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A Framework for Estimating Health Spending in Response to COVID-19

by Paolo Dudine, Klaus-Peter Hellwig, and Samir Jahan

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A Framework for Estimating Health Spending in Response to COVID-19

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Abstract

We estimate the additional health spending necessary to treat COVID-19 patients. We expand a Susceptible Infected Recovered model to project the number of people requiring hospitalization, use information about healthcare costs by country, and make assumptions about capacity constraints in the health sector. Without social distancing and lockdowns, countries would need to expand health systems ten-fold, on average, to assist all COVID-19 patients in need of hospitalization. Under capacity constraints, effective social distancing and quarantine reduce the additional health spending from a range of $0.6–1 trillion globally to $130–231 billion, and the fatality rate from 1.2 to 0.2 percent, on average.

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I. INTRODUCTION

The outbreak of SARS-CoV-2 is confronting healthcare systems around the world with an unprecedented challenge. Its high degree of infectivity has led to a rapid spread across populations in most countries. Those affected can develop COVID-19. While some individuals present no or only mild symptoms, others develop severe symptoms that require professional treatment, ranging from short-term administration of oxygen to, in more severe cases, ventilator assistance in intensive care units (Verity et al., 2020). Despite drastic policy measures to slow the spread of the virus and despite changes in individual behavior, demand for professional healthcare has surged (or is expected to surge) rapidly in many countries (Deasy et al., 2020; Grasselli, Pesenti, Cecconi, 2020; Wells, Fitzpatrick, et al., 2020), resulting in shortages of critical equipment and trained medical personnel and raising concerns that existing capacity could quickly be outstripped. At the same time, the spread of the virus has become an economic crisis as much as it is a health crisis (IMF, 2020a), with the necessary measures to slow down the diffusion of the virus cause a large contraction of economic activity. In response, countries are implementing unprecedented measures to support households and firms and contain the economic disruptions (IMF, 2020b).

Because the first policy priority, saving lives, requires accommodating the increase in health costs (IMF, 2020c), one pressing question in many countries is how much health spending would have to increase in the near-term to (i) mitigate the health effects of COVID-19 on the population and (ii) treat those requiring medical assistance. This question is relevant for several reasons. First, estimates of the additional health spending will help planning and ensure that adequate resources are available to save lives. Second, for countries where financing is constrained, additional funds need to be mobilized from official bilateral and multilateral donors, as well as from non-governmental organizations. Estimates of spending requirements at the country level are crucial both to inform the authorities about how much assistance is needed and to inform donors about how to allocate funds across countries and projects. However, the uncertainty regarding the duration and intensity of the health crisis makes it difficult to estimate health spending required to cope with COVID-19.

In this paper we build a framework to estimate the size of additional health spending required to combat COVID-19 in the near-term, by country, under different scenarios about the diffusion of the virus. We use a simple Susceptible-Infectious-Recovered (SIR) epidemiological model[2] to project the number of people requiring hospital treatment in each country over time. We then combine these estimates with assumptions on existing spare hospital capacity as well as the costs and pace at which countries can expand their capacity in order to derive the increase in health spending that is required to meet additional needs.[3]

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[2] See Hethcote (2000) for a discussion.

[3] This model is implemented through the Excel-based template "DHJ Coronavirus health cost model.xlsx", available along with this paper so that any interested user can produce their own policy scenario and related cost estimates. Our paper can be treated as guidance for using the costing template that we have produced our estimates with.

Our model is simple but rich enough to capture salient features of the way in which pressure on the health system translates into immediate additional health spending. First, the pressure on the health system depends less on total number of COVID-19 cases requiring professional healthcare, but mostly on their distribution over time. Indeed, while the *fixed cost of expanding capacity* depends on the *peak number of cases per unit of time*, the *operating cost* depends on the demand for hospitalization *over time*. Second, irrespective of the number of cases, the additional health spending depends on capacity constraints, both in terms of installed capacity (spare beds, ventilators, and personnel immediately available for COVID-19 patients) and technical constraints to expand it. Finally, insofar as hospitalization is effective at separating infectious patients from those who still have not contracted the disease, expanding capacity can complement other policies in slowing down the diffusion of the virus.

To our knowledge, ours is the first paper that attempts to project the cost for the health sector by country. Indeed, thus far, existing research on the COVID-19 outbreak has focused on the spread of the disease (for example, Ferguson et al., 2020; Chinazzi et al., 2020; Kucharski and others, 2020; Zhang et al., 2020; and Wu et al., 2020), the effect of mitigation policies and social distancing (Ainslie, Walters, and Fu et al., 2020; Cowling, Ali, Ng et al., 2020; Flaxman, Mishra, Gandy et al., 2020; and Walker, Whittaker, et al., 2020), and on the overall economic effects (Berger et al., 2020 and Baldwin and Weder di Mauro, 2020a and 2020b).

Before further discussing the model and its results, it is important to clarify some important aspects of the health response to COVID-19 that are not covered in our framework as well as some limitations of our approach. Specifically:

- Like much of the public policy debate, our model is subject to the existing knowledge gaps about the behavior of COVID-19. Moreover, model estimates are conditional on specific assumptions about past and future containment and mitigation policies and assumptions on how these policies affect the disease dynamics. Model estimates are also conditional on assumptions about the speed and extent of the expansion in health care capacity. Therefore, our estimates can help form a view of the magnitude of health spending needs under *specific scenarios* for a country or a group of countries. Our estimates should not be taken as *unconditional projections* and they are not a substitute for judgment on realistic projections based on country-specific knowledge, if country specific projections are needed. In other words, epidemiological and cost parameters that would fit historical data for a specific country (or group of countries), may be inappropriate for another country (or group of countries). When using the model for a country, specific information (provided this is available) should be used instead of our assumptions. Instead, when deriving total or average health spending for a group of countries, assumptions reflecting averages costs (as we propose) are a viable remedy to data gaps.

- We do not discuss the potential tradeoffs between saving lives and saving livelihoods which have been studied in a range of recent papers (e.g., Acemoglu et al, 2020; Alvarez et al., 2020; Eichenbaum et al., 2020; Gonzales-Eiras and Niepelt, 2020; Hellwig et al., 2020; Jones et al., 2020). Relaxing and navigating these tradeoffs is an important policy question, but one that goes beyond the scope of our paper. Instead, our aim is to keep the framework simple by focusing on how much more spending would be needed to save the lives of those affected with COVID-19.

- We do not present a full-fledged cost benefit analysis. Allegedly, with lockdowns, the number of hospitalizations for traffic accidents, work-related injuries, and serious but not urgent procedures would drop. This would not only free up resources for COVID-19 patients (although the kind of care that they need is likely different from the care that other types of patients need), but, from a cost perspective, it would still allow to "shift" costs from one type of assistance to the other. Hence, we do not address a cost-benefit analysis of different types of prevention and mitigation measures. Specifically, we do not estimate the costs—administrative or economic—associated with Non-Pharmaceutical Interventions (NPIs), such as wide-scale quarantine/lockdown procedures social distancing. This is because the cost of these interventions (for example, community engagement, screening at ports of entry, tracing, enforcing quarantines, etc.) may fall into other (non-health) categories of spending. [4] Similarly, we do not consider the cost of testing. Not only is this because testing strategies may vary greatly from country to country, but also because (i) the optimal testing strategy may depend on the viability of other measures (for example, case tracing), (ii) the optimal testing strategy is not necessarily the one actually adopted, and (iii) while optimal testing may affect the diffusion of the virus (Drozd and Tavares, 2020, and Berger, Herkenhoff and Mongey, 2020), its cost may not depend on the optimal strategy adopted to slow down the diffusion of the virus.

- Our framework focuses on the immediate response to COVID, which has been characterized by concerns over the adequate resourcing of hospitals both in terms of equipment and personnel. We do not consider a number of pressures on health spending both in the short-term, and more notably, the longer term. Among others, these include the cost of transportation (for example, ambulances), public health interventions (such as testing and vaccine and drug development), and the longer-term consequences of COVID (such as increased outpatient services and unwinding the backlog of treatments for other conditions).

- We provide a range of cost estimates. This is because different countries might have different capacity to supply the medical personnel and equipment, drugs, and infrastructure necessary to expand the health sector, while others might need to import most of these from abroad. Hence, we consider two sets of assumptions about costs. In one set, we assume that most variable costs (especially equipment and drugs) are priced the same for all countries, except the wages of medical personnel, for which we use country-specific information. In the other set, we assume that most variable costs, except drugs, are priced locally.

- We do not consider whether costs are borne by the public or the private sector. This is likely to vary considerably by country and depend on the extent to which governments

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[4] See WHO (2020) for a comprehensive list of these measures and of their cost.

will decide to pick up private costs. With our model we derive estimates of the total cost of COVID's impact on the health sector.

- Finally, we treat prices as exogenous. As a result of increased global demand for equipment and supplies coupled with global shortages for some products, prices are currently very volatile and can be expected to respond to changes in policies. We do not model the price behavior and assume that price will remain fixed.

We find that, absent measures to slow down the diffusion of the virus such as social distancing or lockdowns, the expansion of the health system required to hospitalize and cure all those who need specialized care would have been economically and technically unfeasible. Without measures to slow down the virus (and assuming that every infected person infects 2.3 other people over the course of his/her disease), over 85 percent of the population would eventually get infected. Assisting all those developing severe symptoms would have required as much as $15.5 trillion worldwide. This would have been equivalent to about 17.7 percent of world GDP in 2019. In practice, absent measures to slow down the diffusion of the virus, assisting all those in need would have required scaling up health systems by many multiples, which would be unrealistic to expect of many countries. Subject to technical constraints on the expansion of health systems (specifically, that health systems cannot be expanded more than 20 percent), additional health spending would still have amounted to as much as $1 trillion and as low as $582 billion, globally (that is about 1.2 and 0.7 percent of the world GDP in 2019 respectively, depending on cost assumptions). However, the fatality rate would have tripled and reached an average, across all countries, of about 1 percent of the population.

Instead, under a scenario where the spread of the disease is successfully contained, both the additional health spending would drop significantly, to about $130–231 billion globally (or about 0.2–0.3 percent of the world GDP in 2019), and the fatality rate would be 0.1 percent of the population, on average, across countries. In any case, if the fixed costs of installing new capacity is the same across countries, while variable costs for medical personnel vary, in all scenarios additional spending in percent of GDP would be greater in low-income developing countries, and it would be lower in advanced economies.

Our paper is structured as follows. Section II describes the model, outlining the methodology for projecting the number of people in need of hospitalization, the rate at which healthcare capacity can be expanded, and, hence, the numbers that are able to receive hospital treatment. These estimates are combined with unit costs to give the overall cost. Section III describes the calibration of the model parameters and initial conditions as well as how real-time data is used to calibrate the projections. Section IV provides costs projections by country groups under different assumptions about the effectiveness of mitigation policies and constraints on the expansion of capacity in the health sector. Section V concludes.

II. THE MODEL

At its core, our model determines additional health spending related to COVID-19 by (i) multiplying the number of people hospitalized by the corresponding variable costs (per week, per patient) and; (ii) adding the fixed costs of expanding capacity where this is necessary. We begin by adapting a simple SIR model to project the number of people requiring hospitalization. The model-generated disease dynamics (which depend on policies to slow down the spread of the virus), together with a capacity constraint in the health sector, determine the number of those who are hospitalized. Finally, we make simple assumptions about *variable costs* for providing care to COVID-19 patients (in terms of nurses, physicians, medicines and other supplies) and the *fixed costs* of expanding capacity in the health system, to model the total cost of responding to COVID-19.[5]

While our primary objective is to provide annual cost estimates, the analysis is done at a weekly frequency. This allows us to account for the fact that case numbers can change dramatically within a few weeks (or even days), leading to large changes in capacity utilization. The relatively high frequency allows us to incorporate new information on actual disease dynamics in almost real time, and to thereby make prediction as accurate as possible.

