The effect of COVID certificates on vaccine uptake, public health, and the economy

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The effect of COVID certificates on vaccine uptake, public health, and the economy[a]

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Abstract. In the COVID-19 pandemic, governments have used various interventions,[1,2] including COVID certificates as proof of vaccination, recovery, or a recent negative test, required for individuals to access shops, restaurants, and education or workplaces.[3] While arguments for and against COVID certificates have focused on reducing transmission and ethical concerns,[4,5] the effect of the certificates on vaccine uptake, public health, and the economy requires investigation. We construct counterfactuals based on innovation diffusion theory[6] and validate them with econometric methods[7] to evaluate the impact of incentives created by COVID certificates in France, Germany, and Italy. We estimate that from their announcement during summer 2021 to the end of the year, the intervention led to increased vaccine uptake in France of 13.0 (95% CI 9.7–14.9) percentage points (p.p.) of the total population, in Germany 6.2 (2.6–6.9) p.p., and in Italy 9.7 (5.4–12.3) p.p.; averted an additional 3,979 (3,453–4,298) deaths in France (i.e., 31.7%), 1,133 (-312–1,358) in Germany (5.6%), and 1,331 (502–1,794) in Italy (14.0%); and prevented gross domestic product (GDP) losses of €6.0 (5.9–6.1) billion in France, €1.4 (1.3–1.5) billion in Germany, and €2.1 (2.0–2.2) billion in Italy. Notably, the application of COVID certificates substantially reduced the pressure on intensive care units (ICUs) and, in France, averted surpassing the occupancy levels where prior lockdowns were instated. Overall, our findings are more substantial than predicted[8] and may help to inform decisions about when and how to employ COVID certificates to increase vaccination and thus avoid stringent interventions, such as closures, curfews, and lockdowns, with large social and economic consequences.

Introduction

The COVID-19 pandemic has forced many governments to implement previously unthinkable policies. Initially, while some countries aimed to eliminate the virus, others aimed to slow its spread to protect health systems and to win time until vaccines or treatment became widely available.[9,10] Public health measures intended to reduce transmissions have included public venue closures, limitations on social contacts, and travel restrictions. These measures are informed by mathematical simulations[11-13] and by analyses estimating their causal effects on the dynamics of the epidemic.[14,15] COVID certificates – certifying vaccination, recovery, or a recent negative test – enable, through digitisation, targeted interventions dependent on an individual's risk of transmitting the virus or of having a severe form of the disease. As with other policy choices, the use of COVID certificates has often been questioned for ethical and political reasons,[4,5] while advocates have mainly focused on the potential to help control the virus.[16] May they also incentive vaccine uptake? As vaccines are increasingly available, hesitancy and refusal to be vaccinated have become the main obstacles to high vaccine coverage in many parts

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of the world.[17,18] Historically, policy makers have considered several options to increase vaccine uptake, ranging from communication and outreach strategies to monetary (dis)incentives and mandates.[19] Today, COVID certificates may lead to additional incentives to get vaccinated. The impact of this intervention on vaccine uptake, as well as on health and economic outcomes requires investigation.

In Europe, the use of COVID certificates for travel was agreed upon within the European Union (EU) in June 2021.[20] Several member states, including France,[21] Germany,[22] and Italy,[23] have since adopted COVID certificates for many domestic social activities. We focus on these countries as they began at similar times to use COVID certificates to regulate entry to public venues, restaurants, cafes, bars, shops, etc. (on 12 July 2021[21], 10 August 2021[22], and 22 July 2021[2,3], respectively). The three countries also have comparable per capita vaccine supply[25], demographics, health infrastructure, and economies. Our objective is to offer an approximate measure of the effect of the widespread use of COVID certificates, specifically how much they incentivised vaccine uptake, protected public health, and strengthened the economy. This study may thus help to inform decision-making on whether, when, and how to employ COVID certificates.

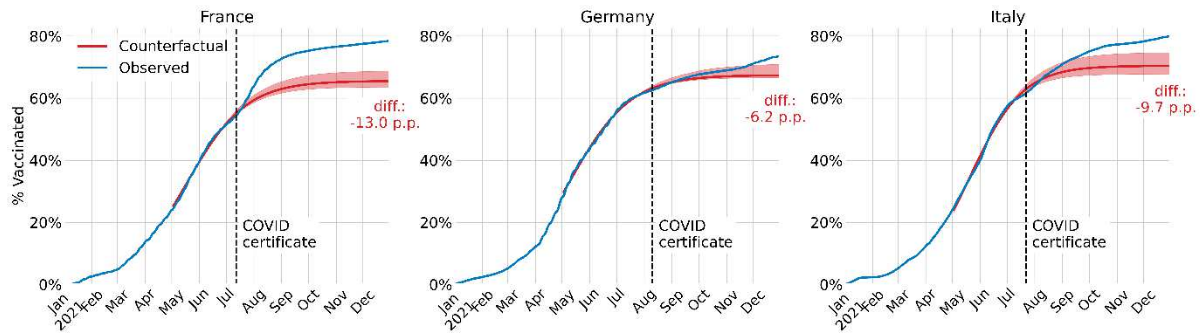
COVID certificates spur vaccination

We estimate the COVID certificate's contribution to vaccine uptake in France, Germany, and Italy by constructing counterfactuals, that is, by modelling vaccine uptake without the intervention, using a standard model from innovation diffusion theory.[6,25,26] The model relies on growth theory with capacity limits and captures the way in which an innovation – the vaccine – is gradually taken up by a population, where early adopters are then rejoined by followers. It is posited that cumulative uptake follows a logistic curve and that the population's average willingness to get vaccinated is proportional to overall uptake (see Methods B).

Our model choice is validated by the well-established econometric method of synthetic control[7] (see Methods B). This involves estimating the post-intervention vaccine uptake trajectory of each of the three countries based on a weighted average of countries that did not adopt COVID certificates but have similar vaccine uptake prior to the intervention – the control group. While synthetic control offers a valuable addition to our analysis, it also has some limitations in our context. The method requires a sufficiently large control group, which becomes infeasible as more and more countries have adopted COVID certificates. Further, synthetic control requires that the countries in the control group are not affected by interventions in other countries, which is questionable given the interdependence of COVID-related policies, and cross-border travel.

Findings. The effects of COVID certificates on vaccine uptake turned out to be sizeable (Fig. 1). On the day of its respective announcement, in France, 53.8% of the population had received at least one dose of a COVID-19 vaccine, in Germany 62.5%, and in Italy 61.6%. By the end of 2021, the first-dose vaccine uptake had risen to 78.2%, 73.5%, and 80.1%, respectively. How much of this increase can be attributed to COVID certificates? To answer this question, we estimate the counterfactual proportion of the population that would have received at least one dose by end-2021, absent of COVID certificates, for France at 68.3%, Germany at 66.4%, and Italy at 68.6%. Thus, we attribute 13.0 (95% CI 9.7–14.9) percentage points (p.p.) for France, 6.2 (2.6–6.9) p.p. for Germany, and 9.7 (5.4–12.3) p.p. for Italy of vaccine uptake to the incentives created by COVID certificates. Note that all three countries further extended the use of COVID certificates in the months following their adoption, ranging from their requirement in workplaces to the integration of a booster dose and its evolution to vaccine certificates. Our estimates include the incentives created by these additional extensions. The overall effect is significant in France and Italy, but in Germany only from November 2021 onwards, when the use of COVID certificates was extended to workplaces. The results are in line with studies analysing the immediate period after the intervention in various countries using cross-country or state comparisons,[27-30] and are overall more substantial than predicted.[8]

Figure 1: Estimated vaccine uptake with and without COVID certificates.



The cumulative proportion of the whole population who received at least one COVID-19 vaccine dose in the actual intervention deployment (blue) and in the no-intervention counterfactual scenario (red). The red shaded area is the 95% confidence interval. The black dashed vertical line is the date of the announcement of the COVID certificate.

Importantly, the effect of COVID certificates on vaccine uptake was also sizeable among the older population. By the end of 2021, we attribute for France 8.9 (8.0–9.4) p.p. to the incentives created by COVID certificates among the population over 60 years old. For Italy the figure is 4.4 (2.9–5.2) p.p. (see Methods B). Germany did not publish age-dependent vaccine uptake statistics until mid-September 2021, so we cannot build a counterfactual for vaccine uptake among the older population in Germany.

