ACCSCIENCE PUBLISHING

Global Health Economics and Sustainability

ORIGINAL RESEARCH ARTICLE

Cost–benefit analysis of far-UVC lamps for reducing indoor infection transmission in Switzerland and Germany: Insights from the CERN Airborne Model for Indoor Risk Assessment (CAiMIRA)

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Abstract

Far-UVC light (wavelengths 207–230 nm) can be used directly overhead and has germicidal capabilities to improve indoor air quality. This study evaluates the cost–benefit analysis of implementing far-UVC devices in various settings in Switzerland and Germany. To our knowledge, this is the first study to model the feasibility of direct-acting UVC light in occupied settings, diverging from the consensus on the use of upper-room germicidal UVA and UVB systems. We used the CERN Airborne Model for Indoor Risk Assessment (CAiMIRA) to model infection risk reduction in restaurants, offices, and waiting rooms, considering factors such as room size, occupancy, and ventilation rates. Three scenarios were analysed: a normal winter (22 weeks), a COVID-19-like pandemic (4-week wave), and a severe pandemic (8-week wave). Avoided infections were translated into healthcare, economic, and quality-adjusted life years (QALY) metrics. Costs included purchasing, installing, maintaining, and operating UVC lamps. In Switzerland, cost–benefit ratios ranged 30–290 during a normal winter, 65–430 during a COVID-like pandemic, and 2,300–20,500 during a severe pandemic. In Germany, cost–benefit ratios ranged 10–110 during a normal winter, 30–190 during a COVID-like pandemic, and 1,000–9,000 during a severe pandemic. Far-UVC lamps are a highly cost-effective solution for societies during normal winter and pandemic scenarios. Future studies should focus on implementation in the settings studied; they seem to represent a safe and effective measure for infectious disease control, but need real-world validation.

Keywords: Indoor air quality; Ultraviolet light; Far-UVC lamp; Cost-effectiveness; Switzerland; Germany; Respiratory disease; Pandemic preparedness

Academic editor:
Mihajlo Jakovljevic M.D. Ph.D. MAE

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Citation: Matysik, S., Christian, E., Bohmann, B, Bächler, L., Krüger, S., Chamaa, M. E., Baumeister, M. & Eu, S. (2026). Cost–benefit analysis of far-UVC lamps for reducing indoor infection transmission in Switzerland and Germany: Insights from the CERN Airborne Model for Indoor Risk Assessment (CAiMIRA). *Global Health Econ Sustain*, 4(1):125-144.
https://doi.org/10.36922/GHES025360061

Received: September 2, 2025

Revised: February 24, 2026

Accepted: March 9, 2026

Published online: April 3, 2026

1. Introduction

Ultraviolet light has been investigated as a disinfection technology for the past century, but its use indoors has been limited to indirect, upper-air disinfection due to concerns about excessive UV radiation exposure (Hessling *et al.*, 2021; International Commission on Non-Ionizing Radiation Protection [ICNIRP], 2004; Park, Mistrick, & Rim, 2022; Reed, 2010). Far-UVC light falls within the 207–230 nm wavelength range and is of interest for its ability to be used directly overhead while retaining germicidal capabilities (Truong *et al*., 2023; Welch, Aquino de Muro, *et al*., 2022). Indoor environments are particularly conducive to the transmission of airborne pathogens, contributing to the propagation of infectious diseases. For example, over 90% of SARS-CoV-2 infections occurred indoors (Bulfone *et al*., 2021). Since many people spend most of their time indoors, technologies to improve indoor air quality are crucial for mitigating the transmission of pathogens (Saravanan, 2004; Simoni *et al*., 2003). Far-UVC light, with wavelengths between 200 and 230 nm in the UV spectrum, represents a promising approach for real-time infection mitigation (Eadie *et al*., 2022). Lights directly overhead in busy indoor environments provide an opportunity to neutralise the threat posed by pathogens as they emerge from a contagious person. The duration of exposure to UV light required to break down pathogenic DNA or RNA depends on many factors, including transmission dynamics and the specific pathogens involved (Hessling *et al*., 2021; Naito *et al*., 2022; Truong *et al*., 2023).