A. Modelling Infected, Susceptible, Recovered, and Deceased

We begin by estimating the number of people that will require professional healthcare as a result of COVID-19. Following the standard SIR framework, in each period (a week), a person is in one of the following four states:

- *Susceptible*. These are people who have not been infected yet but are susceptible to becoming infected. S_t (a stock variable) indicates the number of susceptible people at period *t*. S_0 can be assumed to be a fraction of the population (that is, it is possible to assume that a fraction s of the population was born immune).

- *Infected*. These are the people who have contracted the virus and can currently infect others. We use I_t to indicate the total number of people with the virus *in period t* (a stock variable) and NI_t (a flow variable) to denote the number of new infections (people who contract the virus) in *period t.*

- *Recovered*. These are people who were infected and have recovered. R_t (a stock variable) indicates the total number of people who recover *up to period t*.

- *Deceased*. These are the people who have died. D_t (a stock variable) indicates the total number of deceased *up to period t.*

Because we are interested in simulating costs (which we compute in American dollars), for convenience, throughout the model our stocks and flows are measured in units (that is, in number of people).

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[5] In our model, health costs are transparently linked to the dynamics of infection in the population. That is, costs as increasing in response to the numbers of people infected and requiring hospitalization. In reality, authorities may seek to expand capacity pre-emptively. This is simply a timing effect and does not materially alter our results or modelling strategy.

As the medical science currently presumes short-term immunity after recovery (see Altmann, Douek, and Boyton, 2020, and references therein), for simplicity we assume that this is the case also for long-term immunity:

Assumption 1: Immunization. *Those who recover from COVID-19 are no longer infectious and no longer susceptible.*

By definition of Infected, Susceptible, Deceased, and Recovered, and by Assumption 1, it follows that, in every period *t*:

$$S_t + I_t + D_t + R_t = (1-s)POP_0$$

where POP_0 is the population at time zero and s is the fraction of the population that has in-built immunity. Furthermore, the dynamics for the population are given by:

$$POP_t = POP_{t-1} - \Delta D_t$$

B. Modelling the Number of Those Hospitalized and in Need of Hospitalization

To map the volume of infected into a demand for healthcare, we further divide the stock of infected into three groups:

- *Not requiring hospitalization*. We assume that, in each period, a constant fraction z of the newly infected develop severe symptoms and require hospitalization. The remaining, $1 - z$, are either asymptomatic or develop symptoms that can be treated at home. These people may require outpatient healthcare, but as they do not require hospital resources, we do not model these costs. We use NH_t to indicate the total number of people who do not require hospitalization *in period t,* and RH_t to denote the total number of people requiring hospitalization *in period t*.

- *Requiring but not obtaining hospitalization*. We assume that the health sector in each country is subject to capacity constraints. These constraints can be relaxed over time if more beds, nurses, and physicians are made available. However, when these constraints are binding, some of those requiring hospitalization may not obtain it. Letting $AVLB_t$ be the number of total beds available to COVID-19 patients during period t and RNH_t be the total number of people requiring but not obtaining hospitalization at period t, we have:

$$RNH_t = \min\{0, RH_t - AVLB_t\}$$

- *Hospitalized.* These are the people who require hospitalization and get hospitalized. Due to capacity constraints, H_t, the number of people hospitalized during period t, is:

$$H_t = \min\{RH_t, AVLB_t\}$$

Therefore, at each point in time, the following identity holds:

$$I_t = NH_t + RH_t = NH_t + RNH_t + H_t$$

For simplicity and without loss of generality, we assume that individuals are characterized by the maximum severity of their condition (that is, we abstract from the process whereby someone with mild symptoms can develop severe ones, and consider that these people develop immediately severe symptoms) and that individuals cannot move between the different infected sub-groups:[6]

Assumption 2: No change in the severity of symptoms. *We assume that an infected person with severe symptoms will need hospitalization until either death or recovery. Similarly, we assume that a person with mild symptoms will never get worse and require hospitalization. In other words, there is no transition across the group of those with mild and severe symptoms.*

C. Modelling Capacity Constraints in the Health Sector

We next model healthcare capacity and constraints to expand capacity to determine those requiring but not receiving treatment. Iteratively, this allows to determine the shortfall by which capacity should be expanded.

We begin by computing the number of hospital beds (B_0), nurses (N_0), and physician (P_0) available at period 0 (that is, initial installed capacity) using data from the World Bank Open Data set.[7] We assume that only a fraction, av, of existing beds will be available to accommodate COVID-19 patients:

$$AVLB_0 = av \cdot B_0 .$$

This assumption captures the fact that treating COVID-19 patients requires specialized equipment (for example, ventilators and personal protective equipment) and that hospital beds continue to be needed to treat other, non-COVID-19, patients.[8]

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[6] It is possible to assume other types of transition. For example, one could assume that a person is first asymptomatic, and then develops severe symptoms with a certain probability the next period. Relative to our model, modelling this transition would only introduce a lag between the period a person becomes infectious, and the period when he/she needs hospitalization. Adding this transition would not significantly alter the dynamics nor the stocks of infectious people who do not need hospitalization, those who need but not receive it, or those who need and receive hospitalization. Another model could consider the possibility that a person can be asymptomatic, symptomatic with mild symptoms, or symptomatic with severe symptoms. Conversely, one could also consider that those with severe symptoms transition back to having mild symptoms. Modelling these flows would add precision to the model but would require calibrating more transition parameters, as well as more estimates of (or assumptions about) the differential cost of treating patients with mild symptoms relative to the cost of treating patients with severe symptoms, and of treating them at home or in a hospital.

[7] The wage differential between physicians and other medical personnel varies greatly across countries, and so does their ratio. As data is available for nurses and physicians, taking these differences into consideration helps adding realism to the cost estimates.

[8] The fraction of existing beds available to accommodate Covid-19 patients at the start of the health crisis is not likely to remain fixed during the pandemic as it might depend on policies to contain the diffusion (continued)

We further assume that more beds can be added over time, but the speed at and extent to which this can be done is limited.

Assumption 3: Capacity constraints. *New beds can be installed next period for only a fraction nb of existing patients requiring but not obtaining hospitalization. In addition, beds can be scaled only up to a certain multiple of existing total bed capacity. That is, there is a ceiling on the total number of beds that a country's health system can have at any point in time. This ceiling is expressed as a multiple (cap) of total installed capacity at period 0.*

Based on capacity constraints, the stock of available beds is:

$$AVLB_t = \min\{AVLB_{t-1} + nb \cdot RNH_{t-1}, AVLB_0 + (cap-1) \cdot B_0\}$$

Finally, we assume that, in any period, the ratio of *additional* nurses and physicians to bed must remain the same, that is:

$$N_t = \frac{N_0}{(1-av)B_0} AVLB_t \quad \text{and} \quad P_t = \frac{P_0}{(1-av)B_0} AVLB_t{}^{9}$$

It is important to note that some developing countries face vast shortages of medical staff. This means that the constraint to the expansion of capacity would come from the difficulty in expanding medical staff, rather than beds. Either way, the assumption that the bed to nurse and doctor ratios remains the same allows to set the capacity constraint (*cap*,) as a function of the number of new nurses and doctors that can feasibly be mobilized.

D. Timing of Events, and Laws of Motion

The timing of events is as follows (Figure 1):

- In each period, a susceptible person can either become infected, or remain susceptible. As soon as they become infected, the person will be either develop severe symptoms (and so require hospitalization) or not. If requiring hospitalization, the infected person

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of the virus. For example, if elected surgeries are cancelled over time, space will free up for Covid-19 patients. Similarly, lockdowns might cause a reduction of urgent care for traffic or labor-related accidents. Hence, the parameter *av* should reflect the availability of existing beds *at peak* (that is, after all responses have been considered), as well as the fact that some resources needed to treat Covid-19 patients (for example, ventilators) cannot easily be scaled up.

[9] This specification assumes that any bed available for COVID-19 patients in period 0 is spare. Attending any COVID-19 patients (including those who will occupy the batch of existing and available $AVLB_0$ beds) would require over-time (or extra shifts) for existing nurses and physicians, which would imply additional costs. Alternatively, we could have computed the additional nurses (and physicians) using

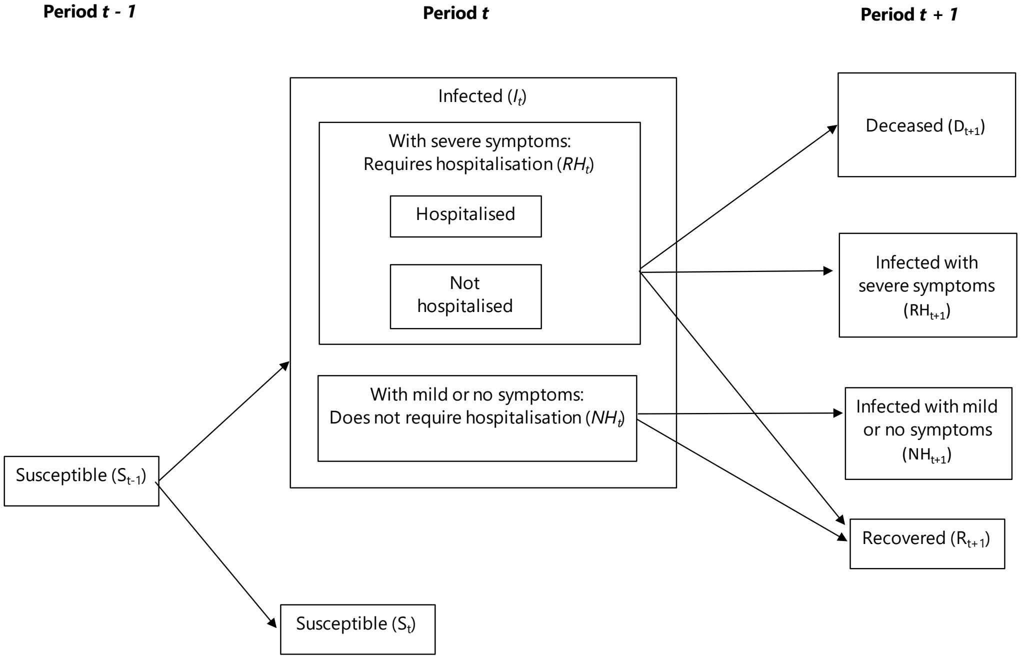
$$N_t = \frac{N_0}{B_0}\min\{0, AVLB_t - B_0\}$$

The formula that we use implies a slight overestimation of health personnel relative to alternative formulas.

will be hospitalized depending on the numbers of available beds relative to the stock of those requiring but not obtaining hospitalization.

- In the next period, any infected person can either recover, die, or remain infected.

Figure 1. Timing of Events and Flows from One State to the Other



Letting $j \in \{H, RNH, NH\}$, we model flows between states by defining the following *conditional* probabilities. Conditional on an individual being infected:

- d^j is the probability that an infected person in group *j dies* the next period.
- r^j is the probability that an infected person in group *j recovers* the next period.
- $k^j = d^j + r^j$ is the probability that an infected person in group *j* is not infected the next period, either because of death or recovery. Assuming that death or recovery are Bernoulli trials, $\frac{1}{k^j}$ is the length of time a person should expect to remain infected.

Given these definitions, we make the following two assumptions:

Assumption 4: Mortality and recovery probability. *We assume that the conditional probabilities* d^j *and* r^j *remain constant over time. Further, we assume that* $d_t^H < d_t^{RNH}$*, that* $r_t^H > r_t^{RNH}$*, and that* $d_t^{NH} = 0$.

