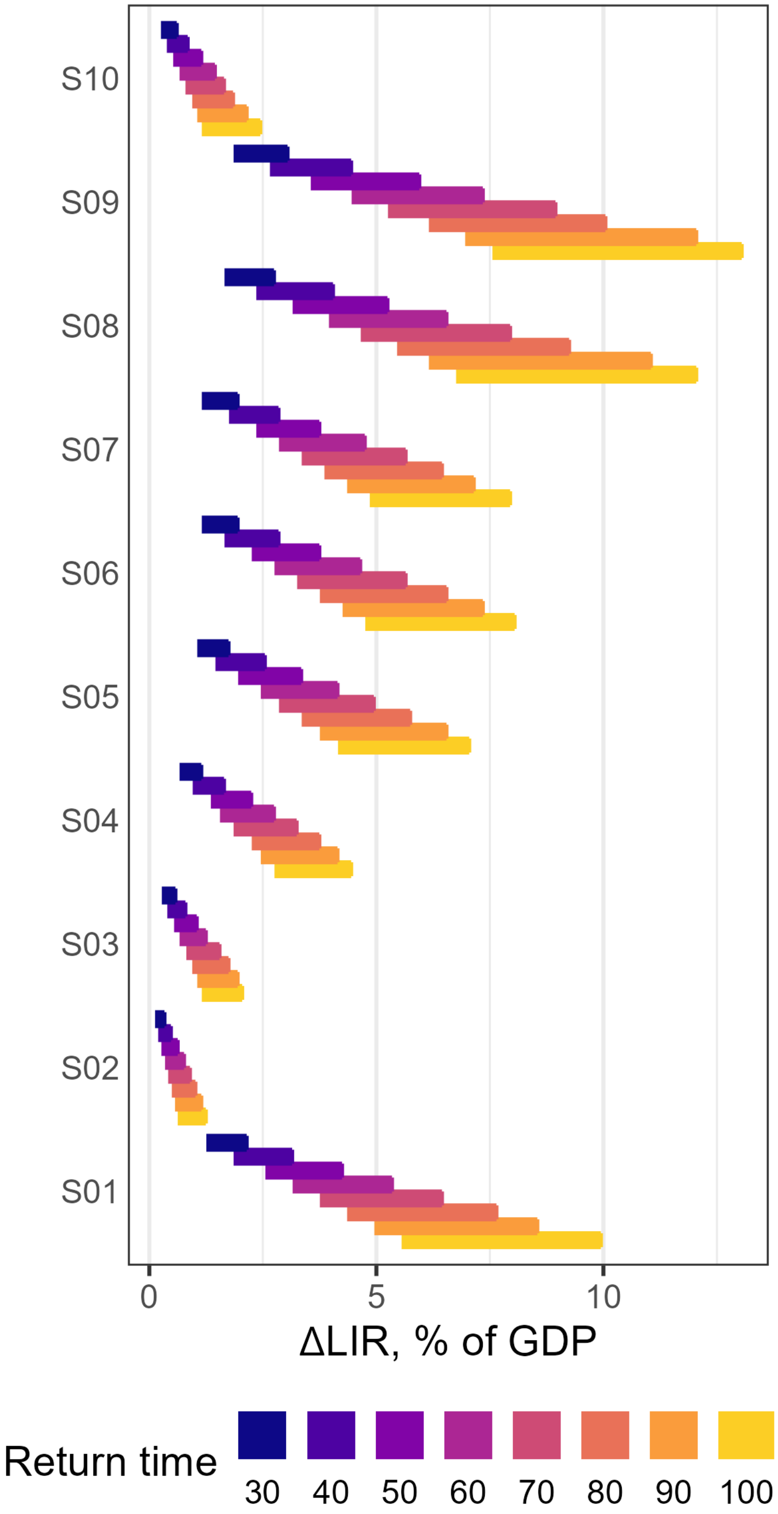

Figure C.11: **ΔLIR as a % of global GDP for different pandemic severities,** in the event that the pandemic is caused by SARS-X, with return time given in years, so that, for example, a pandemic with a return time of 30 years has an annual probability to occur of 1/30.