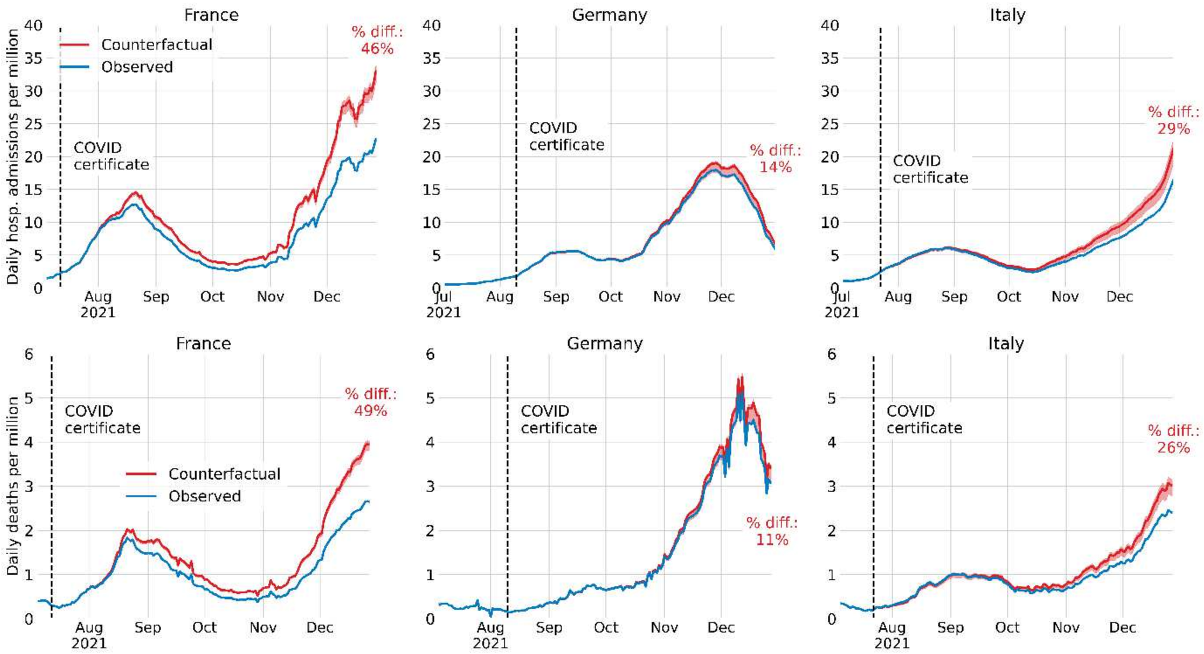
Impact of COVID certificates on public health

The effectiveness of COVID-19 vaccines against hospitalisation, ICU admission, and death has been well documented, including for the Delta variant, which was prevalent throughout the period of study. We estimate the average effectiveness, considering the various vaccines and waning immunity, to be 81% after one dose and 92% after two doses (see Methods C).[31-35] We focus on the direct protection provided by vaccines, but omit the contribution of vaccines to reducing overall transmission and the fact that COVID certificates may alter epidemic dynamics.

To estimate the public health impact of vaccine uptake, we construct counterfactuals for second-dose vaccine uptake based on the observed lag between the first and second doses. Booster uptake does not factor in our model, as, during the period under consideration, these were not available to individuals who were not fully vaccinated before the announcement of the COVID certificate. We consider age-stratified uptake estimates when available; in particular, this is the case for France and Italy for deaths and for France for hospital admissions (see Methods C).

Findings. We estimate the number of hospital admissions and deaths that would have occurred from the announcement of COVID certificates until the end of 2021 (see Methods C and Fig. 2). In France, an additional 32,065 (26,566–35,306) hospital admissions would have occurred, in Germany 5,229 (-1,774–6,822), and in Italy 8,735 (2,999–12,261). Additional deaths in France would have been 3,979 (3,453–4,298), in Germany 1,133 (-312–1358), and in Italy 1,331 (502–1,794). Notably, the impact of additional vaccine uptake increases over time, and while the effect is significant for France and Italy over the whole time it is only so for Germany during the last months of 2021. The expected number of hospital admissions (and deaths) would have been 31.3% (31.7%) higher in France, 5.0% (5.6%) higher in Germany, and 15.5% (14.0%) higher in Italy. Even more substantial, by the end of 2021, hospital admissions (and deaths) would have been 46% (49%) higher in France, 14% (11%) higher in Germany, and 29% (26%) higher in Italy.

Figure 2: Estimated hospital admissions and deaths with and without COVID certificates.



Daily deaths (top row) and hospital admissions (bottom row) per million (7-day rolling average) in the actual intervention deployment (blue) and in the no-intervention counterfactual scenario (red). The red shaded area is the 95% confidence interval. The daily death counterfactuals for France and Italy and the daily hospital admissions counterfactual for France are computed using an age-stratified model. The other counterfactuals are not based on age-stratified models due to unavailable data. The black dashed vertical line is the date of the announcement of the COVID certificate.

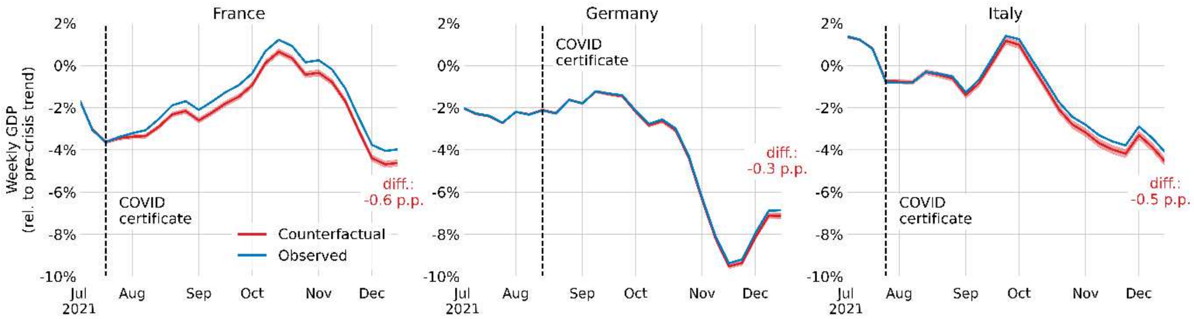
Impact of COVID certificates on economic activity

COVID certificates may spur economic recovery in the short run, as newly vaccinated people can safely resume in-person economic activities, including working on-site and consuming goods and services in brick-and-mortar businesses (direct effect). Furthermore, an indirect effect results from avoiding restrictions, through public health measures, on social, education, and economic activities. Here, we conduct a quantitative analysis of the overall economic effect of COVID certificates based on the weekly GDP estimates provided by the OECD Weekly Tracker.[36] Resorting to a high-frequency indicator of economic activity is necessary to exploit the weekly variations in vaccination rates to identify the effect of vaccine uptake on economic activity. This paper innovates compared to previous analyses[37], as the use of a high-frequency GDP proxy allows quantitative estimates of the economic impact of variations in vaccination rates.

The impact of COVID certificates on the economy is modelled through its effect on vaccine uptake and the elasticity of the latter to weekly GDP, using data from all OECD and G20 member countries as used by the OECD Weekly Tracker (see Methods D). The average effect of vaccination on GDP is estimated using a closed-form model in which weekly GDP is regressed on first-dose vaccination, lagged by a month to account for the time between first and second dose and time to full effectiveness.[37] In addition, health outcomes, also lagged by a month, are controlled for, as they may be confounding factors influencing both vaccine uptake and GDP. Furthermore, we control for vaccination and health outcomes in the main trade partners to avoid the possible confounding effect of trade and other economic spillovers,[37] and for average weekly temperature, which influences virus diffusion.[38] Finally, we add week and country fixed effects to control for any common seasonal effect and any country-specific but time-invariant effect, such as demographic or geographical characteristics.

Findings. The average effect of a 1 p.p. increase in the share of vaccinated people on weekly GDP one month later is 0.052 (0.042–0.061) p.p. A complete vaccination roll-out would thus drive GDP up by 5.2 p.p., which corresponds to approximately 85% of the loss observed in 2020. We estimate counterfactual weekly GDP trajectories for France, Germany, and Italy based on estimated counterfactual vaccine uptake (Fig. 3). By the end of 2021, without the policy intervention, weekly GDP would have been 0.6 (0.5–0.8) % lower in France, 0.3 (0.1–0.4) % lower in Germany, and 0.5 (0.3 – 0.6) % lower in Italy, amounting to GDP losses across the second half of 2021 of €6.0 (5.9 – 6.1) billion in France, €1.4 (1.3–1.5) billion in Germany, and €2.1 (2.0–2.2) billion in Italy. (See Methods D.)

Figure 3: Estimated weekly GDP with and without COVID certificates.