Assumption 5: Equal duration of infection. *As estimates of COVID-19 duration are available for the population at large, we assume for simplicity that* $k^{H}=k^{RNH}=k^{NH}=k$.

The total number of deceased and recovered corresponds to the number of people who are not susceptible nor infectious any longer. With:

$$\begin{aligned}\Delta R_t &= r^{H}H_{t-1}+r^{RNH}RNH_{t-1}+r^{NH}NH_{t-1}\\ \Delta D_t &= d^{H}H_{t-1}+d^{RNH}RNH_{t-1}\end{aligned}$$

By Assumption 4, it follows that the stock of people who cannot infect (nor be infected) any longer is a constant fraction of the stock of infected:[10]

$$\begin{aligned}\Delta(R_t+D_t) &= \left(d^{H}+r^{H}\right)H_{t-1}+\left(d^{RNH}+r^{RNH}\right)RNH_{t-1}+r^{NH}NH_{t-1}\\ &= k\left(H_{t-1}+RNH_{t-1}+NH_{t-1}\right)\\ &= k\cdot I_{t-1}\end{aligned}$$

Now, let:

- β_t be the average number of people infected by an infectious person per unit time This parameter (the number of adequate contacts for infection) depends on people's social behavior. Therefore, it can change over time.
- $\rho 0_t$ be the number of people that an infected person infects over the course of his/her disease (the *basic reproduction number*). For simplicity and without loss of generality we assume that an infected person becomes automatically infectious and we consider:

$$\rho 0_t=\frac{\beta_t}{k}$$[11]

In each period, each infectious person will infect β_t other people. However, of these, only a fraction $\frac{S_t}{POP_t}$ are susceptible to contracting the disease. Furthermore, we account for the fact

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[10] Here we note that if $k^{H}\neq k^{RNH}\neq k^{NH}$, then the probability that the ratios of infected that either recover or die (that is, the parameter k for the population) would change over time and depend on the population shares of the *RNH*, *NH*, and *H* groups. Formally:

$$k_t=\frac{\Delta(R_t+D_t)}{I_{t-1}}=\frac{\left(d^{H}+r^{H}\right)H_{t-1}+\left(d^{RNH}+r^{RNH}\right)RNH_{t-1}+r^{NH}NH_{t-1}}{I_{t-1}}=k^{H}\frac{H_{t-1}}{I_{t-1}}+k^{RNH}\frac{RNH_{t-1}}{I_{t-1}}+k^{NH}\frac{NH_{t-1}}{I_{t-1}}$$

[11] If we allow β change over time, ρ0 would be the sum of those infected in week 1 (under β1), in week 2 (under β2), and so on so forth. Overall, the basic reproduction number at period *t* would depend on the mass of those who have been already infectious for 1, 2,... weeks.

that those infectious people that are hospitalized are removed from the general population with the following assumption:

Assumption 6: Quarantine of hospitalized persons. *We assume that only a fraction α of those hospitalized are adequately quarantined. The others can still infect other susceptible people. This assumption captures the heterogeneity in hospital conditions and safety measures across countries and allows assuming that hospitals can become clusters of diffusions (if α is set equal to 1). It also provides hospitalization an additional role to saving lives directly: it helps prevents the spread the infection.*

Altogether, the total number of new infections is:

$$NI_t = k \cdot \rho 0 \cdot \frac{S_{t-1}}{POP_{t-1}} \cdot (I_{t-1} - \alpha H_{t-1})$$

from which the stocks of susceptible and infected people follow:

$$\begin{aligned} S_t &= S_{t-1} - NI_t \\ I_t &= I_{t-1}(1-k) + NI_t \end{aligned}$$

Further, because of Assumption 5, the stock of infected requiring (not-requiring) hospitalization can be simply expressed as:

$RH_t = z \cdot I_t$ and $NH_t = (1-z)I_t$ [12]

Finally:

$$D_t = D_{t-1} + d^H H_{t-1} + d^{RNH} RNH_{t-1}, \text{ and}$$

$$\begin{aligned} R_t &= R_{t-1} + r^H H_{t-1} + r^{RNH} RNH_{t-1} + r^{NH} NH_{t-1} \\ &= R_{t-1} + (k - d^H) H_{t-1} + (k - d^{RNH}) RNH_{t-1} + k \cdot NH_{t-1} \\ &= R_{t-1} + k \cdot I_{t-1} - \Delta D_t \end{aligned}$$

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[12] Assumption 5 (equal duration of infection across groups) is crucial to simplify the computation of the stock of infected with mild/severe symptoms. If that is not the case (that is, if $k^{NH} \neq k^{RNH} \neq k^H$) then one would have to keep track of the total stock of each group separately. Also, Assumption 5 allows that we do not need to keep track of who is hospitalized. As the probability of *existing* the status H (either because of death or recover) is the same as that of exiting the status *RNH*, it does not really matter for the aggregate numbers *Dt* and *Rt* whether or not infected people with severe symptoms flow in and out of hospitalization.

E. Modelling the Cost Structure

The next step is to combine the number of people requiring professional care given capacity constraints and infection dynamics with unit cost modelling.

We consider two types of health cost in the model:

- *Variable costs*. These include the weekly cost of each additional nurse *(cn)* and physician *(cp)* required to treat COVID-19 patients, as well as the cost of medicines, material, and other variable costs related to factors such as administration, cleaning, patient transportation, etc. *(cm)*. Weekly variable costs VC_t are therefore given by:

$$VC_t = cn \cdot N_t + cp \cdot P_t + cm \cdot H_t$$[13]

- *Fixed costs*. These comprise the acquisition of new beds *(cnb)*, and the construction of new facilities (fc_100) which we compute for every 100 new beds. To be clear, new beds are in addition to all those already existing in a country. Also, new facilities include any type of new infrastructure (not necessarily a new hospital) that can be used to accommodate the new beds, and that can be installed rapidly. For simplicity, we compute cumulative costs for the year, without keeping track on the week in which they emerge (that is, when a new bed is purchased for *cnb*, or when the next 100th bed is purchased for (fc_100). Therefore, fixed costs *FC* are given by:

$$FC = cnb \cdot \max\left\{0, \max_t \left\{AVLB_t - B_0\right\}\right\} + fc\_100 \left\lfloor \frac{\max\left\{0, \max_t \left\{AVLB_t - B_0\right\}\right\}}{100} \right\rfloor$$

where $\lfloor . \rfloor$ is the floor function (that is, the largest integer smaller than the argument of the function). Note that our model assumes that while fixed costs are sunk, variable costs can increase and decrease with the number of patients. This is equivalent to assuming that additional medical personnel are laid off once the caseload falls.

III. PARAMETRIZATION OF THE MODEL AND TEMPLATE

We consider 214 countries and territories and we project volumes of people and costs for the 52 weeks between March 8, 2020, and March 7, 2021.

To run the model, we consider separately the epidemiological parameters and those determining the cost and health sector capacity, from the policy parameters. Policy parameters reflect the

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[13] As we discussed in relation to the stock of additional nurses and physicians, one could assume that the cost of an *additional* nurse/physician is different from the cost of an *existing* nurse/physician caring for a COVID-19 patient. That is, one could think that the cost of nurses and physicians assisting the flow of patients who will occupy the stock of AVLB0 beds is lower/higher than the cost of the new nurses and physicians assisting those patients who will occupy additional beds. Our estimates of variable costs would be higher/lower or equal to those obtained from such an alternative model.

result of policy and define specific policy scenarios. We use these to derive additional health spending under different policy scenarios. For example, we allow the basic reproduction number change following the introduction of social distancing and lockdown procedures. Also, we consider the speed and extent of the expansion in health capacity a policy parameter.

For each category, we further differentiate, based on available information, between parameters that are country specific and common across countries. The former are parameters for which country-level information exists, information which we either incorporate directly into the model or combine with other (common across countries) parameters. For the latter, country-specific estimates are either not available or not available for a large group of countries. We assume that these take the same value across all countries. Given, the highly specific nature of country policies and a lack of quantitative information at the country-level, and to allow comparability across countries, we impose that policy parameters are the same across all countries in each of the scenario that we will consider.

A. Epidemiological Parameters

These include (Table 1):

- **The share of the population that is immune at time zero, *s, and total population.*** Without further information, we assume that $s = 0$ for all countries. For total population, we use the UN Population survey as the primary source. If population data is missing for a country, we use World Bank Open Data on total population.

- **The average duration of the infection, *k*.** There is large dispersion and uncertainty around this parameter, but studies suggest that, on average, the infection lasts two weeks at most following the development of symptoms (Zhang, Litvinova, Wang et al., 2020). However, as it is not clear whether a person is infectious during the incubation period (of one week, on average), and because the disease duration may be longer for those developing severe symptoms, we assume that $k = 0.4$ for all countries (Verity and others, 2020). This corresponds to an average duration of 2.5 weeks.

- **The basic reproduction number, $\rho 0$.** The basic reproduction number depends crucially on the timing and severity of distancing measures as well as relevant country-specific factor such as demography, population density, and access to basic sanitation. Due to the compounding effect inherent in the exponential dynamics of the model, the projected number of cases is extremely sensitive to changes in $\rho 0$. For our model we assume that the basic reproduction number in the first weeks of the crisis (see discussion below for the basic reproduction number as a policy variable) was 2.3 for all countries. This is based on early estimates of this number (Kucharski and others, 2020; Wu, Leung and Leung, 2020) and on the number used in estimates from the Imperial College COVID-19 response team (see Ferguson and others, 2020). There is high uncertainty about this parameter and 2.3 lies in the lower range of estimates (Alimohamadi, Taghdir, and Sepandi, 2020). However, we find that 2.3 is high enough to produce substantial infection across the population.

- **The share of those hospitalized who cannot infect others, α .** We assume that almost all those hospitalized do not infect others. Although this parameter should be lower in countries where the health system is weak, we do not have country specific data to calibrate this parameter by country. Hence, we set α to be 0.99 for all countries.

- **The conditional probability of developing severe symptoms, z.** Ferguson et al (2020) provide estimates of the rate at which individuals develop severe symptoms by age group. We combine these estimates with information on the age structure of population from the UN Population Survey to produce country specific demography-weighted probabilities. Because country-specific calibration of this parameter may result into a very low average probability of developing severe symptoms if compared to other studies (Verity and others, 2020, and Zhang, Litvinova, and Wang, 2020), we allow scaling up country specific estimates by a factor γ_z = 1.1, which we assume to be constant for all countries.[14]

- **Conditional probability of death, at every period, for the hospitalized, d^H.** As with the probability of developing severe symptoms, we take age-specific mortality rates from Ferguson et al, (2020) and combine these with information on the age structure of the population from the UN Population Survey to produce country-specific mortality rates (δ^H) for the hospitalized. As with the probability of developing severe symptoms, country-specific calibration may result in a low probability of mortality (Fei and others 2020; Verity and others, 2020, and Zhang, Litvinova, and Wang, 2020). We scale δ^H up by factor γ_δ , which we assume to be the same for all countries.

  To calibrate the probability of death at every period we first derive the life-long probability of death conditional on being hospitalized from the corresponding negative binomial process:

$$\begin{aligned}\gamma_\delta \cdot \delta^H &= d^H + d^H\left(1-d^H-r^H\right)+d^H\left(1-d^H-r^H\right)^2+\ldots \\ &= d^H\sum_{\tau=0}^{\infty}\left(1-d^H-r^H\right)^\tau \\ &= \frac{d^H}{d^H+r^H}\end{aligned}$$

  We then calibrate d^H solving the following system:

$$\begin{cases}\gamma_\delta \cdot \delta^H = \dfrac{d^H}{d^H+r^H} \\ k = d^H + r^H\end{cases}$$

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[14] Acemoglu et al (2020) also highlight the importance of differentiating risks by age group when modeling the policy response to COVID-19.