C.2.5.1 Composition of estimated impacts Our results are aggregate ΔLIRs of advance investments, summing over types of societal loss and then over country samples. We evaluate where investments result in greatest gains by examining their compositions. Figure C.12 shows the composition of the ΔLIR of investments in terms of country income levels and types of loss. Bars show the median % contribution to the ΔLIR of each investment scenario. We find that much of the ΔLIR of advance investments is realised via averted losses of lives, with a lesser economic gain due to earlier lifting of closures, measured by short-term GDP and long-term gains from education. The distribution of ΔLIR across country types varies across scenarios. Blue reference lines in Figure C.12 (right) indicate ΔLIR attributable to LLMIC proportional to population size. Thus there is an increase in equality as a consequence of investments in some but not all scenarios.

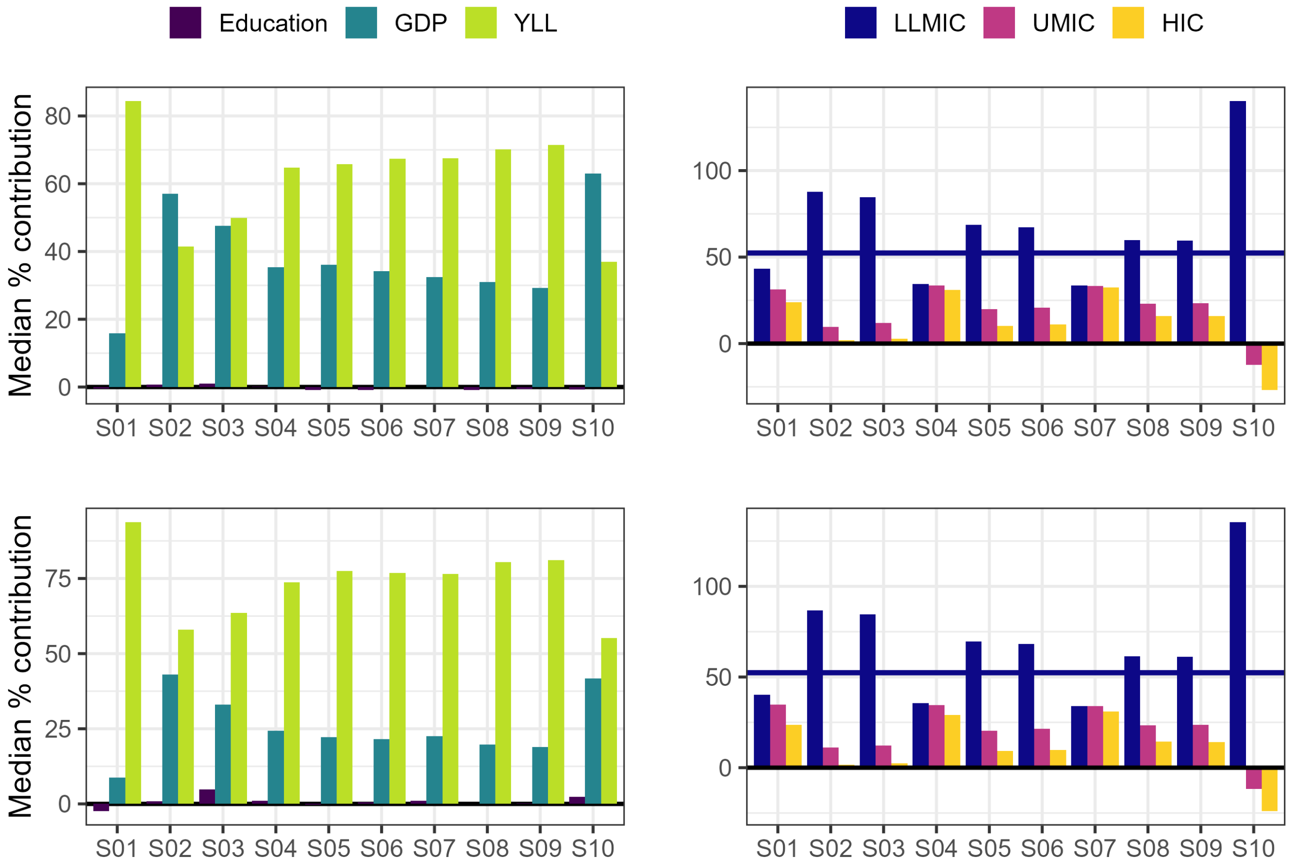

Figure C.12: **Composition of ΔLIR of investments across types of societal loss (left), and country types (right), and conditional on a once-in-thirty-years event (top) and a once-in-one-hundred-years event (bottom) caused by SARS-X.** Horizontal navy lines indicate the proportion of the world's population living in an LIC or LMIC. Where the LLMIC bar reaches this line, the ΔLIR of investments realised in LLMIC is proportional to population.

References

1. CEPI. Broadly Protective Coronavirus Vaccines. https://cepi.net/broadly-protective-coronavirus-vaccines. 2026
2. U.S. BLS. CPI Inflation Calculator. 2025
3. Griffiths U et al. Costs of Delivering COVID-19 Vaccine in 92 AMC Countries. https://www.who.int/publications/m/item/costs-of-delivering-covid-19-vaccine-in-92-amc-countries. 2021
4. Kis Z. Process-Cost Modelling for Producing 100 Million COVID-19 mRNA Vaccine Doses per Year at Injectable Medicines Manufacturing Sites. https://msfaccess.org/sites/default/files/2021-09/COVID19_TechBrief_Process_cost_modelling_ENG.pdf. 2021