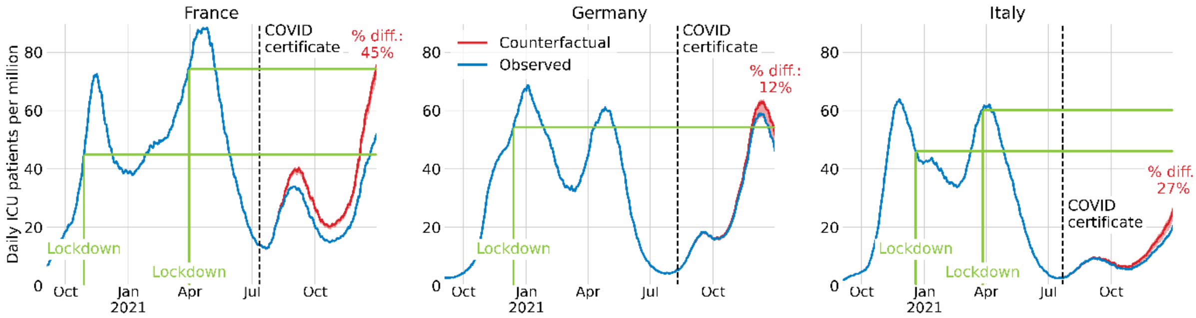
Weekly GDP (3-week rolling average) in the actual intervention deployment (blue) and in the no-intervention counterfactual scenario (red). The red shaded area is the 95% confidence interval. The black dashed vertical line is the date of the announcement of the COVID certificate.

COVID certificates may have prevented lockdowns

By increasing vaccine uptake, COVID certificates reduced the number of patients in ICUs and thus contributed to reducing the likelihood of stricter public measures, including lockdowns. While such decisions are ultimately made by governments, their anticipation and perceived uncertainty are harmful to the economy, also in the mid- and long-term.[39] It is thus instructive to consider the evolution of ICU patients over time and to use levels of previous lockdowns as benchmarks. We exclude the first lockdowns from the analysis, as they represent unrealistic benchmarks for future government action due to unprecedented uncertainty. In France, the number of COVID-19 patients in ICUs per million on the day of lockdown announcement was 44.9 (second lockdown, 28 October 2020) and 74.8 (third lockdown, 31 March 2021). In Germany, it was 54.3 (second lockdown, 13 December 2020). In Italy, it was 53.0 (second lockdown, 12 December 2020) and 60.2 (third lockdown, 27 March 2021).

Findings. By the end of 2021, in France, the number of COVID-19 patients in ICUs was 52.4 per million. We estimate it would have been 76.1 (72.4–78.3) without the introduction of COVID certificates, that is, for the central estimate, an increase of 45% (see Methods C). The policy intervention may thus have been instrumental in preventing the high pressure on ICUs that prompted previous lockdowns (see Fig. 4). By contrast, the additional vaccine uptake in Germany was not sufficient to avert high pressure on ICUs. Consequently, more stringent measures were adopted. Finally, COVID certificates have not played a decisive role in Italy thus far, as we estimate that the pressure on ICUs would have remained at low levels even without the policy intervention.

Figure 4: Estimated ICU patients with and without COVID certificates.



Daily COVID-19 patients in ICUs per million in the actual intervention deployment (blue) and in the no-intervention counterfactual scenario (red). The red shaded area is the 95% confidence interval. The counterfactual for France is based on an age-stratified model. The other counterfactuals are not based on age-stratified models due to unavailable data. Green horizontal lines indicate levels at which previous lockdowns were instated. The black dotted vertical line is the date of the announcement of the COVID certificate.

Discussion

COVID certificates have had a sizeable and robust positive effect on vaccination rates, public health, and the economy in France, Germany, and Italy. Importantly, we aimed to make prudent assumptions on model inputs such as vaccine effectiveness and lags between infection and health outcomes. In addition to the evaluated temporary effect, the incentives created by COVID certificates may be lasting, as parts of the population might have remained unvaccinated without the intervention.

Even though COVID certificates were introduced in similar contexts – i.e., the three largest EU countries, at a time when vaccination campaigns were slowing down and infections were increasing rapidly– the magnitude of the impact varies significantly from one country to another. Understanding these differences deserves attention. Factors could be the various ways in which COVID certificates were announced, the extent of their use, and levels of hesitancy.[17] For example, the announcements in France and Italy were particularly striking, as they were made by the central governments and backed by clear and consistent communication, with COVID certificates being required in most public venues all over the country. By contrast, COVID certificates were introduced in Germany according to the local epidemiological situation, and their enforcement varied across Länder. Further studies should complement our work by assessing the broader effect of COVID certificates on the development of the epidemic. Additionally, long-term social and economic costs and benefits need to be considered as more data become available.

COVID certificates appear to be an attractive, more inclusive alternative to vaccine mandates, focusing on the added benefits of getting vaccinated or tested rather than punitive measures of not doing so. As countries grapple with the highly contagious Omicron variant, COVID certificates might play a decisive role in increasing and maintaining vaccine-induced protection. Nevertheless, governments' policy decisions on COVID certificates should also consider additional factors, including supply of vaccines and tests, political trust, and accessibility for marginalised groups, to not threaten social cohesion or exacerbate already existing inequities.[4,40,41] Finally, international coordination and mutual acceptance of COVID certificates are crucial to prevent deepening the divide between different regions.[3]

Author contributions. MOB, BP, and NW designed the study, built the model, collected data, finalised the analysis, interpreted the findings, and wrote the manuscript. LGJ collected and analysed data. PAg, PAr, AF, PM, and GBW provided guidance, interpreted the findings, and commented on and revised previous versions of this manuscript. All authors read and approved the final manuscript. The corresponding authors had full access to all the data used in the study and had final responsibility for the decision to submit for publication.

Competing interests. AF is a member of the French COVID-19 Scientific Council and a member of the French COVID-19 Vaccine Strategy Committee. PM chairs the French Council of Economic Analysis, an independent council attached to the Prime Minister. GBW is a member of the G20 High Level Independent Panel on Financing the Global Commons for Pandemic Preparedness and Response. The authors declare no other competing interests.

Methods

A. Data sources

All data were retrieved in the first week of January 2022.

Health data. For all OECD and EU countries, the share of the population who received one dose of a COVID-19 vaccine, two doses of a COVID-19 vaccine, hospital admissions per 1 million, daily ICU patients per 1 million, daily deaths per 1 million, and population estimates have been retrieved from Our World In Data.[42] For France age-stratified data on hospital admissions, ICU patients, and deaths was retrieved from official government sources[j] and deaths outside hospitals from the French Institute for Demographic Studies (INED).[k] For Italy age-stratified data on deaths was also retrieved from INED.[l]

Age-stratified vaccine uptake statistics for France and Italy were both retrieved from the European Centre of Disease Prevention and Control (note that such data is not available for Germany).[m]

The share of different vaccines used until the end of 2021 in France, Germany, and Italy (made by BioNTech/Pfizer, Moderna, AstraZeneca, Janssen Pharmaceutica NV) have been retrieved from the official government sources.[n]

OECD Weekly Tracker. The OECD Weekly Tracker (short 'Tracker') provides weekly estimates of economic activity based on Google Trends data and performs well across the 46 OECD and G20 countries in forecast simulations. The Tracker's methodology[36] relies on a machine learning algorithm, which extracts signals from search intensities related to approximately 250 categories of search keywords to infer a timely picture of the economy. It is trained on official GDP series to predict weekly GDP from the weekly Google Trends series. It provides estimates of weekly GDP relative to the pre-crisis trend.

The Tracker is based on several Google Trends variables that were hand-picked to cover a wide range of aspects of economic activity. Importantly, for our analysis, the Tracker only uses search behaviour on economic variables and not health variables. Data about search behaviours can be informative about consumption (e.g., related to searches for "vehicles", "household appliances"), labour markets (e.g., "unemployment benefits"), housing (e.g., "real estate agency", "mortgage"), business services (e.g., "venture capital", "bankruptcy"), industrial activity (e.g., "maritime transport", "agricultural equipment") and economic sentiment (e.g., "recession"), and poverty (e.g., "food bank"). Signals about multiple facets of the economy can be aggregated to infer a timely picture of the macroeconomy.

[j] https://www.data.gouv.fr/fr/datasets/synthese-des-indicateurs-de-suivi-de-lepidemie-covid-19/
[k] https://dc-covid.site.ined.fr/en/data/france/
[l] https://dc-covid.site.ined.fr/en/data/italy/
[m] https://vaccinetracker.ecdc.europa.eu/public/extensions/COVID-19/vaccine-tracker.html#age-group-tab
[n] France: https://covidtracker.fr/vaccintracker/, Germany: https://impfdashboard.de/, Italy: https://www.governo.it/it/cscovid19/report-vaccini/

The OECD Weekly Tracker uses machine learning to predict GDP from Google Trends search data. The relationship between the search volume indices and GDP, f, is learnt at the quarterly frequency using official quarterly GDP series and quarterly aggregates of the search indices. It is then used to disaggregate GDP growth at the weekly frequency by applying f to the weekly search indices. The relationship between Google Trends variables and GDP growth is fitted using a neural network. It is trained using a dataset comprising the whole panel of observations from 46 countries.

The Tracker measures the percentage difference in GDP relative to a pandemic-free counterfactual, where the counterfactual is taken to be the OECD Economic Outlook projection published in November 2019.[43] Formally, the Tracker is defined as

$$T_w = \frac{y_w}{x_w} - 1 ,$$

where y_w is weekly GDP in week w, and x_w is weekly GDP in a no-COVID counterfactual, proxied by a twelfth of quarterly GDP projected by the OECD Economic Outlook prior to the crisis. The Tracker thus measures weekly GDP relative to the pre-crisis trend (Fig. 5).

