Cost-effectiveness Analysis of COVID-19 Vaccination Strategies in the Western Pacific Region: Description of methods

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Contents

1. Introduction

Countries in the World Health Organization (WHO) Western Pacific Region (WPR) have experienced different timing of SARS-CoV-2 epidemics while also facing a wide range of COVID-19 vaccine coverage to date, as access and acceptability have been highly variable across populations and settings. The cost and benefits of additional COVID-19 vaccination programs will vary by population demographics, target population group(s) and delivery strategy selected, whether multiple booster doses are required and how often, and the nature of future COVID-19 epidemic waves, including attack rates and timing of emergence of variants. Furthermore, any vaccination program costs must be weighed against existing health priorities within already strained health and immunisation budgets.

In addition to epidemiological considerations, decision-making on further COVID-19 vaccination programs will require evidence of the incremental cost-effectiveness of additional vaccination strategies compared to a counterfactual strategy without further vaccination. Alongside cost-effectiveness, policymakers must also understand the total cost and resulting budget impact of different vaccination strategies.

In this context, we will estimate the cost-effectiveness of a range of vaccination strategies *compared to no further vaccination,* to mitigate future epidemic waves in populations with differing vaccine uptake and epidemics. We will use outputs from an infection transmission/dynamics model linked to a mechanical agent-based model (ABM) with an additional clinical pathway model which has been described elsewhere.[1]

2. Health economic model overview

The cost-effectiveness model uses as inputs the outputs from a clinical pathways model linked to a mechanical agent-based model (ABM) that in turn, is linked to an infection transmission/dynamics model, as depicted in Figure 1 and described in more detail elsewhere.[1] A population of 100,000 is run through the models, over a three-year period. The first 1.5 years represents the main vaccination program (also referred to as prior or primary vaccination). The second 1.5 years represents the different boosting programs that are considered for the cost-effectiveness analysis, representing different emergence times, transmissibility, boosting times, and boosting frequency. Across all boosting scenarios, 11,000 vaccine doses are administered, representing an 11% vaccine coverage rate for booster doses. The ABM and clinical pathways models provide scenario-specific mean estimates of vaccination doses delivered per 100,000 people, COVID-19 infections (all, symptomatic, hospital admissions and total hospital bed days occupied, intensive care unit (ICU) admissions and total ICU beds occupied), and COVID-19 related deaths by 10-year age groups.

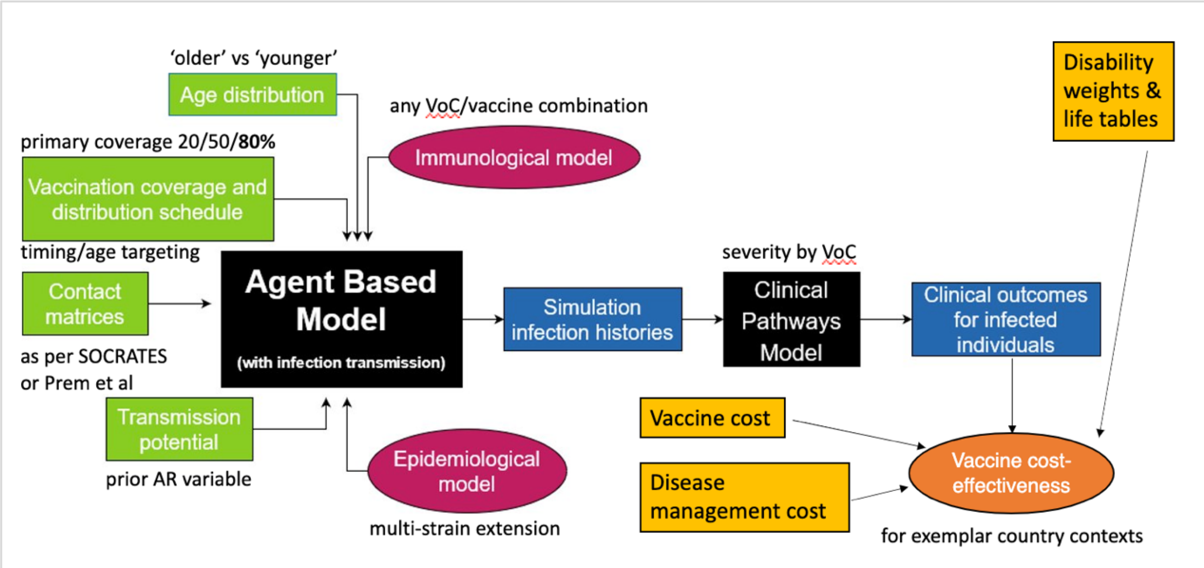


Figure 1. Diagram of cost-effectiveness model (in yellow/orange) as extension to overall simulation procedure.

The cost-effectiveness analysis has been conducted from the healthcare system perspective, including direct medical costs only. The main categories of costs included are (1) programmatic costs related to the vaccination intervention, including vaccine dose costs, wastage, and delivery costs; and (2) disease management costs at home, in outpatient and inpatient settings for symptomatic COVID-19 related illness. COVID-19 testing costs were not included. While these costs have been estimated to be substantial,[2] they remain highly uncertain. In any resurgence, we estimate a much broader use of rapid antigen testing than polymerase chain reaction (PCR) for case ascertainment; thus, the historical use of testing strategies cannot inform future testing use. Furthermore, PCR capacity varies dramatically by country, and the use of different types of tests will likely vary by case numbers. All costs are reported in 2020 United States dollars (USD).

Health outcomes are presented in terms of disability-adjusted life years (DALYs) using disability weights from the Global Burden of Disease study (GBD),[3-8] assumptions on the duration of illness from prior studies, and estimates of life years lost due to premature mortality from WHO life tables.

Future costs and health outcomes were discounted by 3% in the base case.

2.1. Defining exemplar country contexts for cost-effectiveness analysis

All countries in the WPR started COVID-19 vaccination programs in 2021. While countries had different vaccination strategies, in general first doses were assigned to frontline workers, at risk adults and the elderly, followed by the remaining adult population. Programs were expanded to include children aged 12 and above starting in early 2022. Most countries further expanded their vaccine policy to include children 5 years and older in mid-2022.