5. World Health Organization. Public Assessment Summary Report: ErveboTM, Ebola Zaire Vaccine (rVSVΔG-ZEBOV-GP, Live), Merck & Co., Inc. USA. Tech. rep. World Health Organization, 2019 Dec :3
6. Pfizer. Pfizer and the European Commission Enter into Manufacturing Reservation Agreement for mRNA-based Vaccines to Help Protect Against Future Pandemics. https://www.pfizer.com/news/announcements/pfizer-and-european-commission-enter-manufacturing-reservation-agreement-mrna. 2023 Jun
7. PR Newswire. Seqirus and U.S. Government Renew Multi-Year Agreement for Influenza Pandemic Preparedness and Response. Summit, NJ, 2022 Feb
8. Martuscelli C. EU Buys Vaccine Capacity to Prepare for next Pandemic. Politico 2023 Jun
9. Linksbridge SPC. Global Vaccine Market Model. https://www.linksbridge.com/casestudy-gvmm. 2025
10. U.S. Government Accountability Office. Drug Industry: Profits, Research and Development Spending, and Merger and Acquitisition Deals. https://www.gao.gov/products/gao-18-40. 2017

11. Gotham D, Barber MJ, and Hill AM. Estimation of Cost-Based Prices for Injectable Medicines in the WHO Essential Medicines List. BMJ Open 2019 Sep; 9:e027780. DOI: 10.1136/bmjopen-2018-027780

12. Oyatoye I. Costs and Financing Gap of Delivering COVID-19 Vaccine to 133 Low- and Middle-Income Countries. https://immunizationeconomics.org/wp-content/uploads/2024/01/Ibironke-Oyatoye-Costs-and-financing-gap-of-C19v-delivery-in-LMICS_Final.pdf. Cape Town, South Africa, 2023 Jul

13. Moi F, Boonstoppel L, Archer R, and Akilimali P. The Cost of Delivering COVID-19 Vaccines in the Democratic Republic of the Congo. Tech. rep. Geneva: ThinkWell, 2024 Apr

14. Ruisch A et al. The Cost of Delivering COVID-19 Vaccines in Four Districts in Malawi. Cost Effectiveness and Resource Allocation 2025 Jul; 23:36. DOI: 10.1186/s12962-025-00610-2

15. Namalela T et al. The Cost of Delivering COVID-19 Vaccines in Mozambique: A Bottom-up Costing Study. BMC Health Services Research 2025 Apr; 25:521. DOI: 10.1186/s12913-025-12671-3