Figure 5: The OECD Weekly Tracker is a proxy of weekly GDP relative to the pre-crisis trend.

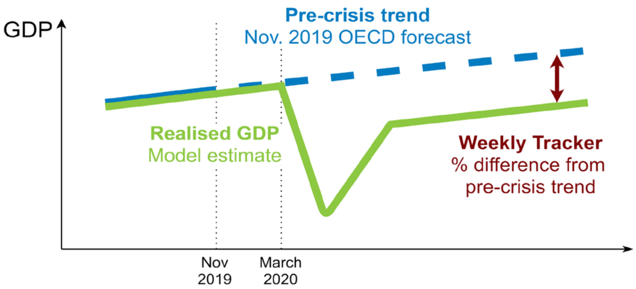
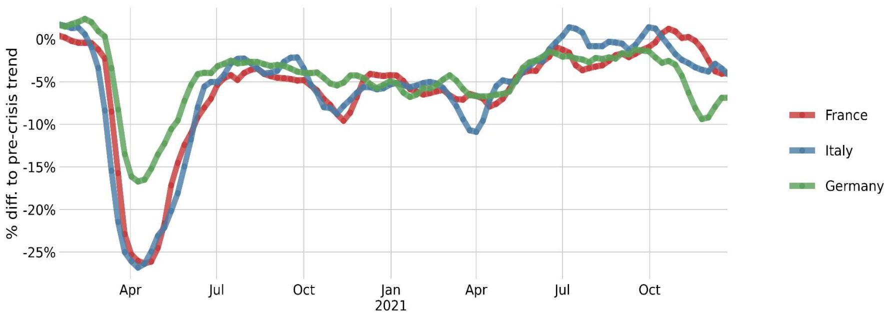


Figure 6: OECD Weekly Tracker for France, Germany, and Italy.[32]



Vaccine acceptance is taken from the University of Maryland Social Data Science Center "Global COVID-19 Trends and Impact Survey" in partnership with Facebook. The survey is administered to a representative sample of Facebook users on a daily basis and includes questions on symptoms, social distancing behaviour, vaccine acceptance, mental health issues, and financial constraints. The acceptance rates used in this paper are built as the quarterly average of the proportion of respondents definitely or probably choosing to get vaccinated if a COVID-19 vaccine was offered to them over the first quarter of 2021. For the United States, acceptance rates were complemented using data from the Johns Hopkins Center for Communication Programs. The acceptance rate for Malta was imputed using the median across countries.

Mobility. A mobility index is built from the Google Mobility reports[o], which document mobility per type of destination relative to the pre-crisis levels at a daily frequency. The mobility index used in this paper is the simple average of mobility towards workplaces and places of retail and recreation.

Temperature. Daily temperature series for the 46 OECD and G20 countries across 2020 and 2021 were collected from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information. The Global Historical Climatology Network daily (GHCNd) provides daily climate summaries from land surface stations across the globe. Temperature data for each station were averaged at the country level.

Policy interventions. For each country, we consider the date when COVID certificates for day-to-day use were announced.

Table 1: COVID certificates: announcement date and regulations for France, Germany, and Italy.

Country	Announcement	Places where COVID certificates are required
France	12 July 2021[21]	Places of entertainment and leisure (e.g., cinemas, festivals, museums, sports, conferences, game rooms, amusement parks, cruise ships), places of social gathering (e.g., bars, cafés, restaurants, clubs), interregional public transport (e.g., domestic flights, trains, and coaches), and department stores and shopping centres with a surface greater than 20,000 square metres.[p]
Germany	10 August 2021[22]	Health care places (e.g., hospitals, care homes), hospitality venues, events, indoor parties, and sports, and for the use of body-related services (e.g., hairdresser, massages, etc.). Mandatory in areas with over 35 COVID cases per 100,000 inhabitants per week.[q]
Italy	22 July 2021[23]	Places of entertainment and leisure (e.g., cinemas, festivals, museums, indoor sports, conferences, game rooms, amusement parks, cruise ships), places of social gathering (e.g., hospitality venues, bars, cafés, restaurants, clubs), interregional public transport (e.g., airports, train stations).[r]

OECD and EU countries that announced the use of COVID certificates before 22 September 2021. Austria, Chile, Colombia, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Israel, Italy, Latvia, Lithuania, Luxembourg, Mexico, Portugal, Romania, Slovakia, Slovenia, Spain, Switzerland, the United States.

Remaining OECD and EU countries. Australia, Belgium, Bulgaria, Costa Rica, Czech Republic, Hungary, Iceland, Japan, Malta, the Netherlands, New Zealand, Norway, Poland, South Korea, Sweden, Turkey, the United Kingdom.

[o] https://www.google.com/covid19/mobility/

[p] https://www.covidpasscertificate.com/france-covid-pass-reopen-vaccinated-tourists/

[q] https://www.bundesregierung.de/breg-en/news/federal-regional-consultation-coronavirus-1949666

[r] https://www.euronews.com/2021/07/23/italy-to-roll-out-covid-health-pass-for-bars-restaurants-and-museums

Donor's pool countries for synthetic control.[s] Australia, Belgium, Czech Republic, Hungary, Japan, Malta, the Netherlands, New Zealand, Norway, Poland, South Korea, Sweden, Turkey, the United Kingdom.

Table 2: Use of COVID certificates in OECD and EU countries (N/A = not before November 2021).

Country	Announcement date	Source
Australia	N/A	https://www.theguardian.com/australia-news/2021/oct/11/victoria-covid-update-vaccine-passports-trialled-as-pfizer-offered-to-all-age-groups
Austria	19/05/2021	https://www.thelocal.com/20210728/europe-how-does-use-of-health-passes-compare-in-europe-2/
Belgium	23/09/2021	https://www.rtbf.be/info/societe/detail_pass-sanitaire-au-restaurant-ou-dans-les-salles-de-sport-en-wallonie-des-avis-partages?id=10847152
Bulgaria	20/10/2021	https://www.euractiv.com/section/politics/short_news/bulgaria-introduces-green-covid-19-pass/
Chile	25/05/2021	https://www.efe.com/efe/espana/sociedad/chile-anuncia-un-pase-de-movilidad-que-otorga-mas-libertades-a-vacunados/10004-4543838
Colombia	25/07/2021	https://labsnews.com/en/notes/colombia-is-working-on-an-electronic-covid-19-vaccination-pass/
Costa Rica	13/10/2021	https://qcostarica.com/as-of-december-1-a-vaccination-certificate-will-be-mandatory-in-costa-rica/
Croatia	01/07/2021	https://www.garda.com/crisis24/news-alerts/496766/croatia-amendments-to-covid-19-countermeasures-will-be-implemented-from-july-1-update-28
Cyprus	09/07/2021	https://www.dw.com/en/cyprus-vaccine-drive-safepass-mandatory-no-more-free-covid-tests/a-58249253
Czech Republic	21/10/2021	https://www.expats.cz/czech-news/article/coronavirus-update-oct-21-2021
Denmark	14/04/2021	https://www.healthcareitnews.com/news/emea/denmark-launches-covid-19-passport-coronapas
Estonia	26/08/2021	https://www.ecb.ee/news/new-coronavirus-restrictions-from-august-26/
Finland	06/08/2021	https://www.helsinkitimes.fi/finland/finland-news/domestic/19724-finnish-government-shows-green-light-to-coronavirus-pass.html
France	12/07/2021	https://www.elysee.fr/emmanuel-macron/2021/07/12/adresse-aux-francais-12-juillet-2021
Germany	10/08/2021	https://www.bundesregierung.de/breg-en/news/federal-regional-consultation-coronavirus-1949666
Greece	16/07/2021	https://www.reuters.com/world/europe/no-vaccines-no-dinner-indoor-greek-restaurants-accept-only-inoculated-customers-2021-07-16/
Hungary	N/A	https://www.euronews.com/travel/2021/10/12/green-pass-which-countries-in-europe-do-you-need-one-for
Iceland	N/A	https://www.euronews.com/travel/2021/10/12/green-pass-which-countries-in-europe-do-you-need-one-for
Ireland	29/06/2021	https://www.bbc.com/news/world-europe-57649546
Israel	07/03/2021	https://www.france24.com/en/middle-east/20210307-israel-opens-restaurants-and-bars-to-customers-vaccinated-against-covid-19
Italy	22/07/2021	https://www.governo.it/it/articolo/comunicato-stampa-del-consiglio-dei-ministri-n-30/17514
Japan	N/A	https://www.japantimes.co.jp/news/2021/12/14/national/japan-start-using-digital-vaccination-certificates-dec-20-via-smartphone-app/
Latvia	10/06/2021	https://www.laprensalatina.com/latvia-to-reopen-indoor-restaurants-to-vaccinated-people/
Lithuania	13/09/2021	https://www.roedl.com/insights/covid-19/lithuania-corona-covid-pass-vaccinated-national-certificate
Luxembourg	02/06/2021	https://www.wort.lu/fr/luxembourg/la-liberte-passera-par-le-covid-check-60b79a27de135b92362283bb
Malta	N/A	https://www.euronews.com/travel/2021/10/12/green-pass-which-countries-in-europe-do-you-need-one-for
Mexico	13/08/2021	https://www.covidpasscertificate.com/mexico-covid-passports/
Netherlands	16/11/2021	https://www.usnews.com/news/health-news/articles/2021-11-16/positive-virus-tests-reach-weekly-high-in-the-netherlands
New Zealand	N/A	https://www.reuters.com/world/asia-pacific/new-zealand-use-vaccine-certificates-delta-persists-2021-10-05/
Norway	N/A	https://www.euronews.com/travel/2021/10/12/green-pass-which-countries-in-europe-do-you-need-one-for
Poland	N/A	https://www.euronews.com/travel/2021/10/12/green-pass-which-countries-in-europe-do-you-need-one-for
Portugal	08/07/2021	https://www.lci.fr/sante/covid-19-le-portugal-elargit-l-usage-du-pass-sanitaire-aux-hotels-et-restaurants-2191149.html
Romania	17/09/2021	https://www.romania-insider.com/romania-green-pass-regulations-economy
Slovakia	17/07/2021	https://www.slovensko.sk/en/news/_digital-covid-pass
Slovenia	12/09/2021	https://www.total-slovenia-news.com/politics/8872-slovenia-tightens-covid-pass-restrictions
South Korea	01/12/2021	https://en.yna.co.kr/view/AEN20211213005851315
Spain	Various[t]	https://www.thelocal.se/20211209/swedens-new-vaccine-pass-plan-for-restaurants-and-long-distance-trains/
Sweden	09/12/2021	https://www.thelocal.se/20211209/swedens-new-vaccine-pass-plan-for-restaurants-and-long-distance-trains/
Switzerland	25/08/2021	https://www.thelocal.ch/20210825/breaking-switzerland-proposes-covid-certificates-indoors-in-bars-restaurants-and-gyms/
Turkey	06/09/2021	https://www.gov.uk/foreign-travel-advice/turkey/coronavirus
UK	08/12/2021	https://www.gov.uk/government/news/prime-minister-confirms-move-to-plan-b-in-england
USA	Various[s]	https://www.covidpasscertificate.com/us-covid-passports/