According to WHO data, 2-dose vaccine coverage varies significantly throughout the Western Pacific (Table A1 and A2 in Appendix). High income, 'older' demographic countries tend to have higher vaccination coverage, ranging from 64.5% in New Caledonia to 87.4% in Singapore with a median of 84.5% in New Zealand (as a proportion of total population as of 22/12/22) (Appendix Reference 1). Lower-middle and upper-middle income countries with younger demographics displayed a much wider range of vaccination coverage ranging from 3.6% in Papua New Guinea (PNG) to 101.9% in Brunei with a median coverage 67.4% in The Philippines. Booster coverage displayed a similar pattern.

In alignment with the two ABM populations, representing differing demographics within the WPR, we consider three key groupings of 'exemplar' countries in terms of: (1) demography (typical 'older' versus 'younger' population demographics); (2) health systems capacity and prior primary COVID-19 vaccine coverage rates (strong health systems and high prior primary vaccine coverage versus relatively weaker health systems and lower prior primary vaccine coverage); (3) income group level (high income versus upper-middle and lower-middle income); and (4) vaccination delivery unit costs and disease management costs.

The representative 'exemplar' countries groupings are as follows, with full details provided in the appendix:

(1) **Group A**: High income country (HIC), ‘older’ population with strong health systems capacity and high (~80%) prior primary vaccine coverage. High unit costs for vaccine delivery and disease management. *(Countries in this group include Japan, Australia, Republic of Korea, and Hong Kong, and are representative of other high income countries in the WPR such as New Zealand)*

(2) **Group B**: Upper- and lower- middle income country (MIC), ‘younger’ population with varying levels health systems capacity and prior primary vaccine coverage (~80% and ~50%). Low-to-high unit costs for vaccine delivery (depending on geography and population size) and low-to-middle unit costs for disease management. (*Countries in this group include Fiji, Samoa, Tonga, Mongolia, Cambodia, Philippines, Lao, Vanuatu, Kiribati, Micronesia, PNG, and Solomon Islands)*

(3) **Group C**: Lower-middle income country, younger population with weaker health systems capacity and low (~20%) prior primary vaccine coverage. Low unit costs for vaccine delivery and disease management. *(Countries in this group, a subgroup of Group B, include PNG and Solomon Islands)*

Some WPR countries are not included in these representative 'exemplar' country groupings (for example, those with demographics that classify as neither 'older' nor 'younger', or those with demographics that match to ‘older’ or ‘younger’ categorisation, but per-capita income level does not). The implications for these countries would need to be considered in light of the findings for **Groups A** and **B**.

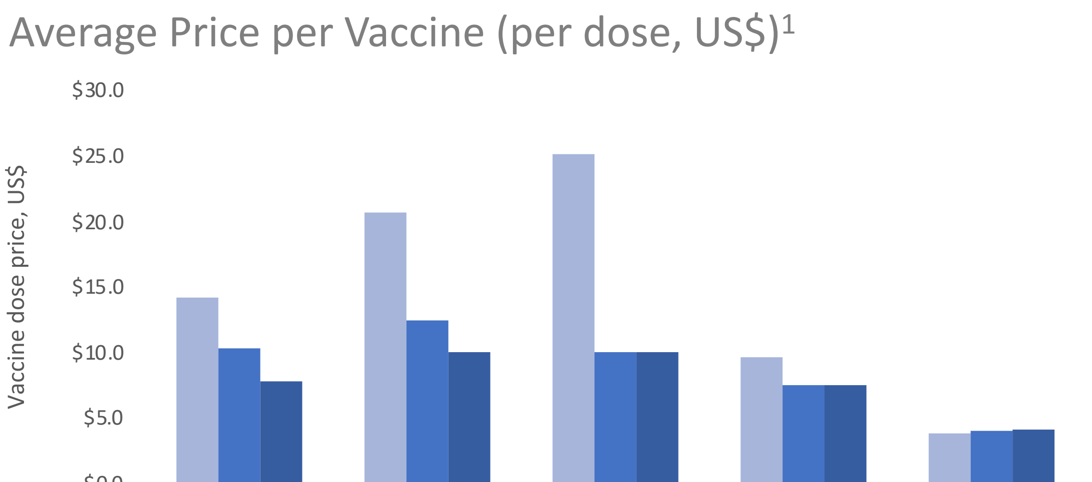
3. Resource use and costs

Inputs and data sources for estimating costs of COVID-19 vaccination and disease management are presented in Table 1.

3.1. COVID-19 vaccine dose cost

COVID-19 vaccine price data were retrieved from the WHO COVID-19 vaccine price report.[9] This report summarizes vaccine dose price data based on the WHO MI4A COVID-19 Vaccine Purchase Database,[10] which includes vaccine purchase data from public sources and data reported by countries through the WHO/UNICEF Joint Reporting Form (eJRF). Countries' names are not available in the dataset; however, the WHO region and income level are provided. Few countries in the Western Pacific Region (WPRO) had available price data, so our study has used global pricing data, by income group. Though AstraZeneca is no longer a preferred vaccine, we have included it in the economic model as it was used widely in the Western Pacific region in 2021 and has the lowest price per dose across all vaccines.

The vaccine dose price used in the base case was the average price per dose for all vaccines: Pfizer BioNTech (Comirnaty), Moderna (mRNA-1273), Janssen (Ad26.COV 2-S), and AstraZeneca (Vaxzevria) by income group. For groups A and C, the ranges were the minimum and maximum prices for high- and lower-middle-income countries respectively. Group B comprises a mix of lower- and upper-middle income countries, so the range was obtained from the minimum and maximum vaccine prices of lower- and upper-middle countries combined (Table 1 and Figure 2).



	All Vaccines	Pfizer	Moderna	Janssen	AZ
HIC	$14.2	$20.7	$25.2	$9.7	$3.9
Upper-MIC	$10.3	$12.5	$10.0	$7.5	$4.0
Lower-MIC	$7.8	$10.0	$10.0	$7.5	$4.1

Figure 2. COVID-19 vaccine price by type of vaccine and income group from WHO vaccine price report

AZ = AstraZeneca; HIC = High income country; MIC = middle income country

[1] C-19 Vaccine price data from public source and as reported by countries to WHO. Data up to March 2022 with unspecified year.