The solution is

$$d^{H} = k \cdot \gamma_{\delta} \cdot \delta^{H}.$$

- **Increase in death rate for those who do not receive hospitalization, d^{RNH}.** We assume that the death rate for those who need but are not hospitalized increases by a constant $\Delta\delta^{\mathrm{RNH}}$ which we set equal to 3 percentage points for all countries.

- **Conditional probability of death, at every period, for those requiring but not obtaining hospitalized, d^{RNH}.** To calibrate d^{RNH} we make a simplifying assumption and assume that death/recovery follow a negative binomial process.[15] Hence, we compute:

$$d^{RNH} = k \cdot \left(\gamma_{\delta} \cdot \delta^{H} + \Delta\delta^{H} \right).$$

Notice that, because of assumption 5, the recovery probability is never used in the model and hence it not needed to estimate costs.

- **Initial number of infected, I_0,, and subsequent numbers of infected, I_t.** We initialize the analysis setting week $t = 0$ as the week ending on March 8th, 2020. This provides us with enough data to set the initial dynamics of the outbreak as precisely as possible. We use country-level data about the observed (that is, reported) number of infections and deaths from the Johns Hopkins University Coronavirus Resource Center to initialize the model with an estimate of I_0 and to check that model-based I_t do not under-estimate the spread of the disease. Specifically, let oc_t be the total number of reported cases *up the end of period t*. Further, let $\overline{D}_t^{t+1}$ denote the observed (reported) number of deaths in weeks $t+1$. Using the country specific probability of death conditional on hospitalization, d^{H}, we derive the number of infected with severe symptoms imputed from the official number of deceased as:

$$\text{Infected with severe symptoms imputed from death} = \frac{\overline{D}_t^{t+1}}{d^{H}}.$$[16]

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[15] To be precise, the life-long probability of death depends on the probability that a person with severe symptoms is eventually hospitalized. For given assumptions about capacity constraints, this probability can be computed exactly, but the closed form is very convoluted, complicating the parametrization of the probability of death.

[16] This assumes that on March 8th, 2020, there was spare capacity in the health systems of all countries, and all COVID-19 patients could be hospitalized.

Also, assuming that only those with severe symptoms would be tested and hence recorded officially as infected, and recalling that only fraction *z* of those infected develop severe symptoms, we set:

$$I_0 = \max\left\{\text{Official cases}\cdot\frac{1}{z},\ \frac{\overline{D}_t^{t+1}}{d^H}\cdot\frac{1}{z}\right\}$$

or 1 if no official data is available.

For subsequent periods, because in our model we must keep into considerations also those who are asymptomatic and would likely not be tested, we allow the model to estimate more infections than those officially reported, but not less. That is, for weeks up to the one ending on May 4, we use data from the Johns Hopkins University Coronavirus Resource Center to set:

$$I_t = \max\left\{\text{Model prediction for } t,\ \text{Official cases}\cdot\frac{1}{z},\ \frac{\overline{D}_t^{t+1}}{d^H}\cdot\frac{1}{z}\right\}$$

B. Capacity and Cost Parameters

To model capacity constraints in the health sector we consider the following assumption:

- **Installed capacity in the health sector, *B_0*, *N_0*, *and P_0*.** We use data from the World Bank Open Data set on the availability of beds, nurses, and physicians to set initial conditions for healthcare capacity. The share of installed ICU beds over total beds varies considerably by country (see Rhodes et al., 2012, and Phua et al., 2020). Based on data of European countries, we assume that av = 3 percent of total hospital beds are available to severe COVID-19 patients, for all countries.[17]

For variable costs we consider two sets of parameters: high, and low variable cost assumptions. With high variable cost assumptions, we use country-specific information about the wages of medical personnel and assume that other variable costs are the same across all countries. These assumptions reflect a situation in which most of necessary supplies (disposable gloves, syringes and vials, linens, but also medicines) need to be imported. These assumptions might be more relevant for countries with very limited capacity to expand the health sector and that need to rely heavily on imports of medical supplies. For low variable cost assumptions, we use country-specific cost estimates from the WHO CHOICE. Because these estimates include all costs excluding drugs, we still assume the same international price for medicines for all countries. Specifically:

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[17] Data on intensive or critical care units is not available for a large group of countries. In our model, assuming a higher share would reduce fixed costs, but not variable costs.

- **Variable costs for nurses and physicians, *cn* and *cp*.** For high variable cost assumptions we use data from the WHO Global Health Expenditure Database on the doctors' wage bill as a share of GDP, and data on the wage bill of doctors and other health staff as a share of total health spending, to derive country specific weekly wages of nurses and doctors. We express all costs in American dollars. For low variable cost assumptions, we set these costs to zero (medical personnel costs are incorporated in the next item).

- **Other variable costs, per week, per patient, *cm*.** For high variable cost assumptions, we assume that these costs are the same for all countries and, based on Dasta et al. 2005, we set them at $4,516 per week per patient.[18] For low variable cost assumptions, we use the WHO CHOICE (inpatient costs in tertiary hospitals—see Stenberg and others, 2018) for all variable costs and we add a cost of imported supplies of U.S. 1,000 for all countries.

For fixed costs we assume the following:

- **Fixed costs.** Because we assume that the demand for new beds would derive from the increase in patients with severe symptoms, we assume that the cost of new beds would have to include ventilators and equipment for intensive care that is currently not existing in the country and that, hence, would have to be imported at an international cost. Thus, we assume that the cost of new beds is $25,000 for all countries. Further, we assume that the cost of the necessary infrastructure to host 100 new beds is $1,000,000 for all countries.

C. Policy Parameters

We run scenarios analysis assuming that policies affect the following parameters:

- **The basic reproduction number after social distancing and lockdown, $\rho 1$.** To capture the time and policy dependence of the basic reproduction number in a simple way, we assume that if social distancing measures are introduced, the basic reproduction number drops from $\rho 0$ to $\rho 1$. The difference between $\rho 0$ and $\rho 1$ captures the effectiveness of social distancing measures. Flaxman, Mishra, Gandy et al (2020) provides estimates of the impact of different social distancing measures and lockdowns on the basic reproduction number and we use this to calibrate the success of mitigation measures.

- **The timing of social distancing measures.** Social distancing measures result in an immediate drop from $\rho 0$ to $\rho 1$ when implemented in week *w*.

- **Capacity constraints.** We assume that capacity can be increased up to a certain multiple of the total bed capacity existing before the outbreak of COVID-19. Also, we consider the speed at which those in need but not obtaining hospitalization can be hospitalized the next period.

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[18] This is likely an underestimate for some AEs, and an over-estimate for some EMEs and LIDCs.

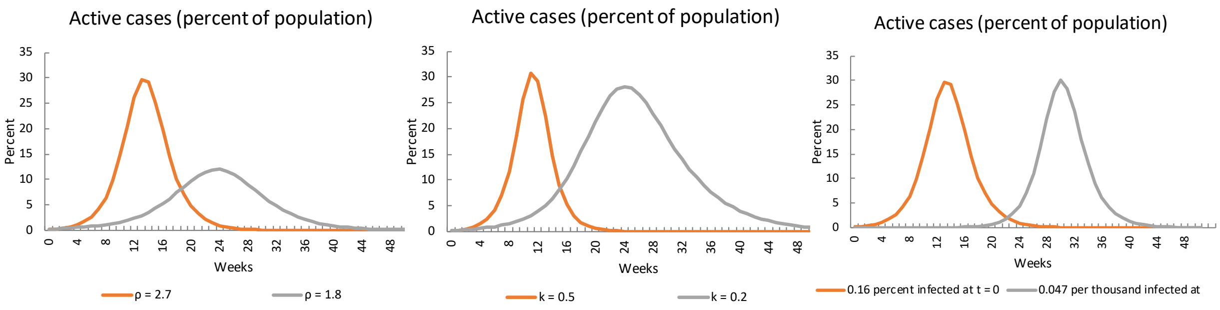
IV. ESTIMATES OF ADDITIONAL HEALTH SPENDING

Before we illustrate some aggregate results, we give some intuition for the results of the model for a single hypothetical country.

In a standard SIR diffusion model, the function that maps the number of infected at every period looks like a bell curve (Figure 2, Panels a, b, and c). This is because, as more and more people contract the virus, the number of susceptible people decreases (recall that those who recover are neither infectious nor susceptible any longer). While at the beginning of the outbreak many people can contract the virus and the number of cases per period increases exponentially, later on there are fewer and fewer people who can get infected and the number of infections per period declines.

The height of the peak depends on the parameters k (the average duration of the disease) and ρ (the basic reproduction number, that is the number of people whom an infectious person can infect). The greater their product, the higher the number of infected at peak and the thinner the "tail" of the distribution over time (Figure 2, Panel a and b). However, the shape of the distribution responds more to changes in ρ than to changes in *k*. This can be seen comparing Panels a and b of Figure 2. In Panel a, the basic reproduction number underlying the gray line is 2/3 the one underlying the orange line. In Panel b, the *k* underlying the gray line is less than half the one underlying the orange line. Yet the change in the shape of the two lines is more pronounced in Panel a than in Panel b. The period when the peak is reached depends instead on the number of infected people at time zero, I0. The greater I0, the sooner the peak will occur (Figure 2c).

Figure 2. The Time Profile of Infections, and of Hospitalization



a. Changing ρ (while keeping k the same)

b. Changing k (while keeping ρ the same)

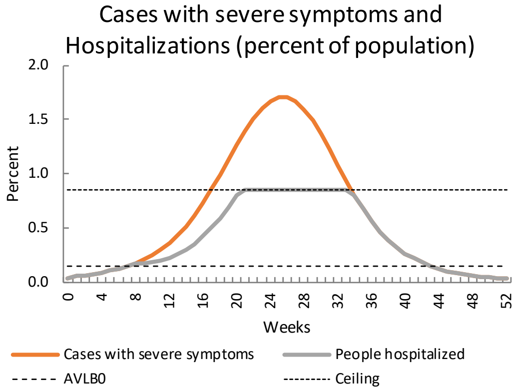
c. Changing I_0 (while keeping ρ and k the same)

Source: Authors' Calculations.

Because the number of infected people developing severe symptoms is a fraction of all infected, the curve of the number of people in need of hospitalization follows a similar shape (Figure 3). However, the curve of the hospitalizations may not look like the curve of severe cases. At the beginning, as $AVLB_0$ beds are available to COVID-19 patients, all those who need hospitalization receive it. So, until all initially available beds ($AVLB_0$) are occupied, the curve of hospitalizations follows the same curve as that of people with severe symptoms (who require hospitalization). Once these beds are fully occupied and new beds are needed, the curve of the people hospitalized lies between the curve of people with severe symptoms and the $AVLB_0$ line, depending on the speed at which the gap can be filled. When the ceiling on overall capacity is reached, the number of hospitalizations becomes a flat line. Because stepped up capacity remains permanent, once the number of people developing severe symptoms drops sufficiently, all those who require hospitalization will be accommodated.