16. Tumusiime C et al. The Cost of Delivering COVID-19 Vaccines in Kampala, Uganda. Tech. rep. Uganda: ThinkWell, 2024

17. Yesmin A et al. The Cost of COVID-19 Vaccine Delivery in Bangladesh. Human Vaccines & Immunotherapeutics 2024 Dec; 20:2411820. DOI: 10.1080/21645515.2024.2411820

18. Vaughan K, Smith E, Schütte C, Moi F, and Boonstoppel L. The Cost of Delivering COVID-19 Vaccines in Côte d'Ivoire. Tech. rep. ThinkWell & Genesis Analytics, 2023 Jul

19. Noh DH et al. Cost of COVID-19 Vaccine Delivery in Nine States in Nigeria via the U.S. Government Initiative for Global Vaccine Access. BMC Health Services Research 2024 Oct; 24:1232. DOI: 10.1186/s12913-024-11645-1

20. Banks C et al. The Cost of Delivering COVID-19 Vaccines in the Philippines. Tech. rep. Geneva: ThinkWell, 2023

21. Nguyen VM et al. The Cost of Delivering COVID-19 Vaccines in Vietnam. BMC Health Services Research 2024 Jul; 24:779. DOI: 10.1186/s12913-024-11202-w

22. Nonvignon J et al. Estimating the Cost of COVID-19 Vaccine Deployment and Introduction in Ghana Using the CVIC Tool. Vaccine 2022 Mar; 40:1879–87. DOI: 10.1016/j.vaccine.2022.01.036

23. Yeung KHT et al. Estimating the Delivery Costs of COVID-19 Vaccination Using the COVID-19 Vaccine Introduction and Deployment Costing (CVIC) Tool: The Lao People's Democratic Republic Experience. BMC Medicine 2023 Jul; 21:248. DOI: 10.1186/s12916-023-02944-1

24. Orangi S, Kairu A, Ngatia A, Ojal J, and Barasa E. Examining the Unit Costs of COVID-19 Vaccine Delivery in Kenya. BMC Health Services Research 2022 Dec; 22:439. DOI: 10.1186/s12913-022-07864-z

25. Vaughan K, Mokena OT, Rankgoane-Pono G, Keetile M, and Griffiths UK. Costs of Delivering COVID-19 Vaccine in Botswana during the Height of the Pandemic: A Retrospective Study. BMC Health Services Research 2025 Mar; 25:405. DOI: 10.1186/s12913-025-12455-9

26. Edoka I et al. Costs of the COVID-19 Vaccination Programme: Estimates from the West Rand District of South Africa, 2021/2022. BMC Health Services Research 2024 Jul; 24:857. DOI: 10.1186/s12913-024-11251-1

27. Kis Z and Rizvi Z. How to Make Enough Vaccine for the World in One Year. https://www.citizen.org/article/how-to-make-enough-vaccine-for-the-world-in-one-year. 2021

28. Vaccines Europe. Vaccines Europe Analysis of Vaccine Production Lead Times. 2024

29. Feddema JJ, Fernald KD, Schikan HG, and Van De Burgwal LH. Upscaling Vaccine Manufacturing Capacity - Key Bottlenecks and Lessons Learned. Vaccine 2023 Jul; 41:4359–68. DOI: 10.1016/j.vaccine.2023.05.027

30. Gouglas D et al. Estimating the Cost of Vaccine Development against Epidemic Infectious Diseases: A Cost Minimisation Study. The Lancet Global Health 2018 Dec; 6:e1386–e1396. DOI: 10.1016/S2214-109X(18)30346-2

31. Lo AW, Siah KW, and Wong CH. Estimating Probabilities of Success of Vaccine and Other Anti-Infective Therapeutic Development Programs. Harvard Data Science Review 2020 May. DOI: 10.1162/99608f92.e0c150e8

32. CEPI. Delivering Pandemic Vaccines in 100 Days. https://static.cepi.net/downloads/2024-02/CEPI-100-Days-Report-Digital-Version_29-11-22.pdf. 2022

33. CEPI. CEPI 2022–2026 Strategy. https://static.cepi.net/downloads/2023-12/CEPI-2022-2026-Strategy-v3-Jan21_0.pdf. 2021