Table 1. Inputs for estimating COVID-19 vaccination and disease management costs.

Parameter	**Base case (range)**	**Source of data and rationale**
Cost per dose of vaccine ($)		
Group A (all high income)	14.2 (3.9–25.2)	Data from WHO COVID-19 vaccine price report.[9] Base case is mean by income group across vaccines; range is the minimum and maximum by vaccine type.
Group B (all middle income)	7.8 (4.0–12.5)	
Group C (middle income, low cov)	7.8 (3.9–25.2)	
Delivery cost per dose ($)		
Group A (80% coverage)	23.1 (11.1–33.6)	Data from government reports[11 12] or studies[13 14]. Base case is average across group A countries with cost data; range is minimum and maximum of costs.
Group B (50 or 80% coverage)	9.8 (0.7–19.1)	Data from UNICEF reports.[15 16] Base case assumes the cost at 70% coverage; range is minimum and maximum of costs
Group C (20% coverage)	7.7 (2.5–10.5)	Data from UNICEF reports.[15 16] Base case assumes double the cost at 70% coverage; range is minimum and maximum of costs
Proportion of doses wasted		
Group A (all high income)	10% (0–20)	Data from UNICEF reports.[15 16] Assumes range from no dose wasted to double the proportion of doses wasted.
Group B (all middle income)	10% (0–20)	
Group C (middle income, low cov)	10% (0–20)	
Cost for non-hospitalized case ($)[1]		
Group A (all high income)	75 (53–115)	Data from medical fee schedules,[17-20] studies,[21] or WHO-CHOICE[22]. Base case is average of available cost data; usual range estimation above.
Group B (all middle income)	52 (21–131)	Data from Torres-Rueda, *et al.*[2]
Group C (middle income, low cov)	31 (28–35)	Data from Torres-Rueda, *et al.*[2]
Cost for hospitalization without ICU, per day($)		
Group A (all high income)	351 (209–657)	Data from medical fee schedules,[17-20] studies,[21] or WHO-CHOICE[22]. Base case is average of available cost data; usual range estimation above.
Group B (all middle income)	52 (34–99)	Data from Torres-Rueda, *et al.*[2]
Group C (middle income, low cov)	41 (40–42)	Data from Torres-Rueda, *et al.*[2]
Cost for hospitalization needing ICU, per day($)[2]		
Group A (all high income)	2594 (825–4284)	Data from medical fee schedules,[17-19] studies,[21] or WHO-CHOICE[22]. Base case is average of available cost data; usual range estimation above.
Group B (all middle income)	543 (295–1273)	Data from Torres-Rueda, *et al.*[2]
Group C (middle income, low cov)	347 (341–353)	Data from Torres-Rueda, *et al.*[2]
Cost per COVID-related death ($)		
Body bag	65 (fixed)	Data from Torres-Rueda, *et al.*[2]

Costs are reported in 2020 United States dollars. ICU – intensive care unit; CHOICE – CHOosing Interventions that are Cost-Effective.

[1] Cost for non-hospitalized case includes two visits to a clinic.

[2] Costs of hospitalized critical case from original report included both ICU and non-ICU bed days and thus have been inflated by 20% to represent the cost of an ICU bed day alone.

3.2. COVID-19 vaccine delivery cost

The cost of COVID-19 vaccine delivery remains uncertain. Delivery costs will vary by vaccine type (including cold chain requirements), country health systems capacity, delivery mechanism and target population and coverage level. In all scenarios explored, a set number of doses (11,000) are delivered to a population of 100,000, equivalent to a coverage of 11% of the total population. While the different scenarios explored (high risk versus random versus paediatric boosting) likely have different delivery costs associated with them, given the underlying uncertainty, we assume the same delivery costs across all scenarios. Delivery costs are generally assumed to be U-shaped, decreasing as coverage increases due to shared fixed costs across a larger population being vaccinated, and increasing at very high coverage levels due to difficulties in vaccinating hard-to-reach populations. For Groups A and B countries, given high to moderate prior vaccination coverage, we assume booster doses would be delivered at the same unit cost per dose as the primary doses. We assume across all scenarios that delivery of booster doses even at low coverage levels, would incur the same cost of vaccine delivery as the primary doses.

3.2.1. Group A ('Older' population, high income countries)

There are no consistent estimates of vaccine delivery costs for high-income countries. We sought to estimate or find COVID-19 vaccination delivery costs for a select number of countries in Group A where data were available, to use as inputs for the modelling. Delivery costs per dose for Hong Kong and Korea were taken from previous publications with assumed COVID-19 vaccination coverage rates of 72% and 80%, respectively.[13 14] Delivery costs per dose for Japan were taken from the Japanese Government's National Treasury's burden for the vaccination measures against the COVID-19 report, at an unspecified coverage rate.[11] Delivery costs for Australia were calculated by dividing the Australian government's reported funding for COVID-19 vaccine distribution and administration in 2020-2022 by the total doses administrated up to mid-2022 (about 80% coverage).[12] These unit delivery costs were used for the 80% and 50% coverage scenarios and multiplied by two to estimate the delivery costs at 20% coverage. We use the average cost across all estimates obtained for the base case delivery cost, and the minimum and maximum delivery cost estimates as upper and lower-bound ranges.

*3.2.2. **Group B and C** ('Younger' population, middle-income countries)*

The COVID-19 vaccine delivery cost estimates used in modelling the 'younger' demographic populations were based on two recent UNICEF reports that provided estimates for low- and middle-income countries (LMICs).[15 16] These delivery costs refer to the costs associated with delivering vaccines to target populations exclusive of vaccine purchase costs. The costs estimated in both reports are financial costs, including (1) variable costs (e.g., cold chain equipment, per diem for outreach, personal protective equipment, vaccine transport, and management, etc.) and (2) fixed costs (i.e., handwash station, training, planning and coordination, social mobilization, pharmacovigilance, behavioural and social data collection). For this study, we assumed the economic costs required for a cost-effectiveness analysis, would be similar to the financial costs, and therefore used these estimates in the base case.