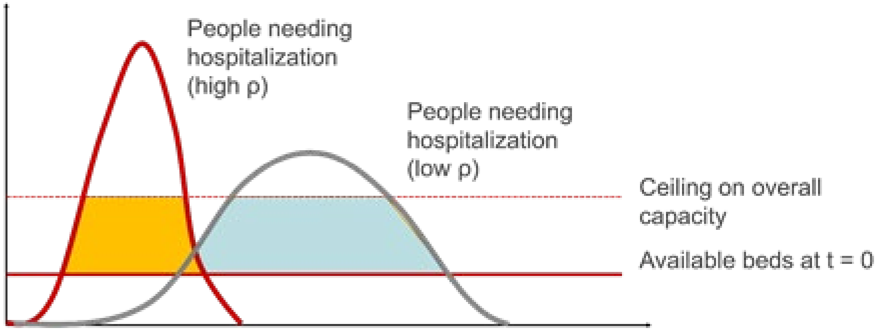
Now, in our model the fixed costs of expanding the health system depend only on the number of additional beds. That is, fixed costs are proportional to the extent to which overall capacity can be expanded. Graphically, fixed costs are proportional to the difference between the peak of hospitalizations and the number of beds initially available to COVID-19 patients, ($AVLB_0$) at a certain *point in time* (Figure 4). Variable costs, instead, are proportional to the number of people who receive hospitalizations *over time*. Graphically, variable costs are proportional to the integral of the hospitalizations curve. Hence, variable costs depend not only on the constraint on overall capacity but also on the shape of the distribution of people who develop severe symptoms. For example, when the capacity constraint is binding (as in Figure 4), a flatter curve of people developing severe symptoms does not change fixed costs but it implies that variable costs will be faced for longer time. Of course, because more people can now receive hospitalization, there will be fewer deaths.

Figure 3. Cases with Severe Symptoms, Capacity Constraints and Hospitalizations



Source: Authors' Calculations.

Figure 4. The Dynamics of Fixed and Variable Costs



Source: Authors' Calculations.

A. A Benchmark Scenario: Health Spending with No Social Distancing Measures

To set a benchmark, we first run a counterfactual epidemiological scenario in which no country has adopted measures to slow the diffusion of the disease. That is, we consider the case where the basic reproduction number remains 2.3 for the entire horizon (52 weeks) of our analysis. This scenario serves as an extreme for producing the largest number of infected and deceased. Because hospitalization of patients helps reduce the spread of the disease, we benchmark the number of diseases to the case where there is no expansion in health care capacity.

In this benchmark scenario, the peak of infection would be reached within the 52-week horizon for all countries (Figure 5). Owing to differences in the number of cases at the beginning of the infection, the peak would be reached earlier in advanced economies (at week 24, on average), than in emerging market economies and low-income developing countries (week 27 and 32, respectively). In all countries, the virus would eventually infect around 90 percent of the population. Because the probability to develop severe symptoms depends on the age composition of the population, the share of total population who would eventually need hospitalization would vary across countries, but it would average 9.1 percent across all countries and be as high as 14.5 percent in advanced economies, and as low as 5.3 percent in low-income and developing countries. However, in many countries, at the peak, the number of people with severe symptoms (hence, requiring hospitalization) would be many multiples of the *total* installed beds before the beginning of the pandemics. On average, heath systems around the world would have to be scaled up 12-fold to accommodate all COVID-19 patients at any time. The pressure on the health system would be greater in low-income developing countries (LIDCs).

If there were no capacity constraints and health systems around the world could be increased to *any desired scale*, the cost to hospitalize all those COVID-19 patients who need hospitalization would amount, worldwide, to around $15.3 trillion of with high variable cost assumptions (Figure 6) and around $9.5 trillion of in a low variable cost assumptions. This is equivalent to 17.7 and 10.9 percent of 2019 world GDP respectively. The total amount would be different by country groups, owing to different variables costs per medical personnel across countries. However, in percent of GDP, additional health spending would average between 6.9 and 9.8 percent of GDP in advanced economies (AEs), between 14.3 and 23.6 percent of GDP in emerging market economies (EMEs), and it would reach between half and a multiple of GDP in LIDCs. Because hospitalization would effectively function as a quarantine, the virus would diffuse less than absent a health response. Indeed, hospitalizations in Figure 6 are almost the same as the number of people developing severe symptoms in Figure 5. Of course, because COVID-19 can be lethal even if one receives all needed care, mortality among the population would still be greater than zero, but it would average 0.3 percent of the population across all countries.

While it is imaginable to envision that beds, or hospitals, can be scaled up many times, assuming that specialized medical personnel can be scaled up at any rate rapidly is a more heroic assumption. Hence, we consider a more realistic scenario where overall capacity of the overall health sector can be expanded by 20 percent. In this case, with high variable cost assumptions the increase in health spending would total, worldwide, slightly more than $1 trillion of (Figure 7), equivalent to 1.2 percent of the world GDP in 2019. The greater dollar amount would be needed in AEs (about $417 billion). When scaled by GDP, it is LIDCs where health spending would have to increase the most. On average, additional health spending would reach 5.8 percent of GDP in LIDCs, against 1.7 percent of GDP in EMEs (on average), and 0.8 percent of GDP in AEs. With lower cost assumptions, health spending would need to increase about $283 billion in AEs, 271 in EMEs, and 30 in LIDCs. However, although the pressure on health spending is lower, when there are constraints to the expansion of capacity in the health sector not everyone who needs hospitalization would get it. At best, 2.2 percent of the population would be hospitalized. As a result, the total number of deceased would increase four times and average about 1.1 percent of the population across all countries and be as high as 1.8 percent of the population in AEs.

As a robustness check, we also consider increasing the basic reproduction number to 2.9. The picture would not change much. As we expect, the peak of infections would be reached sooner (around week 21, on average across all countries), the share of population eventually infected would be much higher (around 96.4 percent), and the peak of severe cases to total beds would increase (to over 17.8, on average across all countries). The total cost of accommodating all patients who need hospitalization would increase to $19 trillion with high variable cost assumptions, as, at peak, cases would require a much larger expansion of the health system. Yet, fatalities would increase to 0.4 percent of the population (on average). However, the expansion of the health system required to treat all those who need hospitalization would likely be technically not feasible. With expansion of capacity capped at 20 percent of existing beds, additional health spending, world-wide, would reduce to $863 billion in a high variable cost case (as cases would be higher, but also decline faster), but fatalities would reach, on average across all countries, 1.2 percent of the population.

B. Health Spending with Successful Lockdown and Social Distancing Measures

We now consider a set of scenarios in which lockdowns and social distancing measures successfully reduce the basic reproduction number to 0.9, in all countries, by week 8. When the basic reproduction number is below 1, the virus eventually disappears from the population. The peak of infections would be registered in week 9 in all countries (by the dynamic of the model)

Without expansion of the health care system, the infected would reach 6.5 percent of the population in AEs, 1.8 percent in EMEs, and 0.2 in LIDCs (Figure 8). The difference in these numbers is mostly explained by the fact that the initial number of infections is higher in AEs than in the other two groups. Although lower infections imply a lower number of people developing severe symptoms (hence, requiring hospitalization), still the number of severe cases requiring hospitalization would reach about 60 percent of total beds installed at time $t = 0$ in AEs, 20 percent in EMEs, and slightly less than 2 percent in LIDCs. Because we assume that only 3 percent of total beds can be used for COVID-19 patients with severe symptoms, health spending would need to be scaled up in many countries, particularly AEs and EMEs, but not in the average LIDCs.

Absent capacity constraints, health spending would have to increase by a total in between 281 and $426 billion world-wide (depending on whether we use high or low variable cost assumptions), or about 0.3–0.5 percent of the world GDP in 2019. Specifically, between 282 and $322 billion would be needed in AEs, between 65 and 104 billion in EMEs, and between 0.3 and 1.1 billion in LIDCs. As a percent of GDP, health spending would have to increase, on average, by as high as 0.5 percent of GDP in AEs, 0.3 in EMEs, and 0.1 in LIDCs (Figure 9). Fatalities would only reach, on average, 0.03 percent of the population in AEs, 4 every 100,000 people in EMEs and 0.2 every 100,000 people in LIDCs. However, in many countries this would still require expanding capacity beyond what might be *technically* feasible. In AEs, the entire health sector would have to expand, on average, 43 percent in AEs, and 14 percent in EMEs. In LIDCs, owing the very low number of initial cases, installed capacity would suffice for the average country.

With a realistic limit of 20 percent on the expansion of health sector capacity, costs would be lower than what would be necessary to hospitalize all those who develop severe cases. But this is the case only because technical constraints prevent the installation of more beds and facilities., Yet, additional health spending would not be much lower than if capacity could be expanded indefinitely. Health spending would still need to increase by total of about \$110–186 billion in AEs, 20–43.6 in EMEs, and 0.3–1.1 billion in LIDCs. The total world-wide would be as low as 130 and as high as \$231, or about 0.2–0.3 percent of the world GDP in 2019. In percent of GDP, health spending would need to increase, on average, 0.2 percent of GDP in AEs, between 0.1 and 0.2 percent of GDP in EMEs, and 0.1 in LIDCs. However, lower monetary costs would come at a higher death toll. Relative to the case where there is no cap on the expansion of the health system, the average fatality rate would be 2.6 times as high in AEs (0.7 percent), 2.4 times as high in EMEs (10 for every 100,000 people), and about the same in LIDCs (Figures 9 and 10).

C. Health Spending with Less Successful Lockdown and Social Distancing Measures

If lockdowns and social distancing measures reduced the basic reproduction number to only 1.5 by week 8 in all countries, then infections could reach 53 percent of the population in AEs, on average, 46 percent in EMEs, and 28 percent in LIDCs. At peak, severe cases would be many multiples of installed hospital capacity: about 2.8 in AEs, 2.9 in EMEs, and 3.9 in LICDs (Figure 11).

With a ceiling of 20 percent on the expansion of total capacity in the health sector, under high variable cost assumptions additional health spending would amount to a total slightly above \$1 trillion, world-wide, or 1.2 percent of the world GDP in 2019. Additional health spending would total \$470 billion in AEs, 535 in EMEs, and 55 in LIDCs. On average, cost would be about 0.9 percent of GDP in AEs, 1.7 percent of GDP in EMEs, and 4.3 percent of GDP in LIDCs, which could reach as much as 11 percent of GDP in a few countries. As there would be more infections and not all those in need would be hospitalized, the average fatality rate would increase manifolds relative to the scenario where the basic reproduction number is kept below 1. Deaths would amount to 0.8 percent of the population, on average, in AEs, 0.3 percent in EMEs, and 0.1 percent in LIDCs.

V. CONCLUSION

In this paper, we have set out a simple but rich framework for estimating the healthcare costs associated with the SARs-CoV-2 outbreak. In doing so, we have built on a canonical SIR diffusion model by introducing different severities of symptoms (to account for different impact on demand for healthcare in different countries), the existence of constraints on both overall capacity of healthcare system and the rate at which these can be eased, and different health outcomes depending on access to healthcare. Moreover, we have set out methods to tailor these variables to the specific characteristics of different countries. As such, our framework goes beyond simply attaching unit costs to each case of COVID-19 infection as it recognizes that costs are fundamentally determined by the intersection of the supply of healthcare (determined by existing capacity and the ability of healthcare systems to scale capacity up) and the additional demand healthcare posed by COVID-19 patients (determined by the rate at which the infection spreads and the rate of severe symptoms in the population), both of which vary by country. We parametrized our model using available data on COVID-19 cases and health care costs by country. The framework to implement our model is available along with this paper.

We find that the cost of responding to the pandemic in a benchmark scenario of no capacity constraints and no social distancing/quarantine measures would reach over $15 trillion, globally. As a share of GDP, costs would vary from an average of 10 per cent of GDP for advanced economies, to 24 per cent for emerging economies and over 100 per cent for low-income ones. Against this, a scenario where effective social distancing/quarantine measures are put in place and healthcare capacity can expand up to a limit of 20 per cent sees global costs fall to just under $231 billion. Spending as a share of GDP falls to an average of 0.3 per cent in advanced economies, 0.2 per cent in emerging economies, and 0.1 per cent in low-income developing economies.