Indoor air technologies provide effective mitigation of disease transmission when used in combination. The cornerstones of indoor air quality technology are:

- *Ventilation* improves air quality by moving air, either naturally or mechanically. It depends on a reasonable frequency of air changes to reduce respiratory airborne particle accumulation (Li *et al*., 2007; Park, Mistrick, & Rim, 2022).
- *Filtration* physically removes particulate matter and, in some cases, pathogens through different materials and processes (Dubey *et al*., 2021).
- *Upper-air UV germicidal light* is typically used indirectly in upper-room levels or as part of an air conditioning system, as the high wavelength is dangerous for human exposure (United States Department of Health and Human Services & Centers for Disease Control and Prevention [CDC], 2009; Park, Mistrick, & Rim, 2022).

Far-UVC light adds to this repertoire as it can be installed overhead in occupied indoor spaces due to its enhanced safety profile.

Far-UVC light is effective at inactivating airborne viruses, such as influenza viruses and SARS-CoV-2, by damaging their proteins and nucleic acids (Blatchley *et al*., 2023; Naito *et al*., 2022; Welch, Buonanno, *et al*., 2018; Wigginton *et al*., 2012). Non-enveloped viruses with robust capsid proteins require higher doses and longer exposure times to achieve similar inactivation levels (Ma *et al*., 2021). There is variation among pathogen types and even strains; however, consistent antimicrobial activity is demonstrated, and it may take longer to reduce the pathogen load in the room (Eadie *et al*., 2022; Hessling *et al*., 2021).

The ICNIRP has recommended exposure limits for UV radiation to protect the skin and eyes: a dose limit for 222 nm far-UVC light of 240 J/m^2 (24 mJ/cm^2) and an exposure time limit of 8 h/day and 40 h/week (ICNIRP, 2004). The ICNIRP exposure limits serve as the basis for the European standards (European Commission, 2011), which are based on recommendations from the 1970s (Far UV Technologies, 2021; Sliney & Stuck, 2021). Based on safety studies from the last decade, the American Conference of Governmental Industrial Hygienists (ACGIH) raised its recommendations in 2021 (ACGIH, 2021; Far UV Technologies, 2021; Sliney & Stuck, 2021). Now, for UVC, the threshold limit values are 250 mJ/cm^2 at 180 nm and 3.1 mJ/cm^2 at 275 nm, which are comparable to the ICNRP guidelines (Environmental Health & Safety, n.d.).

There have been numerous studies evaluating the effects of far-UVC as a potential carcinogen, with results demonstrating absorption within the outermost layers of the skin and eyes, and no increased risk (Hessling *et al*., 2021; Welch, Aquino de Muro, *et al*., 2022; Yamano *et al*., 2020). A key safety consideration for far-UVC is whether a filter to remove longer wavelengths of light is included (Eadie *et al*., 2022). There may be unknown longer-term effects of far-UVC exposure, for instance, on the skin microbiome and immune system, which remain underexplored (Maverakis *et al*., 2010; Patra *et al*., 2020). Additionally, standard UV safety measures for installers and maintenance personnel with high occupational exposure would be recommended for new or faulty devices (United States Department of Health and Human Services & CDC, 2009).

Furthermore, far-UVC light can interact with atmospheric molecules, such as oxygen and volatile organic compounds, leading to the formation of ozone and harmful radicals indoors (Graeffe *et al*., 2023; Link *et al*., 2023; Peng *et al*., 2023). Directive 2008/50/EC mandates ozone concentration limits of less than 120 μg/m^3 over an 8-h average period (European Parliament, 2008). Monitoring of ozone precursors, such as nitrogen oxides and volatile organic compounds, is required to ensure compliance with air quality standards. Initial data show that minimal ventilation is required to mitigate the effects of far-UVC on indoor particulate matter, although this is reliant upon a low external ozone concentration (Park & Rim, 2024). In brief, adherence to the ICNIRP limits for far-UVC usage in combination with ventilation appears reasonably practicable and safe based on current understanding.

The increasing risk of emerging infectious diseases and recent experience during the COVID-19 pandemic underscore the importance of measures to reduce transmission in indoor settings (Mahon *et al*., 2024). Studies have demonstrated great variation in the efficacy of personal protective and environmental infection control measures (Fadlallah *et al*., 2024; Sachs *et al*., 2022).