34. Glennerster R, Snyder CM, and Tan BJ. Calculating the Costs and Benefits of Advance Preparations for Future Pandemics. Vol. 71. Palgrave Macmillan UK, 2023. DOI: 10.1057/s41308-023-00212-z

35. Kazaz B, Webster S, and Yadav P. Incentivizing COVID-19 Vaccine Developers to Expand Manufacturing Capacity. https://www.cgdev.org/sites/default/files/incentivizing-covid-19-vaccine-developers-expand-manufacturing-capacity.pdf. 2021

36. UN. World Population Prospects 2024, Online Edition. 2024

37. The Network for Greening the Financial System. NGFS Climate Scenarios for Central Banks and Supervisors - Phase V. https://www.ngfs.net/en/publications-and-statistics/publications/ngfs-climate-scenarios-central-banks-and-supervisors-phase-v. 2024 Nov

38. Intergovernmental Panel on Climate Change Working Group 3. Climate Change 2014: Mitigation of Climate Change. Cambridge and New York: Cambridge University Press

39. Newman R and Noy I. The Global Costs of Extreme Weather That Are Attributable to Climate Change. Nature Communications 2023 Sep; 14:6103. DOI: 10.1038/s41467-023-41888-1

40. van Essen H et al. Handbook on the External Costs of Transport. Luxembourg: Publications Office of the European Union, 2020. ISBN: 978-92-76-18184-2

41. HM Treasury. The Green Book. 2022

42. Sunstein CR. Valuing Life: Humanizing the Regulatory State. Chicago: The University of Chicago Press, 2014. ISBN: 978-0-226-78017-7

43. Broome J. The Value of Life in the Social Cost of Carbon: A Critique and a Proposal. Journal of Benefit-Cost Analysis 2024; 15:110–26. DOI: 10.1017/bca.2024.21

44. UN General Assembly. Resolution 217A (III), Universal Declaration of Human Rights, A/RES/217(III). 1948 Dec

45. Marani M, Katul GG, Pan WK, and Parolari AJ. Intensity and Frequency of Extreme Novel Epidemics. Proceedings of the National Academy of Sciences of the United States of America 2021; 118. DOI: 10.1073/pnas.2105482118

46. The Economist. The Pandemic's True Death Toll. https://www.economist.com/graphic-detail/coronavirus-excess-deaths-estimates. 2024 Jun

47. Hashemi Shahraki A, Carniel E, and Mostafavi E. Plague in Iran: Its History and Current Status. Epidemiology and Health 2016 Jul; 38:e2016033. DOI: 10.4178/epih.e2016033

48. Walker PG et al. The Impact of COVID-19 and Strategies for Mitigation and Suppression in Low- and Middle-Income Countries. Science 2020; 369:413–22. DOI: 10.1126/science.abc0035

49. Doohan P et al. Mitigating Future Respiratory Pandemics in Low-, Middle- and High-Income Countries: A Modelling Study of Health, Economic and Educational Losses. 2026. DOI: 10.21203/rs.3.rs-9418446/v

50. Piburn J. Wbstats: Programmatic Access to the World Bank API. Oak Ridge National Laboratory. Oak Ridge, Tennessee, 2020

51. Feenstra RC, Inklaar R, and Timmer MP. The Next Generation of the Penn World Table. American Economic Review 2015; 105:3150–82

52. UN Tourism. Key Tourism Statistics. 2023

53. UN Tourism. International Tourism and COVID-19. 2023

54. Jarvis CI et al. Social Contact Patterns Following the COVID-19 Pandemic: A Snapshot of Post-Pandemic Behaviour from the CoMix Study. Epidemics 2024 Sep; 48:100778. DOI: 10.1016/j.epidem.2024.100778

55. Tatar M et al. COVID-19 Vaccine Inequality: A Global Perspective. Journal of Global Health 2022 Oct; 12:03072. DOI: 10.7189/jogh.12.03072

56. Johnson R et al. Costs and Impacts of Vaccine Preparedness Investments for SARS-X Pandemics: DAEDALUS Code and Model Description. https://github.com/robj411/p2_drivers. 2026