[s] Bulgaria, Costa Rica, and Iceland have been removed from the donor pool used for the synthetic control method due to lack of data for covariates.

[t] By 22 September 2021, COVID certificates were in place in several parts of the country.

B. Estimation of vaccine uptake

The impact of COVID certificates on vaccination uptake rates is estimated using *innovation diffusion theory* and validated by the *synthetic control* method.

Innovation diffusion theory[6,25,26] attempts to formalise the way in which an innovation is gradually taken up by a population, where early adopters are then rejoined by followers. The model relies on growth models with capacity limits, i.e., logistic curves. In our context, vaccines are the innovation that every (eligible) person may choose to adopt.

Denote by t_0 the date when the vaccine is introduced and by $x(t) \in [0,1]$ the cumulative fraction of the population who has received at least one dose at date t. Thus, by assumption, $x(t) \in [0,1]$ for all t, the function $x(t)$ is nondecreasing, and $x(t)=0$ for all $t \leq t_0$. The innovation diffusion model depends on three additional parameters: $p > 0$ is the 'coefficient of innovation', i.e., is the instantaneous rate at which a non-vaccinated person opts to get vaccinated, independent of how many people are already vaccinated; $q > 0$ is the 'coefficient of imitation', i.e., the rate at which a non-vaccinated person is influenced by the fraction of vaccinated people; and $0< K \leq 1$ is the capacity, i.e., the fraction of the population that is eventually eligible and willing to get vaccinated.

Mathematically, the innovation diffusion model is described by the ordinary differential equation

$$f'(t) = (1 - \frac{f(t)}{K})(p + qx(t)), t \geq t_0 \; and \; f'(t) = 0 \; elsewhere.$$

The unique solution to the latter differential equation is given by:

$$f(t) = K \frac{1-e^{-(p+q)(t-t_0)}}{1+\frac{q}{p}e^{-(p+q)(t-t_0)}}, t \geq t_0 \; and \; f(t) = 0 \; elsewhere.$$

Logistic functions model the diffusion of an innovation in the absence of major shocks, including supply shortages or policy interventions. While this is the case over the time period considered (i.e., date of announcement of COVID certificate to 31 December 2021), an extension to 2022 may be less appropriate due to the exogenous shock caused by the Omicron variant becoming dominant in France, Germany, and Italy.

Parameters t_0 p, q, and K are estimated using the least-square method to fit the data on vaccine uptake. The fit is computed three months before the announcement of a country's COVID certificate and then extended to the end of the year; the start date is chosen because by then the majority of the adult population was eligible for vaccination. We use the function 'curve_fit' from Python's package 'scipy.optimize' over vaccine uptake and synthetic counterfactuals. We use block bootstrap to account for time dependence in the data with 1,000 iterations and 30 non-overlapping blocks.[44] The 95% confidence intervals are shown and reported throughout.

Counterfactual vaccine uptakes. For each country, denote by $V_t(v)$ for $v \in \{0,1,2\}$ the proportion of the population having received v doses at time t. For the first dose, the counterfactual is denoted by $\hat{V}_t(1)$ and is obtained from the estimation described above. Let T_0 denote the date when COVID certificates are announced in each country and T_1 be 31 of December 2021. Then, $\hat{V}_t(1)$ is equal to $V_t(1)$ for all $t \leq T_0$ and is equal to the estimate obtained through the innovation diffusion model for all $t \in [T_0, T_1]$. To obtain a counterfactual for fully vaccinated individuals, we consider the same ratio between first and second doses between the counterfactual and realised scenarios three weeks prior, that is:

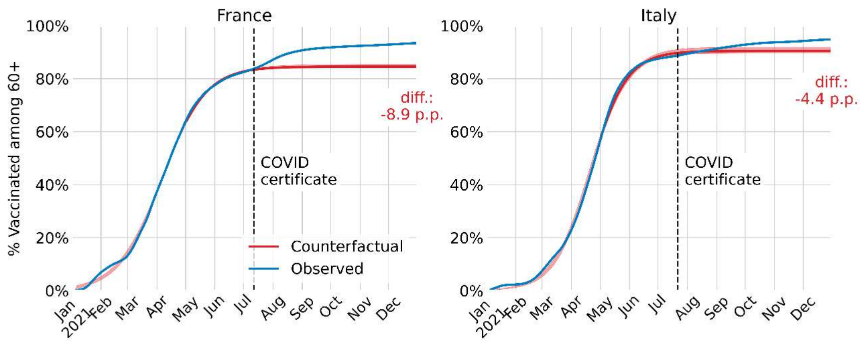
$$\hat{V}_t(2) = \hat{V}_{t-21}(1) \cdot \frac{V_t(2)}{V_{t-21}(1)}.$$

Three weeks is chosen as this is the minimum gap required between the two vaccine doses. Finally, $\hat{V}_t(0) = 1 - \hat{V}_t(1) - \hat{V}_t(2)$. We do not consider a counterfactual scenario for boosters.

Age-stratified vaccine uptake. To estimate age-stratified vaccine uptake, we consider the population aged 60 and over (60+) and the rest separately. This is particularly relevant, as health outcomes are generally more severe for the elderly population. As age-stratified data are not available for several OECD and EU countries, the synthetic control method cannot be applied due to an insufficient donor pool. We thus use the innovation diffusion model to construct a counterfactual for the 60+ group for France and Italy (there are insufficient age-stratified data for Germany, as it is only available from mid-September). For all vaccination statuses v, the realised vaccination uptake for 60+ is denoted by $V_t^{60+}(v)$, and the counterfactual is denoted by $\hat{V}_t^{60+}(v)$. To ensure consistency with our overall estimates, we set counterfactual vaccine uptake for the 59 years old and below as the difference between the overall and the 60+ estimates.