Slowing early transmission is a crucial first step in epidemic and pandemic responses (Sachs *et al*., 2022). However, emerging or newly mutated pathogens often spread before relevant mitigation measures are implemented. To give time for pathogen-specific responses, such as vaccination, to be enacted, non-pharmaceutical interventions, including restrictions on movement, social distancing, and mask wearing, can be implemented, but are subject to individual compliance (Cowling & Aiello, 2020; Sachs *et al*., 2022). Far-UVC may complement existing non-pharmaceutical intervention options by reducing pathogen load indoors without being as disruptive as those interventions. Furthermore, there can be flow-on benefits for other infectious diseases, such as seasonal colds and influenza, following non-pharmaceutical interventions.

Far-UVC represents a novel component for pandemic preparedness and response. As part of a comprehensive approach, far-UVC may complement other public health measures in prevention, mitigation, and response efforts to disease outbreaks. This study adds to the existing literature by addressing whether investments in mitigating indoor infections using far-UVC provide worthwhile returns in Switzerland and Germany. Previously, the cost–benefit ratios associated with the utilisation of far-UVC light had not been determined. To our knowledge, this is the first study to model the feasibility of direct-acting UVC light in occupied settings, diverging from the consensus on the use of upper-room germicidal UVA and UVB systems. Here, we aim to lay a foundation for further research and inform policymakers about the predicted costs and effectiveness of far-UVC technology.

2. Data and methods

2.1. Methodology

This study used cost–benefit analysis to assess the relative impact of implementing far-UVC devices in common settings in Switzerland and Germany. Using the CERN Airborne Model for Indoor Risk Assessment (CAiMIRA), we evaluated the expected changes in infection risk from the introduction of far-UVC lamps, ensuring they remain within the allowed exposure limit of 8 h. (Henriques *et al*., 2022). CAiMIRA is a model of airborne pathogen transmission in indoor settings that quantifies the risk of long-range airborne transmission of SARS-CoV-2, enabling the assessment of workplace protective measures. This has since been adapted to power the World Health Organisation's Indoor Airborne Risk Assessment (ARIA) tool (World Health Organisation, 2024).

2.2. Choice of setting

Germany and Switzerland were chosen because they represent contexts in which the authors have an in-depth understanding of individual and government behaviour. In this cost–benefit study, we focused on three specific environments: restaurants, offices, and waiting rooms in hospitals and doctors' offices. Our selection was based on the undesirability of mask use in restaurants and offices, and on the higher likelihood of contagiousness and the presence of more vulnerable individuals in medical waiting rooms. Also considered was the frequency with which a typical person would encounter the spaces; thus, we avoided custodial settings, for instance, which also had very high transmission risk (Kinner *et al*., 2020; Pearce *et al*., 2021). We excluded schools, despite their documented high incidence during initial epidemic phases, as we considered it unlikely that schools would be the first places to trial a new technology, both due to the increased vulnerability of children and their inability to provide consent (Banholzer *et al*., 2023; Mossong *et al*., 2008). These settings align with CDC recommendations for selecting locations for upper-room UV germicidal irradiation and priority spaces identified in the literature, and are extrapolated to use cases for far-UVC (CDC, 2021).

2.3. Parameters used

To model the impact of introducing far-UVC lamps, we defined specific parameters for each environment, as described in Table A1. These parameters included room size, number of people, number of infected people, duration of stay, and activity level). The parameters were based on a combination of published literature (including time-use surveys) (Destatis, 2024). The number of infected people was varied to reflect different levels of population incidence based on the Robert Koch Institute's COVID and influenza reports (Robert Koch Institute (2021), 2023a, 2023b, 2026). Additionally, we assumed a general ventilation rate of 5 air changes per hour (ACH) in all rooms, reflecting a blend of mechanically ventilated and naturally ventilated rooms (Dimitroulopoulou & Bartzis, 2013). While there are guidelines on recommended ventilation rates in the new building code, this assumption was constrained by limited existing studies on ventilation in existing buildings. A decision was made to estimate 5 ACH due to the number of variables in the remaining modelling in this study.