In the latest UNICEF report, COVID-19 vaccine delivery costs were estimated for countries achieving a 70% of total population coverage (equivalent to 92% coverage rate in population ≥12 years of age) in four different scenarios (leveraging fixed delivery sites, balancing human resource protection, protecting human resources partially, protecting human resources fully).[16] In the earlier report, which focussed on achieving 20% coverage, the estimation was based on the leveraging fixed delivery sites scenario only. For consistency, we have chosen the delivery costs under this scenario as the base case, which assumed 10% of the available workforce allocated to delivery, 85% fixed site delivery, and 15% outreach delivery. The fixed-outreach proportion was close to the data for the Western Pacific region in 85 National Deployment and Vaccination Plans (86%-14%).[16] In the leveraging scenario from the earlier UNICEF report, the average cost per dose delivery at 20% coverage was approximately double that of achieving 70% coverage, as fewer people shared fixed costs. Due to the lack of country-specific estimates at 20% coverage, we also assumed that the delivery costs at 20% coverage were double those at 70% coverage. We also assumed that the 50% and 85% coverage scenarios had the same unit delivery costs as the 70% coverage scenario. Delivery cost estimates used in the model are provided in Table 1.

3.3. COVID-19 treatment cost

3.3.1. ***Group A*** *('Older' population, high income countries)*

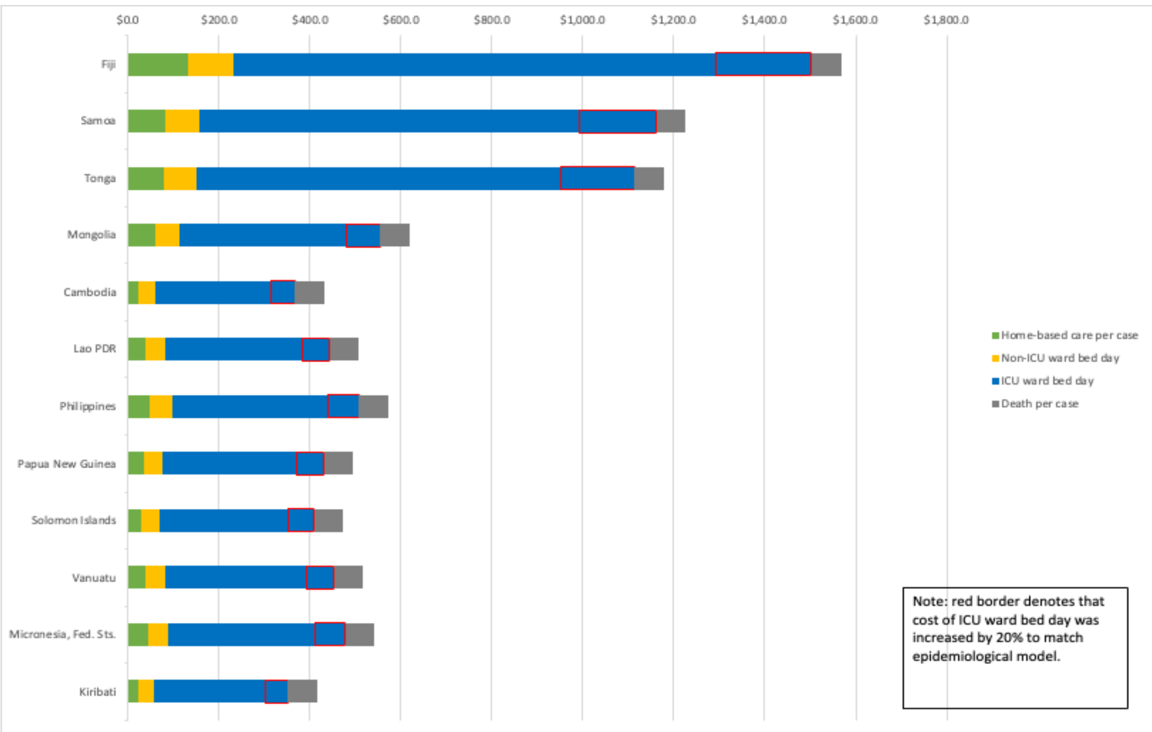
Detailed cost estimates for management of COVID-19 infections were estimated for a small number of countries in Group A, where these were readily available. Based on costing methods by Torres-Rueda *et al.* (2021) as described below and used for middle-income countries (Groups B and C)[2], we used the Australian medical fee schedules and publicly available government data to calculate the three types of case management costs.[18 20] We used the same method to estimate the case management costs in Japan by applying the Japanese medical fee schedule [17]. Of note, in the home-based cases in HICs, we have excluded the home-based bed-day cost due to lack of detailed costing method in the reference article. Also, in hospital-based critical cases, we dropped the general ward bed-day input and changed the number of units per input for ICU bed-day from 0.66 to 1. Malaria testing was included in all LMICs hospital-based cases, but we removed it from the costs for HICs, given that HICs are predominantly low-prevalence malaria regions where this testing may not be a routine admission test. The costs of inpatient cases in Hong Kong were taken from a cost-effectiveness study of the COVID-19 vaccine in Hong Kong, with the source being the public charges for non-eligible persons.[14 19] The costs of hospitalisation cases in Korea were obtained from a COVID-19 cost-effectiveness analysis in Korea, which employed the cost estimations by Korea Disease Control and Prevention Agency.[21] The outpatient costs for home-based care in Korea were based on WHO CHOICE unit costs (2011), which we adjusted for inflation and currency conversion.[22] The cost per COVID-19 related death only includes the cost of a body bag based on the study by Torres-Rueda *et al.* 2021, and thus is likely to be underestimated.

3.3.2. **Group B and C** *('Younger' population, middle-income countries)*

All disease costs for LMICs were available directly from a model-based cost estimations study.[2] The study used data from three LMICs (Ethiopia, Pakistan, and South Africa) as the model references to extrapolate the case management costs for home-based care, hospitalisation for severe care, and critical care across all LMICs. The original costs reported in the study were inflated to 2020 USD.

Home-based care costs are defined as the cost per mild-to-severe case requiring home-based care, including 1) the cost of home-based care bed-day; 2) the cost of community-based care via a clinician's visit. The number of bed-day and clinician visit was set at 5 and 2, respectively.