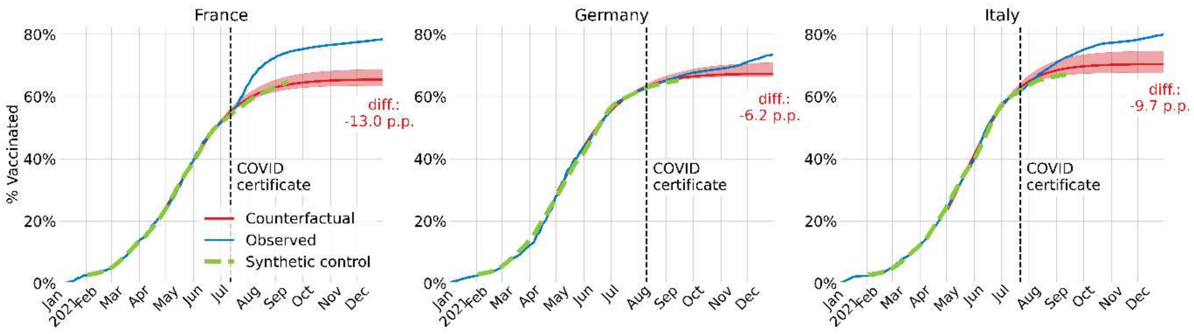
For the population aged 60 years and older, the fit is computed from the start of 2021 to the date of the announcement of the COVID certificate and then extended to the end of the year; the start date is chosen because by then the majority of the 60+ population was eligible for vaccination (see Fig. 7). We use the function 'curve_fit' from Python's package 'scipy.optimize' over the vaccine uptake counterfactuals. The robustness of the fit is obtained through standard bootstrap with 1,000 iterations. The 99% confidence intervals are very small and thus not reported in detail (i.e., within $\pm 0.5\%$).

Figure 7: Realised and counterfactual vaccination rates for the population over age 60.



Model validation via synthetic control. Fig. 8 shows the estimated vaccination uptake via synthetic control for France, Germany, and Italy. Its computation is described below. The synthetic control for each country falls into the 95% confidence interval of the counterfactual based on innovation diffusion theory. This gives additional validation for the model choice.

Figure 8: Estimated vaccine uptake via synthetic control and innovation diffusion theory with and without COVID certificates.



Synthetic Control[7,45,46] provides a counterfactual based on the evolution of nontreated countries, i.e., countries that did not implement COVID certificates. This counterfactual is computed as a weighted average of the nontreated units. To this end, we define the control group as the OECD and EU countries that did not resort to COVID certificates during this period. This choice is motivated by broad socioeconomic resemblance and sufficient vaccine supply. The weights applied to the nontreated units are chosen to minimise the error of the synthetic control in the pre-treatment period. The impact of COVID certificates on vaccination is thus estimated as the difference between vaccination after the implementation of the policy and the counterfactual –14 countries feature in the *donor pool* of nontreated countries and include OECD and EU countries that did not implement COVID mandates before 22 September 2021 and have sufficient data availability (see list above). We posit that after this date the synthetic control method is no longer feasible due to an insufficient donor pool.

For each treated country (France, Germany, Italy), the synthetic first-dose vaccination rate ($SV_{i,t}$) is computed as a weighted average of the vaccination rates in the donor countries:

$$SV_{i,t} = \sum_{j=1}^{J} \omega_j V_{j,t} \ ,$$

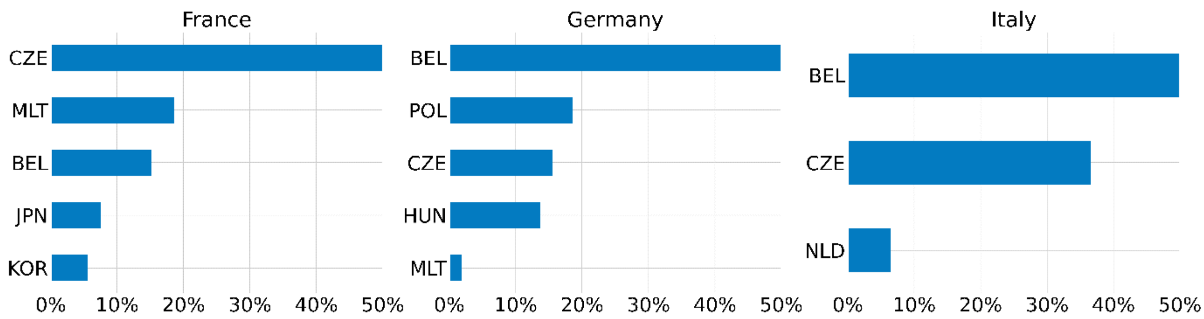
where $J = 14$ is the number of countries in the donor pool, and $\nu_j$is the weight associated with $V_{j,t}$ and the vaccination rate in country j. The weights are in the interval $[0,1]$ and sum to one to avoid extrapolation.[7] They are chosen to minimise the error prior to the treatment, which occurs in T_0:

$$min_{\omega} \sum_{t=1}^{T_0} [(V_{i,t} - \sum_{j=1}^{J} \omega_j V_{j,t})^2 \ + \sum_{k=1}^{K} \lambda_k \, ({X_{i,t}}^k - \sum_{j=1}^{J} \omega_j {X_{j,t}}^k)^2] \ .$$

The weights ω_j are chosen to minimise a composite loss function that includes, on the left, the mean squared prediction error of the pre-treatment outcome, and, on the right, the mean squared prediction errors of K covariates, whose respective importance is weighed by the coefficients λ_k for k between 1 and K. The covariates are selected on the basis of their predictive power of vaccination, and include annual GDP per capita, the average fatalities and cases over the pre-treatment period, the share of the population aged over 65, the average Mobility Index over 2020, and average vaccine acceptance over the first quarter of 2021. The covariate weights are assumed to be constant (i.e., $\lambda_k = \lambda$ for all k), and the weight applied to all the covariates λ is optimised using five-fold cross-validation.

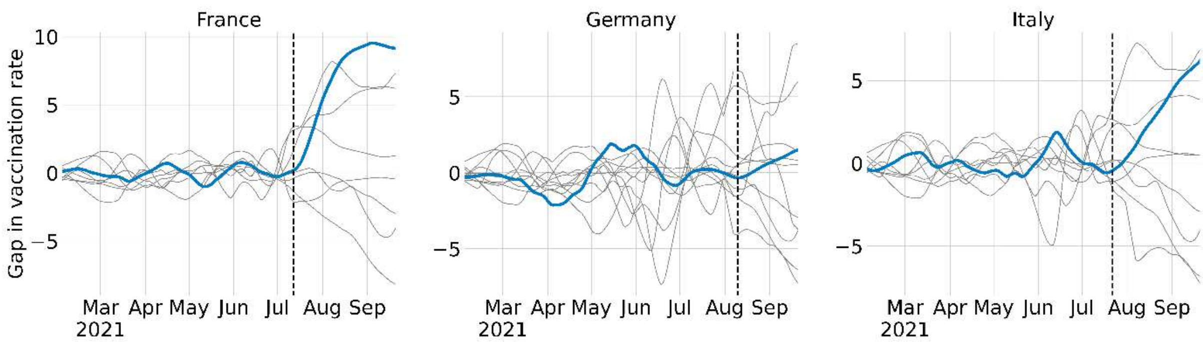
The country weights used for building the synthetic vaccination rates for France, Germany, and Italy are shown in Fig. 9. The three synthetic vaccination rates are built as averages of the vaccination rates from European countries, except for Japan and South Korea, which each account for less than 10% of the French synthetic vaccination rate. All three feature the Czech Republic and Belgium.

Figure 9: Country weights for synthetic control for France, Germany, and Italy.



The significance of the results is assessed using placebo tests.[46] A synthetic vaccination rate $SV_{j,t}$ is built for each country j in the donor pool (placebos); see Fig. 10.

Figure 10: Placebos for France, Germany, and Italy.

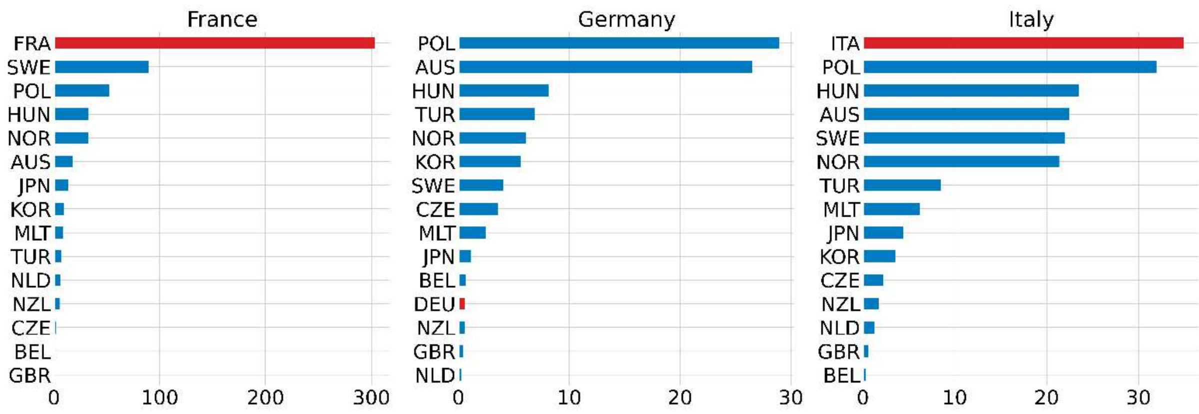


Inference is performed by comparing the ratio of the root mean squared prediction errors ($RMSPE$) of the synthetic vaccination rate for the treated country after and before the treatment to the distribution of these $RMSPE$ ratios over the placebos. The ratio between the post-intervention $RMSPE$ and pre-intervention $RMSPE$ for unit j is

$$r_j = \frac{RMSPE_j(post\text{−}intervention)}{RMSPE_j(pre\text{−}intervention)}.$$

A p-value for the inferential procedure based on the permutation distribution of r_j is given by the rank of the treated country's ratio divided by the size of the donor pool. The $RMSPE$ ratios and their permutation distributions for the synthetic vaccination rates in France, Germany, and Italy are shown in Fig. 11. The causal estimates for France and Italy are statistically significant with a p-value equal to 0.071 $(= 1/14)$, while the estimates for Germany are not significant.