The chosen settings aim to depict a wide variety of the most common restaurants, offices, and waiting rooms in Germany and Switzerland. Regarding restaurants, we modelled a regular medium-sized restaurant (100 m^2), an Irish pub (120 m^2), a large fast-food chain restaurant (180 m^2), and a queue for takeaway lunch in a fast-food restaurant. For the waiting rooms, we selected general practitioner, clinical, and emergency department waiting rooms. The office scenarios represent a small (20 m^2, 3 desks), a medium-sized (50 m^2, 8 desks), and a large open-floor office (100 m^2, 20 desks). All our chosen examples were based on reference places, personal measurements, or expert knowledge.

The lamp details used for modelling corresponded to those of the currently available 115 mW Krypton Chloride Excimer lamps (UV222, UV Medico, Denmark). The number of UV lamps was adjusted relative to the room volume to achieve the recommended coverage, as per the published literature.

We defined the prevalence of infectious individuals in indoor settings based on community respiratory disease incidence rates from the Robert Koch Institute. We considered three scenarios: a normal winter with mainly influenza and common colds lasting 22 weeks; a COVID-19-like pandemic lasting 4 weeks; and a more severe pandemic lasting 8 weeks, based on epidemiological studies of respiratory disease incidence increases.

The efficacy of the lamps, characterised by the inactivation constant k, was translated into equivalent ACH based on empirical data presented by Eadie *et al.* (2022). For scenarios involving (natural) ventilation and far-UVC lamps, the ACHs were summed. Using CAiMIRA, we determined the difference in infections with and without far-UVC lamps and computed the number of avoided infections in each setting for each scenario of infectious individuals in space.

2.3.1. Benefits calculations

Our analysis further estimated the monetary benefits of avoided infections, including fewer hospitalisations, reduced sick days, and lower mortality. These benefits were categorised into healthcare cost savings, economic productivity gains, and monetised health benefits (intangible benefits to quality-adjusted life years [QALYs]). The healthcare cost savings were calculated by multiplying the hospitalisation rate by the average hospital stay cost. The economic productivity gains were calculated by multiplying the per-sick-day productivity loss by the average number of sick days in each scenario. The monetised health benefits were calculated by multiplying the average QALY loss per infection by the COVID-19 QALY value given by the Swiss National COVID-19 Science Taskforce (2021). Individual contributions for each, as they relate to compounded calculations (e.g., total benefits), are available in Supplementary File.

Health and economic costs and benefits were informed by the literature and expert opinion. Using this comprehensive approach, we assessed the potential health and economic impacts of introducing far-UVC lamps in various indoor settings.

2.3.2. Cost calculations

The expected costs for far-UVC lamps vary, depending on brand and availability. To model the estimated costs in our analysis, we assumed an installation cost of Swiss Franc (CHF) 1,350 per lamp, a power input of 11 W, and an average life expectancy of 15,000 h (10 years) if used infrequently. For a lamp used for 8 h a day, 5 days a week, and 22 weeks a year (for example, in an office), this would translate into annual costs of approximately CHF 170. It must be noted that the relatively high acquisition costs were divided over the lifetime of far-UVC lamps.

The QALY costs incurred from potential harmful effects, such as ozone formation, were calculated but excluded because there is insufficient published literature regarding this novel technology. An estimate of QALY costs from exposure to ozone by-products was calculated for the Irish pub setting (i.e., UVC lamps in a setting with little or no ventilation). An estimated cost of CHF 165 was added in this case, which was about one-tenth of the implementation costs for the far-UVC lamps. Other potential cost considerations included the risk of carcinogenicity, which was expected to be minimal due to UVC's near-complete absorption in the outer layers of the skin and the eye. Potential atopic effects are difficult to attribute to a single environmental factor, such as UVC, and establishing causation and related costs is beyond the scope of this study.

We compared the cost of other methods for indoor air disinfection. Specifically, the cost of gold-standard high-efficiency particulate air (HEPA)-filtration devices is typically USD 540 (equivalent to CHF 430 or Euro [EUR] 460) per device, with a 60 W power input and a life expectancy of 3 years at the time of writing (the Philips 4000i air purifier was used as an example). Using a filter for 8 h a day, 5 days a week, and 22 weeks a year would cost roughly CHF 200 per year. Again, the acquisition costs were divided over the lifetime of HEPA-filtration devices. The number of HEPA filters was based on the goal of achieving a similar number of ACH, which was translated into the effectiveness of the UV lamps. For the Irish pub example, we calculated 9 lamps or 8 HEPA filters, leading to a yearly cost of CHF 1,500 or CHF 1,550, respectively. Therefore, the costs of far-UVC lamps and HEPA filters are similar, varying only slightly in our selected settings (±20%); cost-effectiveness was to be similar for HEPA and far-UVC under the current assumptions.