Hospitalised severe care costs were calculated per case and per day, including 1) general ward bed-day; 2) diagnostics. Hospitalised critical care costs were also presented per case and per day. Compared with severe cases, the additional costs per case per day were: 1) ICU bed-day; 2) additional resourcing per COVID-related complication. However, as the modelled epidemiological data is presented by ICU admission (rather than combining a patient who has received ICU and general ward care) the cost shown in this report likely underestimates the actual cost per day of a patient treated in an ICU. As general ward costs were considered representative of one-third of the bed day costs, we conservatively inflated the bed day cost by 20% when applying these costs in the economic model. Further clarification is presented in supplementary appendix Table A5 and Table A6.



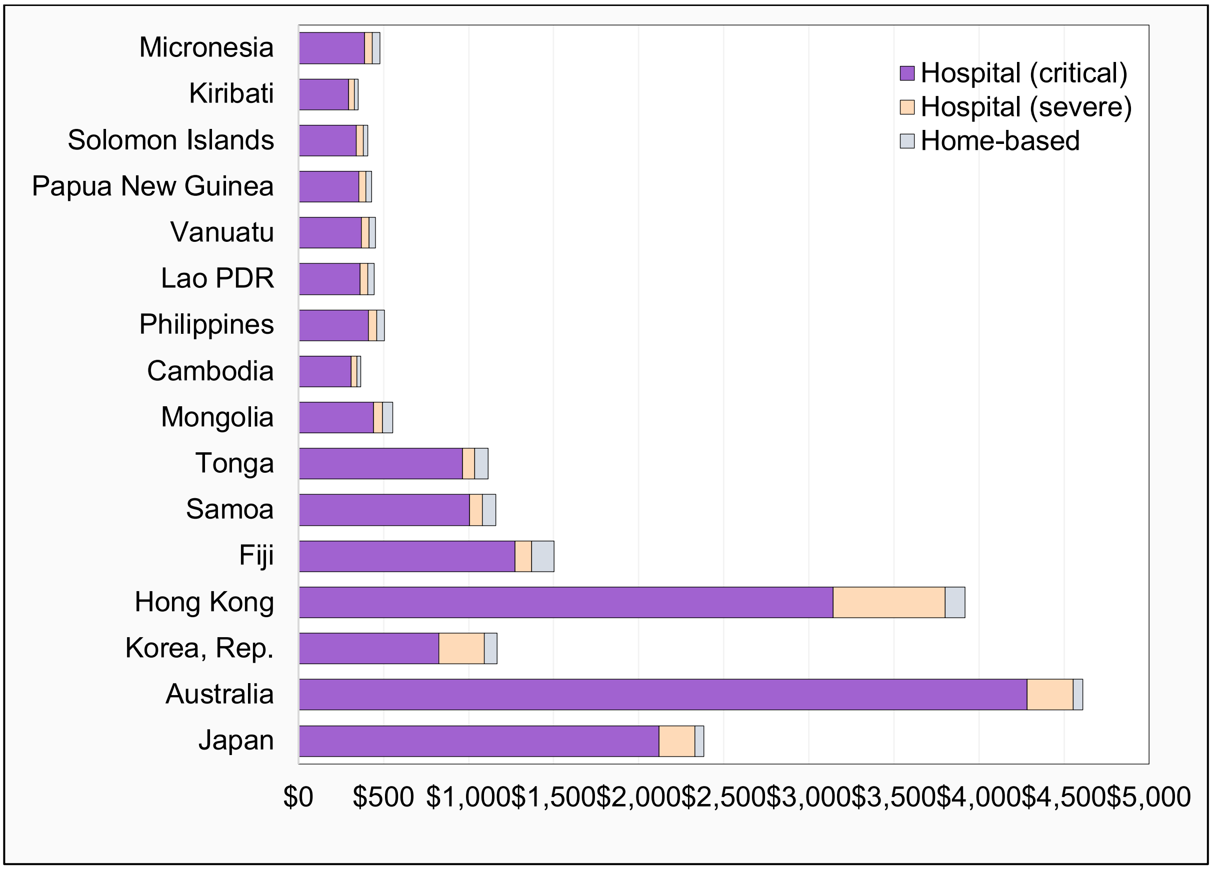


Figure 3. COVID-19 cost of disease management for "younger countries" from

4. Health Outcomes

Health outcomes were presented as disability-adjusted life-years (DALYs) for each modelled scenario. DALYs were calculated as the sum of years of life lost (YLLs) and years lived with disability (YLDs).

4.1. Years of life lost

YLLs following a premature death due to COVID-19 were calculated as the sum of the number of deaths (N) multiplied by life expectancy (L) for the age at death. We obtained the number of deaths and age at death (in ten-year age groups, up to 80 years plus) from the epidemiological model for each scenario. These were multiplied by a reference life expectancy for each exemplar country groupings from WHO lifetables for each 10-year age band. For **Group A,** we use the Japan life table given 'older' high-income countries in WPR have higher life expectancies than the global high-income country lifetable. For **Groups B and C**, we use the global lower-middle income lifetable, given 'younger' countries in WPR have a lower life expectancy than global upper-middle income and the WPR life table. In the base case, we discounted future YLLs at 3% annually according to the following formula:

$$YLL = \frac{N(1-e^{-0.03L})}{0.03}$$

4.2. Years lived with disability

The YLD component was calculated for the acute phase of the disease and post-acute consequences following severe disease. We do not include long-COVID due to a lack of available data to specify this condition. We classified cases into four following mutually exclusive categories–asymptomatic, symptomatic non-hospitalized, hospitalized without ICU stay, and hospitalized with ICU stay. We specified an illness severity pathway for each category consisting of four health states (mild/moderate, severe, critical, and post-acute). The post-acute phase refers to the recovery period following hospitalisation, and has been expressed in other cost-effectiveness models [4]. Based on the illness severity pathway for these categories (

Table 2), we calculated YLDs by summing up the product of time spent in each health state, the disability weight for that state, and the number of incident cases. YLDs have been calculated using the following formula:

$$YLD = \sum_{i} I_i \times L_i \times DW_i$$

where i is an index for health state, I_i is the number of incident cases for each health state, L_i is the duration of disability in years, and DW_i is the disability weight. The duration of illness for each state was based on the average length of hospital and ICU stay from the literature (

Table 2).