The estimates that we present in this paper are inevitably subject to a high degree of uncertainty, reflecting still limited knowledge on a number of key aspects of COVID-19 (for example, the extent to which social distancing measures and lockdowns will be effective at slowing the diffusion of the virus in different countries), together with the uncertainty about health systems' ability to respond to the pandemic. We cannot but caution that any projection of additional health spending must need to take account of the policies set at each country level.

While it is too early to say what the overall cost of COVID-19 will be in terms of health spending, our modelling makes it clear that policy aimed at reducing the cost of contagion helps contain either the costs of providing care to those who need it or, when constraints on the expansion of the health care system are binding, limit the number of deaths. In particular, our analysis suggests that social distancing and quarantine measures combined with a 20 percent expansion of health sector capacity can lower the average fatality rate by almost 1 percentage point relative to a scenario with no measures to slow down the spread of the virus and expansion of the health sector. Though it does not directly address them, our framework also motivates important policy questions around what the appropriate standing level of health system capacity should be and the speed with which resources can be obtained (or redirected) to increase capacity in a time of crises. Such questions are pertinent for both COVID-19 and any future public health crisis and will form an important part of lessons learned from this pandemic.

Table 1. Epidemiological Parameters

Parameter	Default Value	Comment	Type	Source
k	0.4	Share of infected people that is not infectious after 1 week, either because of recovery or death.	Common	Zhang, Litvinova, Wang et al. (2020) Verity et al. (2020)
$\rho 0$	2.3	Average number of new infections per infected person over the duration of infection, when no control measures are taken	Common	Kucharski et al. (2020), Wu, Leung and Leung (2020), Ferguson et al. (2020)
s	0	Share of population that will not never get infected	Common	Assumed
POP	Country specific	Total population	Country specific	UN Population Survey and World Bank Open Data
α	0.99	Share of those hospitalized who cannot infect others	Common	Assumed
z	Country specific	Share of those infected that require hospitalization	Country specific	Ferguson et al. (2020), UN Population Survey, and World Bank Open Data
γ_z	1.1	Multiply estimate of country specific z	Common	Assumed
δ^H	Country specific	Probability of death next period for hospitalized.	Country specific	Ferguson et al. (2020), UN Population Survey, and World Bank Open Data

Scale up mortality δ^H	1.1	Multiply estimate of country specific δ^H	Common	Assumed
d^H	Country specific	Probability of death next period for hospitalized and people requiring but not obtaining hospitalization.	Country specific	Derived
$\Delta\delta^{RNH}$	0.03	Increase in death rate for people requiring but not obtaining hospitalization	Common	Assumed
d^{RNH}	Country specific	Probability of death next period for people requiring but not obtaining hospitalization.	Country specific	Derived
I_0	Country specific	Initial number of infections	Country specific	John Hopkins University

Source: Authors' Calculations.

Table 2. Capacity and Costs Parameters

Parameter	Default Value	Comment	Type	Source
B_0, N_0, P_0	Country specific	Number of beds, nurses, and physicians available at period 0	Country specific	World Bank Open Data
av	0.03	Share of existing beds at time zero, available to Covid-19 patients	Common	Assumed
B_0, N_0, P_0	Country specific	Number of beds, nurses, and physicians available at period 0	Country specific	World Bank Open Data
cn and cp	Country specific (high variable cost scenario) or zero (low cost scenario)	Wage per week of a nurse and physician	Country specific	WHO Global Health Expenditure Database
cm	US$4,516 (high variable cost scenario) or US$1,000 plus country specific costs (low variable cost scenario)	Cost of medicine and other material per week, per hospitalized patient	Common or country specific	Assumed based on Dasta et al. 2005, or WHO CHOICE
cnb	US$25,000	Cost of a new bed and equipment	Common	Assumed
Fc_100	US$1,000,000	Fixed costs associated to expanding capacity by 100 new beds	Common	Assumed

Source: Authors' Calculations.

Table 3. Policy Parameters

Parameter	Comment
ρ1	Average number of new infections per infected person over the duration of infection, when control measures (quarantine, lockdowns, etc.) are taken
W	Number of weeks it will take to switch to ρ1 since the beginning of the outbreak
cap	Multiple of beds available at time zero above which the health system cannot go
nb	Share of patients requiring but not obtaining hospitalization that can be hospitalized next period

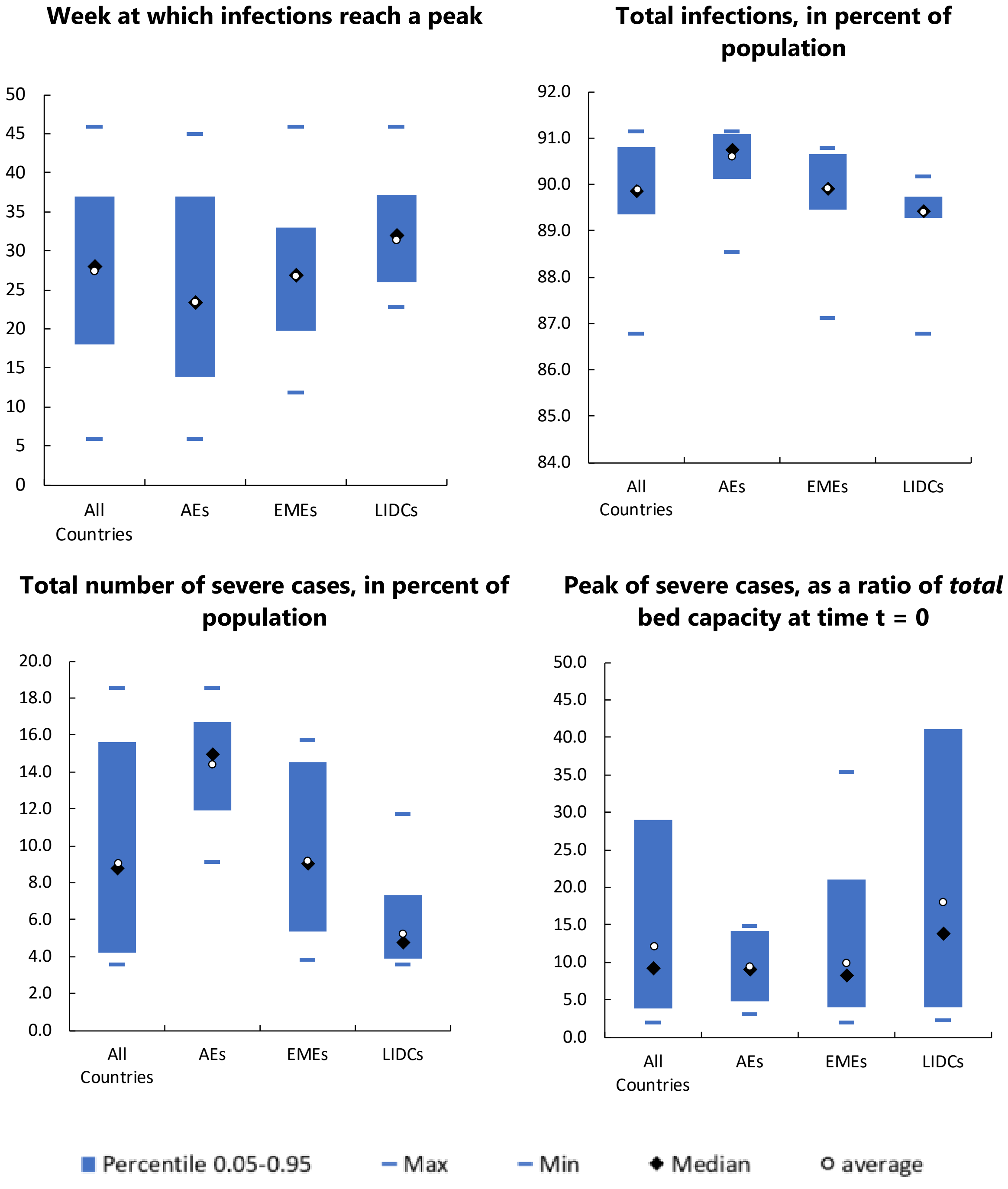
Source: Authors' Calculations.

Table 4. Increase in Health Spending Under Different Scenarios and Cost Assumptions

	Low-cost assumptions Country-group total (U.S. dollar billions)	**High-cost assumptions** Country-group total (U.S. dollar billions)	**Deceased** Country group average (percent of population)
NO MITIGATION			
Unlimited expansion of health sector			
All countries	9,508.5	15,289.7	0.295
AEs	3,179.9	4,751.3	0.561
EMEs	5,449.5	8,928.8	0.288
LIDCs	879.1	1,609.5	0.137
20 percent expansion of health sector			
All countries	582.9	1,042.8	1.060
AEs	282.5	418.1	1.806
EMEs	270.8	545.0	1.061
LIDCs	29.6	79.6	0.578
SUCCESSFUL MITIGATION			
Unlimited expansion of health sector			
All countries	281.8	426.4	0.009
AEs	216.5	321.7	0.036
EMEs	65.1	103.6	0.004
LIDCs	0.3	1.1	0.000
20 percent expansion of health sector			
All countries	130.4	230.9	0.023
AEs	109.9	186.4	0.101
EMEs	20.2	43.5	0.010
LIDCs	0.3	1.1	0.000
LESS SUCCESSFUL MITIGATION			
Unlimited expansion of health sector			
All countries	2,403.6	4,208.2	0.079
AEs	1,130.4	1,903.9	0.176
EMEs	1,154.1	2,074.3	0.074
LIDCs	119.1	229.9	0.025
20 percent expansion of health sector			
All countries	578.3	1,058.4	0.350
AEs	290.7	470.2	0.760
EMEs	264.4	533.3	0.336
LIDCs	23.2	54.9	0.113

Source: Authors’ Calculations.

Figure 5. Benchmark Epidemiological Scenario



Week at which infections reach a peak

Total infections, in percent of population

Total number of severe cases, in percent of population

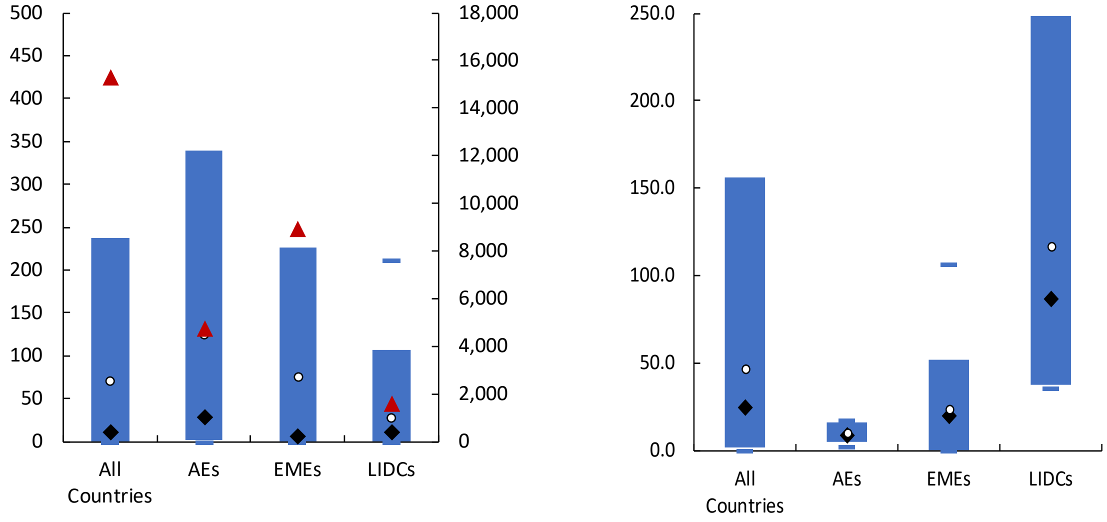
Peak of severe cases, as a ratio of *total* bed capacity at time t = 0

Source: Authors' Calculations.