Figure 11: RMSPE ratios for France, Germany, and Italy.



Overfitting may be an issue with synthetic control. The $RMSPE$ ratios that are used for inference can be recast as follows in the absence of policy intervention:

$$\frac{RMSPE_j(out-of-sample)}{RMSPE_j(in-sample)}.$$

For placebos, the ratio of the post-treatment $RMSPE$ and pre-treatment $RMSPE$ is simply a ratio of the $RMSPE$ taken out-of-sample over the $RMSPE$ measured in-sample, given that the optimal weights are computed using the pre-treatment observations. This ratio is classically understood as a measure of overfitting. If the model overfits, its out-of-sample prediction error is large compared to its in-sample prediction error. As a result, overfitting synthetic control models yields spurious results whose validity is rejected by permutation tests. In the present case, overfitting is limited using several covariates in the fit as well as the resort of cross-validation to select the weights attributed to these covariates.

C. Impact on health outcomes

Vaccine effectiveness. We compute vaccine effectiveness against hospitalisation, ICU admission, and deaths between one week and six months after inoculation when infected with the Delta variant—the dominant strain of SARS-CoV-2 in France, Germany, and Italy over the considered time period—by taking the weighted average over the different types of vaccines (see Table 3).

Table 3. Distribution of the different types of vaccines in France, Germany, and Italy by 31 December 2021.

	France	Germany	Italy
BioNTech/Pfizer	79.5%	72.0%	70.1%
Moderna	11.7%	16.5%	18.2%
AstraZeneca	7.7%	8.4%	10.1%
Janssen Pharmaceutica NV	1.1%	3.1%	1.6%

For mRNA vaccines (BioNTech/Pfizer and Moderna), conservative estimates for the effectiveness are 80%[31] after one dose and 93% after two doses.[32-34] The second estimate integrates the effect of waning immunity, as the protection against severe outcomes is higher than 95% up to 14 weeks after inoculation and above 90% thereafter.[34] For AstraZeneca's vaccine, comparable estimates are 90% after one dose and 85% after two doses.[34] Here, waning immunity explains the lower effectiveness of two AstraZeneca doses versus one. Finally, for Janssen Pharmaceutica NV, the effectiveness after the single dose is estimated at 85%.[35]

The overall vaccine effectiveness against hospital admissions, ICU admissions, and deaths is approximately the same and is also similar across France, Germany, and Italy, that is 81% protection after one dose and 92% after two doses. We do not include the additional protection provided by boosters, as the calculations we perform are only concerned with individuals who were not fully vaccinated before the COVID certificate; therefore, they were not eligible for a booster shot over the period of study.

Realised health outcomes by vaccine status. Let X_t denote the *realised* health outcome (i.e., hospital admissions and patients, ICU admissions and patients, and deaths, for a given country) at time t, and let $X_t(v)$ denote the same outcome by vaccine status $v \in \{0,1,2\}$. When the data by vaccine status are not available, we can derive them from Bayes' rule and the level of protection against the health outcome by vaccine status, $\beta(v)$. The $X_t(v)$'s satisfy the following linear system:

$$\frac{X_t(v)}{V_{t-d}(v)} = \beta(v) \cdot \frac{X_t(0)}{V_{t-d}(0)}, for\ v \in \{0,1,2\}, and\ \ X_t(0) + X_t(1) + X_t(2) = X_t\ .$$

This system admits a unique solution, given by

$$X_t(v) = X_t \cdot \frac{\beta(v)\frac{V_{t-d}(v)}{V_{t-d}(0)}}{\sum_{v'=0}^{2} \beta(v')\frac{V_{t-d}(v')}{V_{t-d}(0)}}, for\ all\ v \in \{0,1,2\}.$$

Note that vaccine uptake has been lagged by d days to account for the lag between infection and the health outcome, l_{hosp}, l_{ICU}, and l_{death}, the lag between vaccination and full effectiveness, $l_{vaccine}$, and the duration of the health hazard, $l_{stay\ hosp}$ and $l_{stay\ ICU}$, which are only relevant for hospital admissions and ICU patients. For example, for a patient who is in an ICU at time t, on average, their admission occurred at time $t - l_{stay\ ICU}$, their infection at time $t - l_{stay\ ICU} - l_{ICU}$, and at that time $N_{t-l_{stay\ ICU}-l_{ICU}-l_{vaccine}}(2)$, people were fully protected by vaccination.

Counterfactual health outcomes by vaccine status. Similarly, let $\hat{X}_t(v)$ denote the counterfactual health outcome (number of hospital admissions, ICU patients, or deaths, for a given country) at time t, with vaccine status $v \in \{0,1,2\}$. Then,

$$\hat{X}_t(v) = X_t(v) \cdot \frac{\hat{V}_{t-d}(v)}{V_{t-d}(v)}\ for\ all\ v,$$

where d is the lag that was introduced in the previous paragraph. The estimated counterfactual number of a given health outcome at time t for a given country is given by:

$$\hat{X}_t = \hat{X}_t(0) + \hat{X}_t(1) + \hat{X}_t(2).$$

Finally, the overall realised and counterfactual of a given health outcome, from the announcement of COVID certificates in the country until the end of 2021, are estimated respectively by

$$X_{total} = \sum_{t=T_0}^{T_1} X_t \text{ and } \hat{X}_{total} = \sum_{t=T_0}^{T_1} \hat{X}_t.$$

The difference $\hat{X}_{total} - X_{total} = \sum_{t=T_0}^{T_1}(\hat{X}_t - X_t)$ is attributed to the adoption of COVID certificates.

Age-stratified health outcomes. When the data are available, we compute age-stratified (i.e., 60 years old and above, and the rest of the population) health outcomes similarly, as well as the corresponding counterfactuals. The total numbers are obtained by summing over all age groups.

The lag parameters.[47] We assume the lag between vaccination and full effectiveness is $l_{vaccine} = 7$ days, the lag between infection and hospital admission is $l_{hosp} = 7$ days, the lag between infection and ICU admission is $l_{ICU} = 10$ days, the total number of days in ICU is 8, so that an ICU patient has been admitted $l_{stay\ ICU} = 4$ earlier, and the average lag between infection and death is $l_{death} = 14$ days. Thus, for hospital admissions, the total lag is $l_{vaccine} + l_{hosp} = 14$; for ICU patients, the total lag is $l_{vaccine} + l_{stay\ ICU} + l_{ICU} = 21$; and for deaths, the total lag is $l_{vaccine} + l_{death} = 21$.

D. Impact on the economy

We estimate the average impact of a marginal increase in vaccination rates on economic activity using two-way fixed-effect regressions. The measure of economic activity used in this paper is the OECD Weekly Tracker, a proxy of weekly GDP relative to the pre-crisis trend, which is available for 46 countries with no publication delay (see Data section). It is regressed on vaccination rates along with controls as well as country and week fixed effects. To estimate the average total effect of vaccination on GDP, we use the following closed-form model:

$$T_{i,w} = \beta V_{i,w-l} + \gamma I_{i,w-l} + \eta X^f{}_{i,w} + \iota Z_{i,w} + \alpha_i + \delta_w + \sigma_{i,w}.$$

Weekly GDP is proxied by the Tracker $T_{i,w}$ and is regressed on the share of vaccinated people lagged by l weeks (l = 4), $V_{i,w-l}$, as well as three vectors of controls, week, and country dummies. The first controls vector $I_{i,w-l}$ includes lagged cases, deaths, reproduction rate, and mobility index, which may have impacted both past vaccine uptake decisions and present weekly GDP.[48] The model also averts confounding effects that could emerge from trade spillovers due to the relative synchronicity of vaccination campaigns across countries by controlling for vaccination and deaths in the main trading partners ($X^f{}_{i,w}$). The vector $X^f{}_{i,w}$ is the weighted average of vaccination rates and deaths in country i's main 10 trading partners, i.e.,

$$V^f{}_{i,w} = \sum_{j=1}^{10} \gamma_{i,j}\ V_{j,w},$$

where $V_{j,w}$ is the vaccination rate in trading partner j and $\gamma_{i,j}$ is the share of exports from country i to trade partner j in total exports from country i. The same formula is used to build the vector of weighted average death rates in trading partners. Last, the model includes the vector of average weekly temperatures $Z_{i,w}$, which can influence virus transmission.[38]

The model is estimated using data from 46 OECD and G20 countries (see Table 4). Denote by * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. The average effect of a 1 p.p. increase in the share of vaccinated people after a month is 0.052*** p.p. in weekly GDP. This order of magnitude seems plausible and implies, if the impact was permanent, that 100% vaccination uptake would increase GDP by 5.2 p.p., which broadly corresponds to 85% of the average GDP loss suffered in 2020 by the countries in the sample. This is consistent with the notion that a complete vaccination would not be sufficient to a return to pre-crisis trends due to partial vaccine effectiveness and the waning-out of vaccine-provided immunity. Adding controls for deaths and vaccination in trade partners decreases the main estimate from 0.054*** to 0.052*** by partialling out the confounding effect of trade spillovers. Finally, the third column models the direct effect by controlling for current cases, deaths, and reproduction rates. This indicates that 83% of the total economic effect of vaccination is through the direct effect on individual behaviour, while the remaining 17% is related to the effect through the impact on virus circulation. Note, however, that we do not estimate the indirect effects independently, as we do not estimate a policy response function.