Table 2. Health states, duration of illness, and disability weights for calculating years lived with disability.

COVID-19 patient category	Health state	Days in state Base case (range)	Disability weight Base case (range)	Notes and sources
A. asymptomatic cases	Not applicable	Not applicable	Not applicable	Zero disability for asymptomatic cases.
B. symptomatic non-hospitalized	Mild or moderate	7.0 (2.0–9.5)	0.051 (0.032–0.074)	GBD 2019 disability weight for moderate lower respiratory infections [3]. Days in mild/moderate state from literature [4 8]. Assume no post-acute phase.
C. hospitalized without ICU stay	Mild or moderate	7.0 (2.0–9.5)	0.051 (0.032–0.074)	Disability weights from GBD 2019 for moderate lower respiratory infections, severe lower respiratory infections and post-acute consequences (fatigue, emotional lability, insomnia) for infectious disease [3]. Using 7 days from symptom onset to hospital, same as category B patients and a Belgian study [5]. Using
	Severe	5.0 (3.0–9.0)	0.133 (0.088–0.190)	
	Post-acute	7.0 (3.5–10.5)	0.219 (0.148–0.308)	

				same number of hospital days (5 days) used in category D patients [6]. Assume 1-week post-acute phase +/- 50% [4].
D. hospitalized with ICU stay	Mild or moderate	7.0 (2.0–9.5)	0.051 (0.032–0.074)	Disability weights from Nomura 2019 [7] (critical) and GBD 2019 (others). Symptom onset to ICU discharge of 18 days [8]. Out of this number, assume 7 days from symptom to hospital [5], 5 days in hospital [6] and 7 days in ICU [6]. Assume 2 weeks post-acute phase +/- 50% [4].
	Severe	5.0 (3.0–9.0)	0.133 (0.088–0.190)	
	Critical	7.0 (4.0–11.0)	0.675 (0.506–0.822)	
	Post-acute	14.0 (7.0–21.0)	0.219 (0.148–0.308)	

5. Cost-effectiveness analysis

5.1. Cost-effectiveness thresholds

Cost-effectiveness thresholds (CETs) for the country groups were based on estimates by Woods *et al* (2016).[23] This study estimated these thresholds for several countries using the opportunity cost of additional costs incurred from interventions, the relationship between country gross domestic product (GDP) per capita, and the value of a statistical life. These CETs were calculated in 2013 US dollar values. The study reports the lower and upper bounds (limits) of the CETs (per quality-adjusted life-year gained) as percentage of GDP per capita in 2013. Ochalek *et al* (2015)[24] estimated CETs per DALYs averted, but only three countries in our study were included (Cambodia, Mongolia, and Philippines).[23]

To obtain CETs for use in this study, we multiplied the CETs as percentage of GDP per capita with GDP per capita in 2020 from the World Bank,[25] rounded to the nearest hundred. The estimates are presented in Table 3. Thereafter, we calculated the average threshold (separately for the lower and upper bounds) for each group. The CET was between $19,000 and $30,000 for **Group A**, between $200 and $1600 for **Group B**, and between $100 and $1000 for **Group C** countries. The thresholds for each country within the groups are available in supplementary appendix Table A3.

Table 3. Estimated willingness to pay thresholds.

Age demographics / prior primary vaccine coverage	Representative countries / Areas	Threshold range (2020 USD)
Group A: Older population (all countries, high vaccination coverage)	Japan, Australia, Republic of Korea, Hong Kong, Brunei Darussalam, New Zealand, and Singapore	$19,000 – $30,000

Group B: Younger population (all countries, varying vaccine coverage)	Fiji, Samoa, Tonga, Mongolia, Cambodia, Philippines, Lao, Vanuatu, Kiribati, Micronesia, PNG, and Solomon Islands	$200 – $1,600
Group C: Younger population (low vaccine coverage)	PNG and Solomon Islands	$100 – $1,000

5.2. Cost-effectiveness results and interpretation

We present the results as incremental cost-effectiveness ratios (ICERs) for the modelled vaccination options compared to a counterfactual of no further vaccination. These ICERs are presented on a cost-effectiveness plane, which shows the DALYs averted and additional costs for the vaccination scenarios (described above) compared to the cost-effectiveness thresholds for the three scenarios. Results that fall below these thresholds indicate a vaccination strategy that is likely to be cost-effective. We have expressed these costs and outcomes per 100,000 people.

We have also performed one-way sensitivity analyses to determine the impact of various cost (vaccine prices and delivery costs) and epidemiological variables on the ICER. We have presented the results of these analyses on a tornado diagram, which indicates the change in ICER when varying parameters within a plausible range, thus accounting for parameter uncertainty. For **Groups B** and **C** countries, we also explore a vaccine price of $0 per dose in a scenario analysis, to explore the cost-effectiveness from a government perspective of having donated vaccines available to some middle-income countries. For these countries, we also explore a scenario analysis involving reducing

Additionally, as we are already varying several key epidemiological and demographic parameters (for example, R0 through high/low transmission scenarios and young vs older populations), we can compare these parameters' influence on CE results to the costing parameters. This process has demonstrated apparent differences in CEA by allocation strategy across that broad variation, so it's unlikely that the conclusions of a more detailed uncertainty analysis would vary substantially.

6. Limitations

There are several limitations of this analysis that warrant mentioning.

1. We do not include testing costs, as previously explained. Testing costs can represent a substantial proportion of total costs related to COVID-19 in some countries, however these remain highly uncertain particularly across modelled future scenarios. It is unclear what impact the exclusion of testing costs would have on findings.
2. While indirect costs due to COVID-19, such as productivity losses, also make up a large proportion of total costs related to COVID-19, these costs have not been included in the current analysis. Accounting for indirect costs would make additional boosting vaccination programs appear more cost-effective than our findings indicate. In future work, a societal perspective may be considered.