Figure 6. Benchmark Epidemiological Scenario with no Capacity Constraints

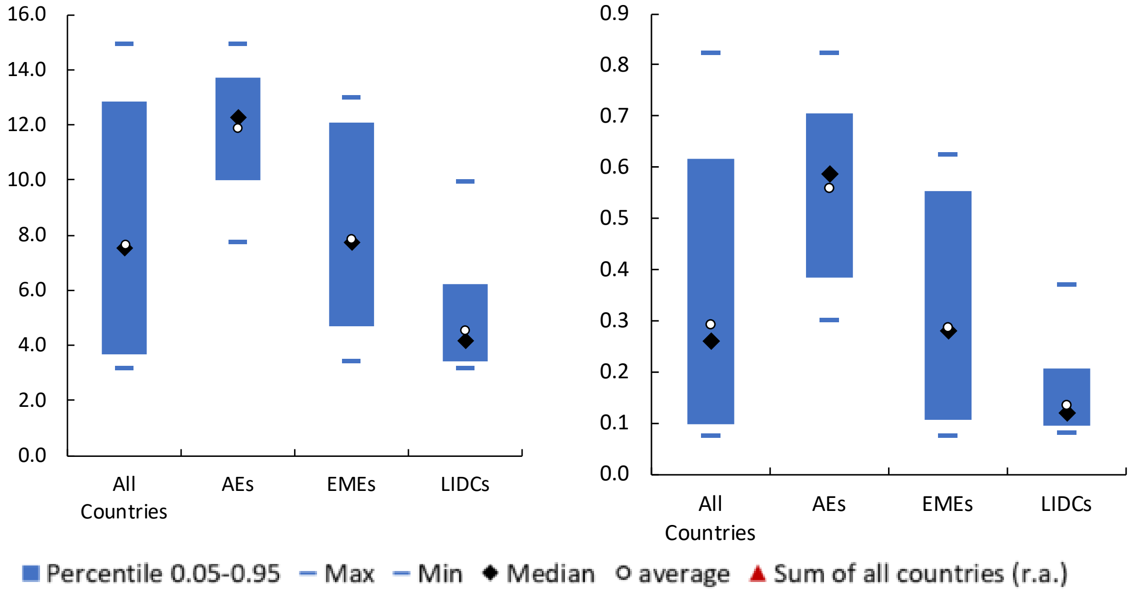
Additional health spending, in U.S. billions (high variable cost assumptions)

Additional health spending, in percent of GDP (high variable cost assumptions)



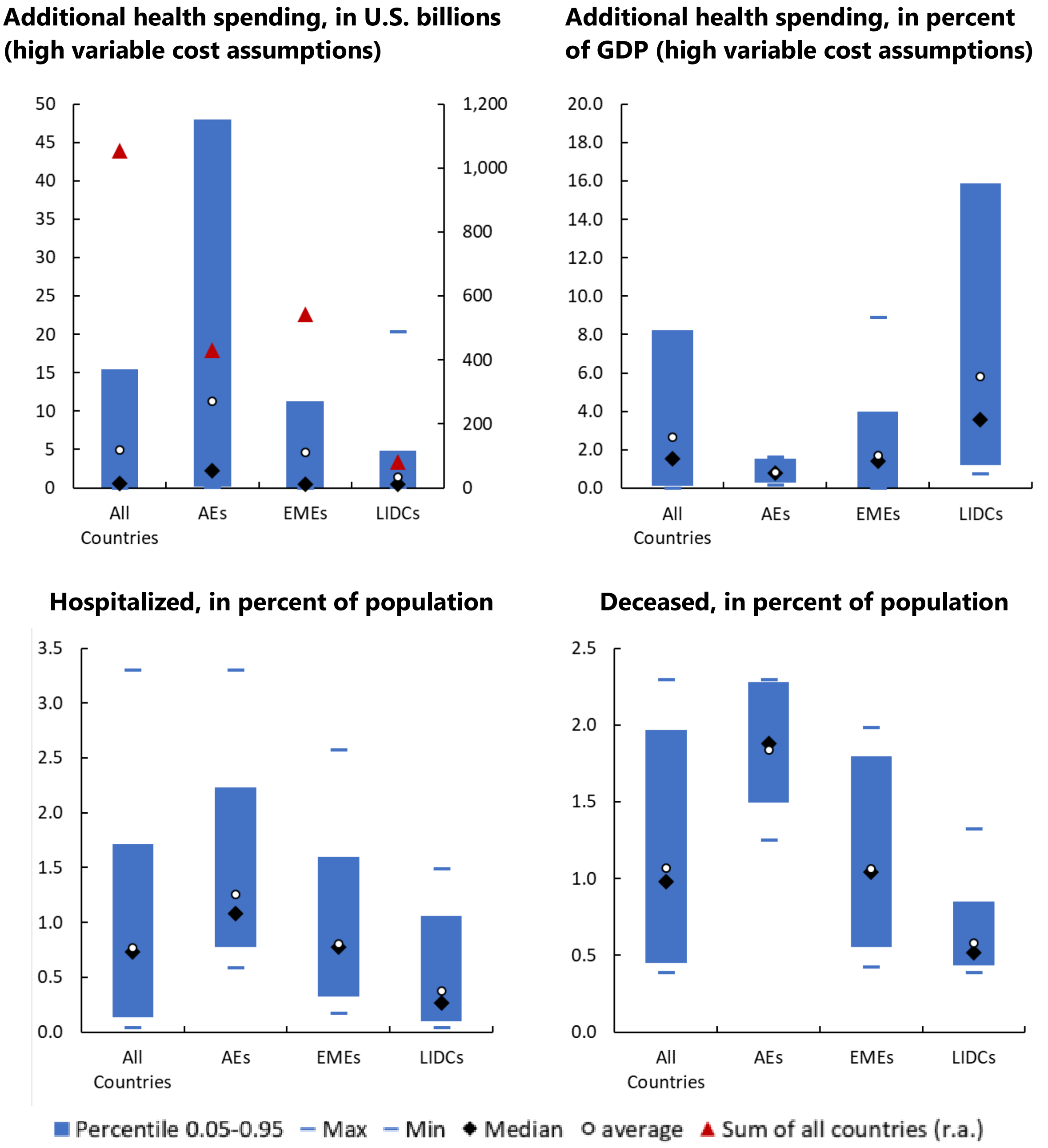
Hospitalized, in percent of population

Deceased, in percent of population



Source: Authors' Calculations.

Figure 7. Benchmark Epidemiological Scenario and 20 Percent Ceiling on the Expansion of Total Health Sector Capacity



Additional health spending, in U.S. billions (high variable cost assumptions)

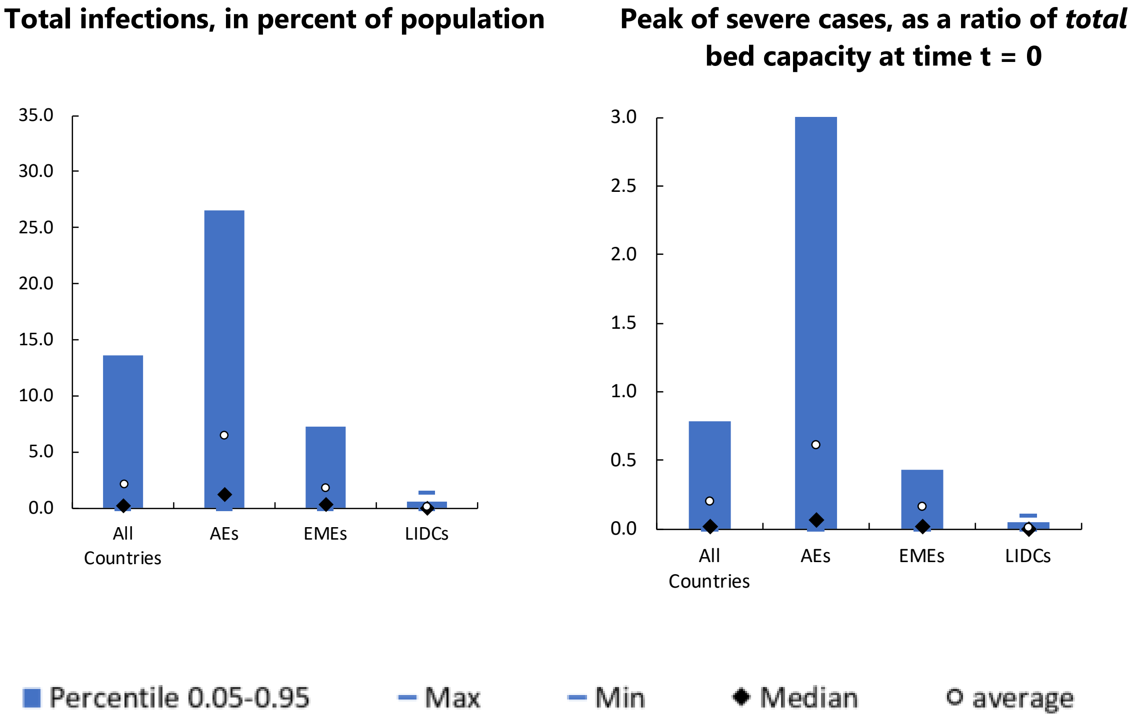
Additional health spending, in percent of GDP (high variable cost assumptions)

Hospitalized, in percent of population

Deceased, in percent of population

Source: Authors' Calculations.

Figure 8. Scenario with Effective Social Distancing, but no Expansion of Capacity

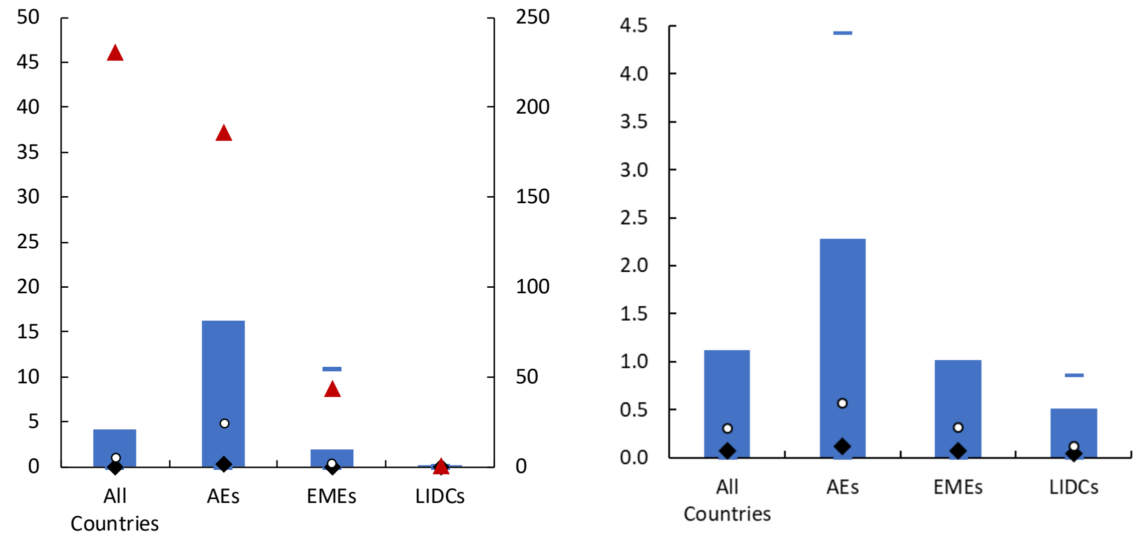


Total infections, in percent of population

Peak of severe cases, as a ratio of *total* bed capacity at time t = 0

Source: Authors' Calculations.