Table 4: Regression results for vaccination-GDP elasticity.

	Baseline	Controls (trade partners)	Direct effect
Vaccinated people (per 100)	0.054*** (0.044, 0.064)	0.052*** (0.042, 0.061)	0.043*** (0.033, 0.052)
Cases (lag)	0.001**	0.001***	0.002***
Deaths (lag)	-0.068***	-0.041***	-0.049***
Reproduction rate (lag)	-1.606***	-1.305***	-0.883***
Mobility Index (lag)	0.057***	0.048***	0.054***
Stringency Index (lag)	0.014***	0.013***	0.007*
Temperature	0.052***	0.008	-0.014
Vaccination of trade partners		-0.093***	-0.090***
Deaths in trade partners		-0.461***	-0.453***
Cases in partners		0.001	0.003***
GDP of partners		0.861***	0.732***
Cases			-0.002***
Deaths			-0.086***
Reproduction rate			-1.667***
Country dummies	Yes	Yes	Yes
Week dummies	Yes	Yes	Yes
Observations	4204	4204	4204
R2	0.774	0.794	0.807
Adjusted R2	0.766	0.787	0.800
Residual Std. Error	2.497 (df=4059)	2.384 (df=4055)	2.309 (df=4052)
F Statistic	96.581*** (df=144; 4059)	105.695*** (df=148; 4055)	112.311*** (df=151; 4052)

* $p < 0.1$, ** $p < 0.05$, and ***$p < 0.01$

The model is used to derive estimates of the counterfactual weekly GDPs without COVID certificates by subtracting the model-based estimation of the impact of COVID certificates on weekly GDP, say $\delta_{i,w}$, from the observed weekly GDP series:

$$\widehat{T_{i,w}} = T_{i,w} - \delta_{i,w}$$
$$\text{with } \delta_{i,w} = \beta(V_{i,w-l} - \hat{V}_{i,w-l}),$$

where $\hat{T}_{i,w}$ is the counterfactual tracker and $\hat{V}_{i,w-l}$ is the counterfactual vaccine uptake. Confidence intervals for counterfactual weekly GDP are derived from the fact that the estimate of the causal impact of COVID certificate on weekly GDP is the product of two random variables:

$$\mathrm{Var}(\delta_{i,w}) = Var(\beta) * Var(\hat{V}_{i,w-l}) + Var(\beta) * E^2(V_{i,w-l} - \hat{V}_{i,w-l}) + Var(\hat{V}_{i,w-l}) * E^2(\beta)$$

$Var(\hat{V}_{i,w-l})$ is estimated from 1,000 bootstrap runs of the logistic model, and $Var(\beta)$ is given by the multivariate regression from Table 4. Then, supposing that $\delta_{i,w}$ follows a normal distribution, its 95% confidence intervals are $[\delta_{i,w} \pm 1.96 * \sigma_{\delta_{i,w}}]$.

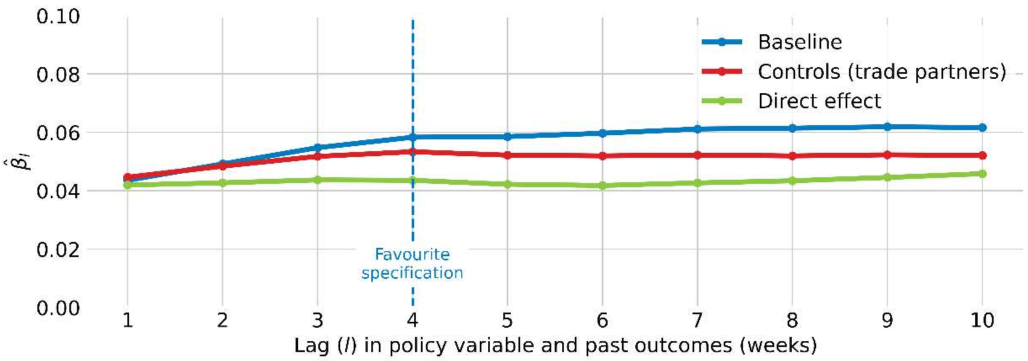
Robustness checks. We complemented our analysis with robustness checks both regarding the statistical method and the modelling assumption that the vaccine-GDP relationship did not vary substantially across the considered time period.

Two-way fixed effects regressions. A recent literature[49-51] has shed light on the limitations of two-way fixed effects regressions when the treatment effect is heterogeneous. Alternative estimators have been proposed[49], which limit the risk of bias by restricting the comparisons between units and times. This literature is still young, and there are currently no satisfactory options for cases where the treatment is dynamic, continuous, and staggered. Experiments with the DIDm estimator[51] were inconclusive, as this estimator is primarily designed for discrete treatments and does not seem to provide reliable results in regard to analysing continuous differences in treatment intensities.

To nevertheless validate our findings with a different statistical method, we reproduced the regressions as in Table 3 without week dummies. Note that this model is underspecified, so the results can only be seen as indicative. For the preferred specification, estimates of the vaccine effect on GDP are of the same order of magnitude, albeit substantially smaller (0.034***). The model, which includes week dummies, remains more plausible, as it seems critical to control for the very large shocks caused by successive COVID infection waves across the globe.

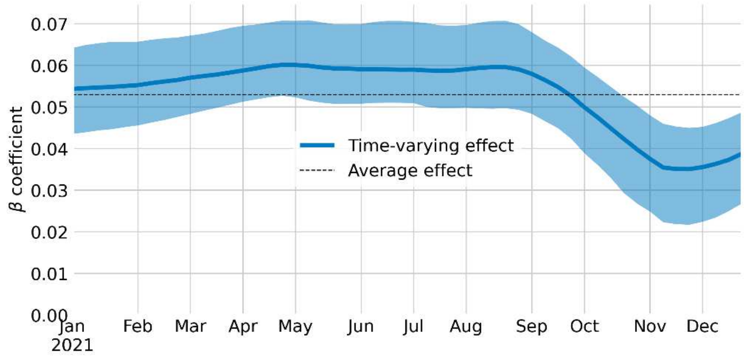
Choice of lag. The main model regresses weekly activity over the vaccination rate lagged by l weeks, which is equal to 4 in the favourite specification. The coefficients of interest were computed for all values of l between 1 and 10. Fig. 12 shows that the main estimates are robust to the choice of lag parameter.

Figure 12: Main regression coefficients for various lag values.



Time-varying relationship between vaccination and GDP. We considered a model with time-varying effects using Double Machine Learning.[52,53] This approach uses machine learning to capture non-linearities and complex interactions while correcting for the bias caused by penalised loss functions. More specifically, we used the R-learner[53], which allows us to include a large number of interaction terms while averting overfitting by applying a penalty term such as the L^2-norm. We apply the R-learner to the regression of weekly GDP on vaccine uptake by including as interaction terms the complete set of overlapping period dummies, $\{P_t{}^w = I_{(t \leq w)}\}_{w \in [1,M]}$, i.e., the dummy P^w is equal to 1 at times t prior to week w, and zero otherwise. Using overlapping period dummies rather than week dummies in the context of a penalised regression allows for smoother time-varying estimates, and both the value of the coefficient associated with the period dummy and the difference between two consecutive coefficients are penalised.[54] This approach yields a time-varying coefficient β (Fig. 13). Given that the interaction terms are common to all countries, this model estimates a time-varying effect without allowing for cross-country heterogeneity. The estimated impact lies between 0.035 and 0.060, with a 95% confidence interval of approximately 0.02 percentage points on average. We note that the estimates do not vary significantly across time, and our average estimator of 0.053 is consistent with this method.

Figure 13: Time-varying estimate of the impact of vaccination on economic activity.



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