3. We have not accounted for vaccine-related side effects, including both the costs and health impacts. These are unlikely to impact on cost-effectiveness findings.
4. We are currently not accounting for the costs or health impacts of long-COVID, due to data limitations.
5. We have not directly considered stochastic uncertainty within the economic model, although this has been considered within the various epidemiological models described elsewhere. Stochastic uncertainty is unlikely to significantly impact the cost-effectiveness results, particularly when compared to the parameter uncertainty considered within the one-way sensitivity analyses. We have also not conducted a full probabilistic sensitivity analysis capturing uncertainty across the economic, epidemiological, and clinical parameters. In future iterations of this collaboration, we hope to capture more uncertainty in all models together; however, this was not feasible in the current timeframe.
6. Finally, a full budget impact has not been conducted alongside this cost-effectiveness analysis. A budget impact should also consider a lower bound vaccine dose cost of $0 for donated vaccines with no financial costs to health systems.

7. References

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8. Appendix

Table A1. Countries and areas in WHO Western Pacific Region (WPR) and characteristics.

Country	Income classification[a]	Younger/ Older	Population size[b]	2 dose Vaccination coverage[c]	Booster coverage[c]
American Samoa	Upper middle	-	45,035	75.05%	43.77%
Australia	High	Older	25,688,079	84.92%	56.06%
Brunei Darussalam	High	Younger	445,373	101.93%	77.49%
Cambodia	Lower middle	Younger	16,589,023	87.33%	62.21%
China	Upper middle	Older	1,412,360,000	86.82%	54.7%
Cook Islands	-	-	17,604*	83.56%	30.38%
Fiji	Upper middle	Younger	924,610	71.33%	18.78%
French Polynesia	High	Older	304,032	66.23%	39.95%
Guam (USA)	High	Older	170,534	83.55%	42.74%
Hong Kong	High	Older	7,413,100	-	-
Japan	High	Older	125,681,593	81.43%	66.67%
Kiribati	Lower middle	Younger	128,874	61.86%	19.61%
Lao PDR	Lower middle	Younger	7,425,057	74.54%	27.86%
Macao SAR	High	Older	686,607		
Malaysia	Upper middle	-	33,573,874	85.06%	50.28%
Marshall Islands	Upper middle	-	42,050	61.89%	36.41%
Micronesia, Federates States of	Lower middle	Younger	113,131	57.53%	26.55%
Mongolia	Lower middle	Younger	3,347,782	66.64%	32.25%
Nauru	High	-	12,511	79.24%	46.75%
New Caledonia	High	Older	271,030	64.49%	32.96%
New Zealand	High	Older	5,122,600	84.87%	56.33%
Niue	-	-	1,653*	100.99%	75.65%
Northern Mariana Islands Commonwealth of the USA	High	-	49,481	78.2%	42.11%
Palau	Upper middle	-	18,024	101.07%	71.11%
Papua New Guinea	Lower middle	Younger	9,949,437	3.46%	0.36%
Philippines	Lower middle	Younger	113,880,328	67.42%	19.38%
Pitcairn Island	-	-	50*	74%	46%
Republic of Korea	High	Older	51,744,876	87.17%	65.63%
Samoa	Lower middle	Younger	218,764	89.54%	39.85%
Singapore	High	Older	5,453,566	87.4%	77.34%
Solomon Islands	Lower middle	Younger	707,851	31.68%	2.54%
Tokelau	-	-	1,399*	163.19%	71.7%
Tonga	Upper middle	Younger	106,017	72.72%	36.24%
Tuvalu	Upper middle	-	11,204	79.05%	46.88%
Vanuatu	Lower middle	Younger	319,137	42.75%	5.39%
Vietnam	Lower middle	-	97,468,029	87.89%	59%
Wallis and Futuna	-	-	10,749*	62.15%	28.46%

Abbreviations: PDR, People's Democratic Republic; SAR, Special Administrative Region; USA, United States of America
[a] Income Classification data sourced from World Bank https://data.worldbank.org/ 22/12/22
[b] Population data from Our World in Data 22/12/22
[c] Data retrieved from WHO Coronavirus (COVID-19) Dashboard https://covid19.who.int/table 22/12/22. Data on 2-dose coverage and booster coverage are estimated based on number of doses administered and total population size
*Data not available from Our World in Data sourced from Worldometer
NOTE: Group A (green) High income, older population with strong health systems capacity and high prior primary coverage; Group B (yellow) Upper- and lower-middle income, younger population with middle-to-strong health systems capacity and middle-to-high prior primary vaccine coverage; Group C (blue) lower middle income, younger population with weak health systems capacity and lower prior primary vaccine coverage; countries that are not highlighted are not included in these representative 'exemplar' country groupings. The implications for these countries would need to be considered in light of the findings for Groups A and B, as they would likely sit somewhere in between these groupings.

Table A2: Median vaccination coverage by age demographic in WPR

Age Demographic	Median 2-dose coverage*	IQR	Range
Younger	67.42%	57.53% - 74.54%	3.46% - 101.93%
Older	84.87%	81.43% - 86.82%	64.49% - 87.4%

*as % of total population, as of 22/12/22

Table A3. Willingness To Pay Thresholds for WPR

Country	GDP per capita in 2020 (A)	% of GDP per capita Woods lower bound (B1)	% of GDP per capita Woods upper bound (B2)	Cost-effectiveness threshold, Woods upper bound (A*B1)	Cost-effectiveness threshold, Woods upper bound (A*B2)
Japan	$40,193	48.3%	48.5%	$19,428	$19,512
Australia	$51,693	48.1%	61.2%	$24,855	$31,651
Korea, Rep.	$31,631	45.0%	50.5%	$14,228	$15,968
Hong Kong	$46,324	45.3%	75.0%	$20,999	$34,741
Fiji	$5,058	10.5%	47.7%	$530	$2,410
Samoa	$4,068	6.6%	47.0%	$267	$1,911
Tonga	$4,625	7.5%	51.4%	$348	$2,376
Mongolia	$4,061	12.4%	47.8%	$505	$1,939
Cambodia	$1,544	4.3%	51.1%	$67	$789
Philippines	$3,299	8.9%	49.5%	$294	$1,633
Lao PDR	$2,630	6.2%	46.5%	$162	$1,223
Vanuatu	$2,870	4.7%	57.0%	$135	$1,637
Papua New Guinea	$2,757	2.7%	39.3%	$76	$1,084
Solomon Islands	$2,251	2.5%	44.6%	$57	$1,005
Kiribati	$1,654	2.5%	49.4%	$41	$817
Micronesia, Fed. Sts.	$3,565	5.4%	55.0%	$193	$1,960
China	$10,435	16.4%	64.8%	$1,711	$6,763
Guam	$34,624	-	-	-	-
Brunei Darussalam	$27,443	35.9%	87.8%	$9,854	$24,102
New Zealand	$41,441	47.8%	50.3%	$19,821	$20,847
Singapore	$59,798	39.2%	108.3%	$23,452	$64,767