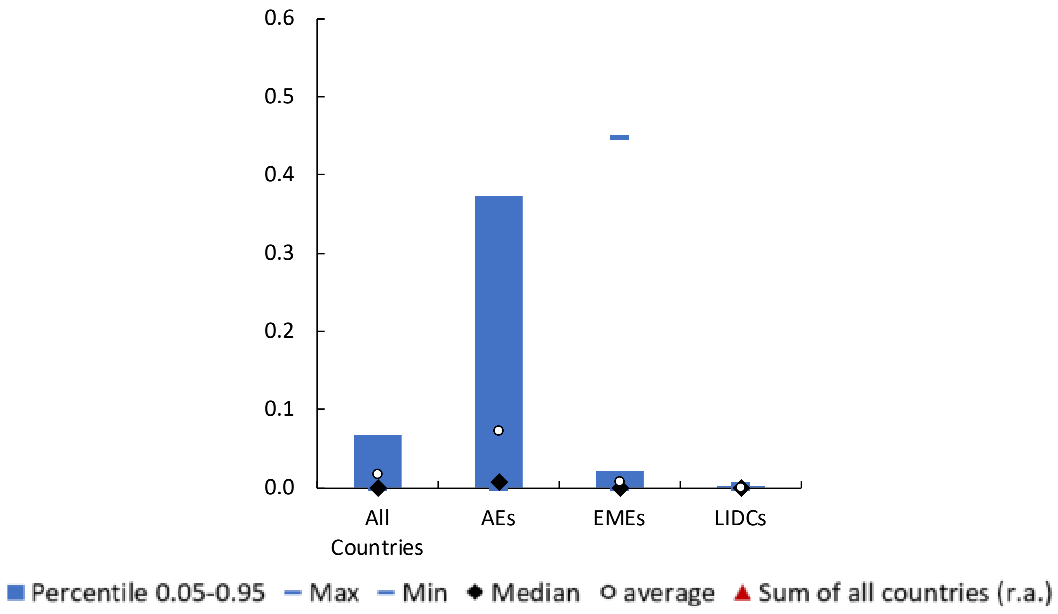
Figure 9. Scenario with Effective Social Distancing, and Unlimited Expansion of Health Sector Capacity



Additional Health Spending, in U.S. Billions (high variable cost assumptions)

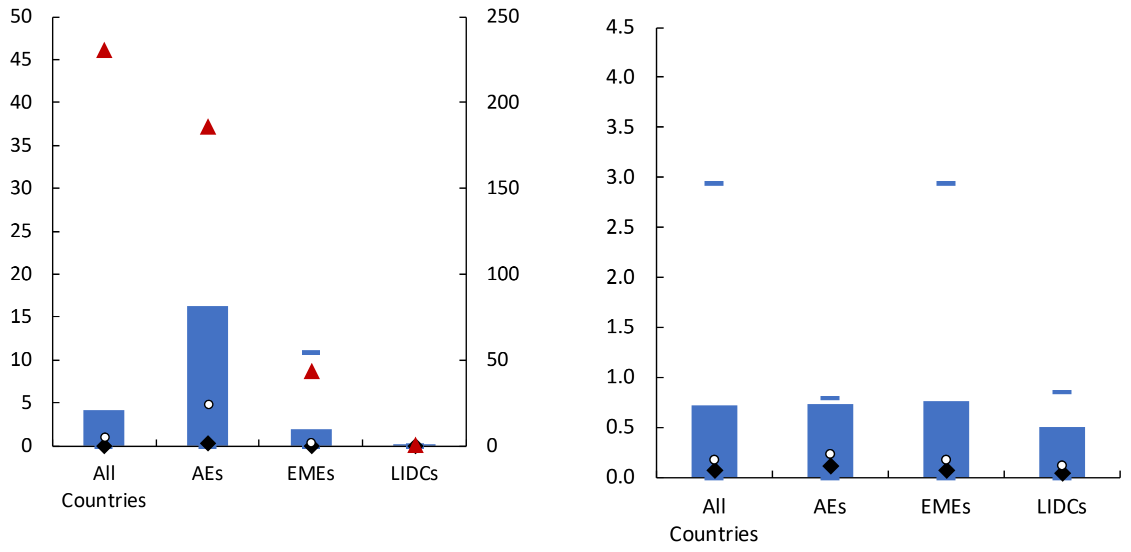
Additional Health Spending, in Percent of GDP (high variable cost assumptions)

Deceased under Unlimited Expansion, in Percent of Population



Source: Authors' Calculations.

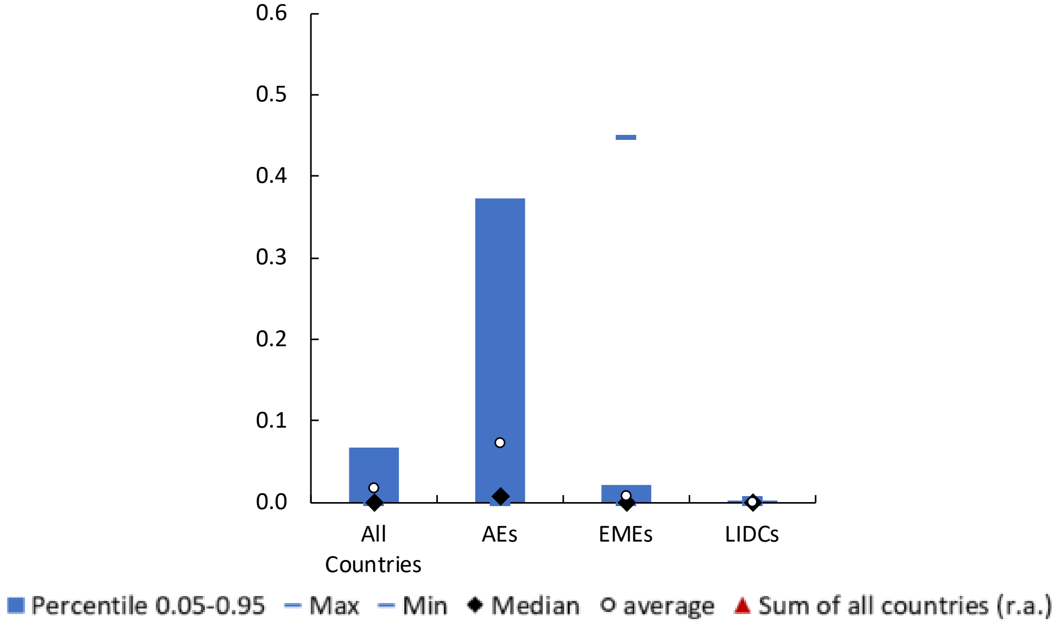
Figure 10. Scenario with Effective Social Distancing, and 20 Percent Ceiling on the Expansion of Total Health Sector Capacity



Additional Health Spending, in U.S. Billions (high variable cost assumptions)

Additional Health Spending, in Percent of GDP (high variable cost assumptions)

Deceased Under Unlimited Expansion, in Percent of Population

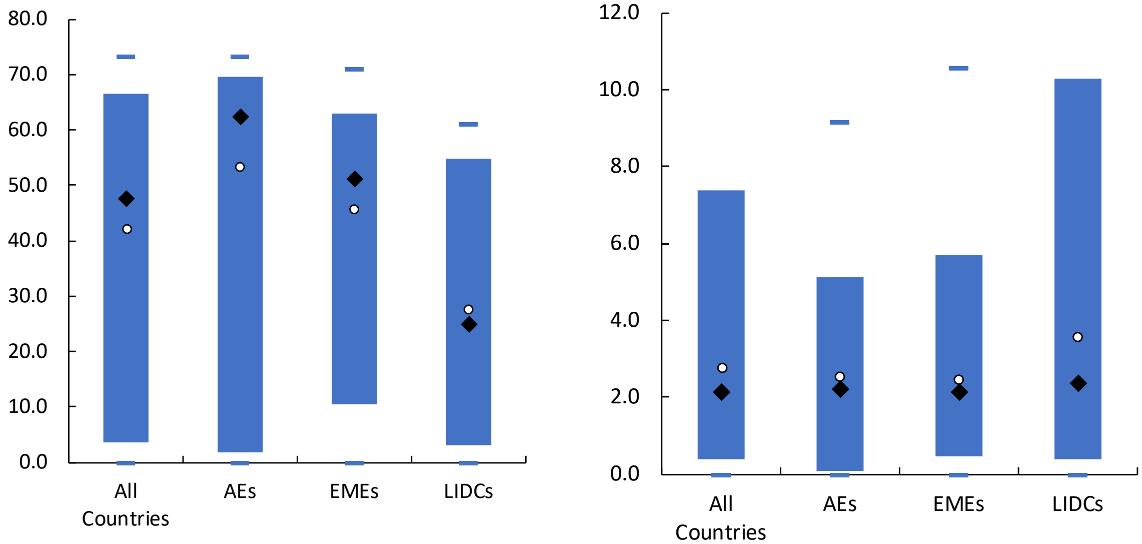


Source: Authors' Calculations.

Figure 11. Scenario with Less Successful Measures to Reduce the Basic Reproduction Number and 20 Percent Ceiling on the Expansion of Total Health Sector Capacity

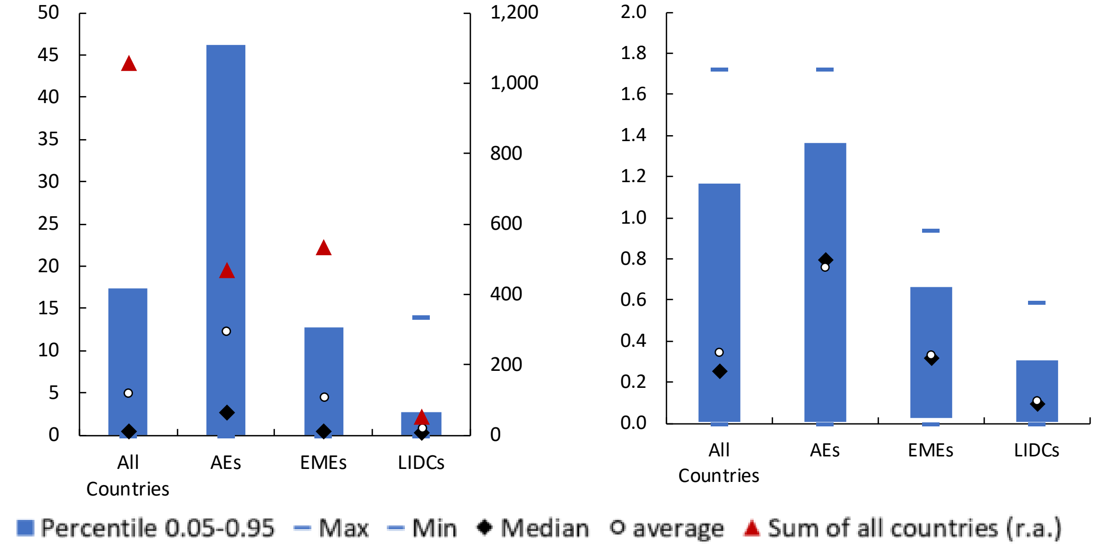
Infected, in Percent of Population

Peak of Severe Cases, as a Ratio of Total Bed Capacity at Time t = 0



Additional Health Spending with 20 percent Limit to Expansion of Health Sector, in U.S. Billions (high variable cost assumptions)

Deceased, in Percent of Population, with 20 Percent Limit to Expansion of Health Sector



Source: Authors' Calculations.

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