Abbreviations: DALY, Disability-adjusted life year; PDR, People's Democratic Republic; SAR, Special Administrative Region; USA, United States of America, USD, United States dollars;
[a] CETs were estimated based empirical estimates collected using marginal costs invested and marginal health outcomes across different NHS jurisdictions (k) assumed VSL = value of a life year = income elasticity for QALY, If similar elasticity for v and k exists than estimates were created based on differing GDP income elasticities
[b] Health care expenditure from Bohari which was initially modelled against U5 and maternal mortality was used on cross sectional data from GBD. Morbidity is estimated with population health estimates. DALY 1-4 information in Table 2 p16
[c] Based on panel data modelled against U5 mortality and adult male and adult female mortality. DALY 1-4 information in table 6 p29

Table A4. Vaccination delivery cost estimates (2020 USD) by country and initial primary vaccination coverage [1]

Country	Group	20% Coverage	50% Coverage	70% Coverage
Australia	A	-	-	$22.3 [2]
Japan	A	-	-	$33.6
Korea, Rep.	A	-	-	$11.1
Hong Kong	A	-	-	$25.3
Fiji	B	-	Assumed to be the same as at 70% coverage	$10.5
Samoa	B	-		$17.8
Tonga	B	-		$19.1
Mongolia	B	-		$13.4
Cambodia	B	-		Not available [3]
Lao PDR	B	-		$1.3
Philippines	B	-		$0.7
Vanuatu	B	-		$5.7
Kiribati	B	-		$29.3 [4]
Micronesia, Fed. Sts.	B	-		$23.1 [4]
Papua New Guinea	B & C	$5.0 [5]	-	$2.5
Solomon Islands	B & C	$10.5 [5]	-	$5.2

[1] Based on UNICEF report 2021-2022 which estimated delivery costs in leveraging fixed delivery sites scenario (10% of the available workforce allocated to delivery, 85% fixed site delivery, and 15% outreach delivery).
[2] Australia 2020-2022 vaccine program budget (including vaccine program implementation, administration and distribution) divided by total administrated doses up to mid-2022 = 1876.7 million /57.92 million ≈ 32.4 AUD ≈ 22.3 USD. Budget data from Minister for Finance of the Commonwealth of Australia; doses administration data from Our World in data 01/07/2022
[3] Cambodia delivery costs were not available in UNICEF report.
[4] Costs of delivery for Micronesia and Kiribati were excluded from the mean delivery cost estimate for the Group B, younger, populations, due to their small population size (~125,000) and high delivery costs.
[5] Assumed to be 2x delivery cost estimates at 70% coverage, based on UNICEF report 2021-2022 in which average delivery cost across LMICs at 20% coverage was double the cost at 70% coverage in leveraging fixed delivery sites scenario.

Table A5. Disease management unit costs (2020 USD) by country

Country	Group	Non-hospitalised, per case	Hospitalised without ICU, per day	Hospitalised with ICU, per day	Death, per case
Australia	A	$53.5	$271.6	$5,294.9	$64.5
Japan	A	$54.0	$208.7	$2,120.5	$64.5
Korea, Rep.	A	$76.8	$267.0	$825.0	$64.5
Hong Kong	A	$114.7	$657.2	$3,144.3	$64.5
Fiji	B	$131.1	$99.0	$1,272.7	$64.5
Philippines	B	$47.0	$48.8	$410.7	$64.5
Samoa	B	$82.1	$73.1	$1,005.9	$64.5
Tonga	B	$79.0	$70.2	$964.3	$64.5
Mongolia	B	$59.8	$53.0	$441.8	$64.5
Cambodia	B	$22.9	$35.9	$308.2	$64.5
Lao PDR	B	$37.3	$42.8	$362.8	$64.5
Vanuatu	B	$37.9	$43.9	$370.8	$64.5
Kiribati	B	$20.8	$34.3	$295.1	$64.5
Micronesia, Fed. Sts.	B	$42.6	$46.1	$388.3	$64.5
Papua New Guinea	C	$34.8	$41.7	$353.5	$64.5
Solomon Islands	C	$28.0	$39.9	$340.9	$64.5

Table A6. Units input and unit costs (2020 USD) for Japan and Australia

	Number of units per input	Japan	Australia
a. Home-based care	per case		
community-based care via clinical visit	2	$27.00	$26.70
Total.a		$54.00	$53.50
b. Hospital-based (severe)	per case/day		
Inpatient ward bed-day (severe)	1	$196.70	$264.10
Chest X-ray	0.125	$19.70	$24.80
Full blood count (including haemoglobin test)	0.125	$27.70	$11.70
Blood urea and electrolyte test (including C-reactive protein test)	0.125	$22.20	$12.20
HIV test	0.125	$26.20	$10.80
Total.b		$208.70	$271.60
c. Hospital-based (critical)	per case/day		
ICU bed-day	1	$1,359.10	$4,744.40
Chest X-ray	10	$19.70	$24.80
Full blood count (including haemoglobin test)	10	$27.70	$11.70
Blood urea and electrolyte test (including C-reactive protein test)	10	$22.20	$12.20
Venous blood gas test	10	$4.20	$4.20
HIV test	0.1	$26.20	$10.80
Acute respiratory distress syndrome	0.47	$22.50	$22.50
Acute kidney injury days	0.04	$10.60	$10.60
Acute cardiac injury days	0.06	$46.30	$46.30
Liver dysfunction days	0.06	$89.30	$89.30
Pneumothorax days	0.01	$7.00	$7.00
Hospital-acquired pneumonia days	0.05	$18.90	$18.90
Bacteraemia days	0.01	$32.60	$32.60
Urinary tract infection days	0.01	$9.00	$9.00
Septic shock days	0.05	$0.80	$0.80
Total.c		$2,120.50	$5,294.90

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