In subsequent years, the prices of HEPA devices decreased, as only the filters required replacement, at a cost of USD 90 (equivalent to CHF 70 or EUR 77) based on the price of a Philips replacement filter. With an increase in market size, the price of far-UVC lamps is expected to decrease as well (E. Mogensen, personal communication, December 13, 2023). Technological improvements, such as transitioning to light-emitting diodes, may further reduce the cost of far-UVC lamps, making them more affordable and sustainable in the long run, as they consume less energy than air filters. An additional externality for consideration is the relative environmental cost of running a system containing a HEPA filter compared to a UVC Krypton Chloride Excimer lamp. Previous research has highlighted the importance of technological innovation to sustain living standards while mitigating carbon footprints, and this may represent a way to sustainably improve indoor air (Aziz *et al*., 2023).

2.4. Statistical analysis

Our calculations were based on estimates from the literature; therefore, they were not derived from a single dataset and could not be used to estimate confidence intervals for the point estimates we presented. We used conservative estimates of multiplier effects; therefore, these cost–benefit analyses were conservative and may have underestimated rather than overestimated the true cost–benefit. Further research could focus on using only data with confidence intervals to more thoroughly capture the range of possible outcomes.

3. Results

3.1. Individual settings

3.1.1. Restaurants

During a normal winter, the effect of installing far-UVC in restaurants was most pronounced on economic productivity (Table 1 for Switzerland and Table 2 for Germany), with benefits stemming from avoiding mild infections and reducing sick days. During a pandemic, the greatest benefits were attributable to avoiding QALY losses. During a severe pandemic, compared with a COVID-19-like pandemic, a 10-fold increase in financial savings was seen for the healthcare system and the national economy.

Next, we studied other hospitality settings, including a pub, a large fast-food restaurant, a queue in a fast-food restaurant, and a medium-sized restaurant. The benefits division was very similar to that of the medium-sized restaurant (Table 3 for Switzerland and Table 4 for Germany). It is postulated that restaurants derive greater benefits from frequent interactions among diverse individuals over extended periods, thereby enhancing pathogen transmission in these environments.

3.1.2. Waiting rooms

In total, we considered four types of waiting rooms: An emergency waiting room, a specialist's office, and a smaller waiting room. All scenarios were in a similar range for the number of avoided infections. Therefore, we decided to report the average across all scenarios. The results are shown in Table 5 for Switzerland and Table 6 for Germany. Similar to a medium-sized restaurant, economic productivity gains matter most during a normal winter in a waiting room, whereas the share of monetised health benefits increased substantially with the severity of a pandemic, as depicted in Figure 1. While during a normal winter most benefits stemmed from reduced sick days, during a pandemic, more benefits stemmed from the health benefits (i.e., increased QALYs). The healthcare cost savings and the economic productivity gains also increased approximately eightfold in a severe pandemic compared to a COVID-19-like pandemic.

Although people visiting a doctor's office or an emergency room are often suffering from acute illnesses, we refrained from adjusting the community incidence rate for waiting rooms, as not every waiting room warrants a higher incidence rate, e.g., in a neurology ward. Consequently, this calculation potentially underestimated the benefits of far-UVC lights in medical waiting rooms. Even though the waiting room scenario yielded a lower monetary benefit than the restaurant example, it should be considered for installing far-UVC lamps, given the vulnerable groups involved and the need to maintain a functioning healthcare system during a pandemic. When we assumed the entire waiting room population to be particularly vulnerable, the healthcare cost savings increased to CHF 710 for a normal winter, CHF 3,600 for a COVID-19-like pandemic, and CHF 18,000 for a severe pandemic. Monetised health benefits increased to CHF 6,600 (normal winter), CHF 77,000 (COVID-19-like pandemic), and 2.8 million CHF (severe pandemic). This indicates an upper-bound prediction. The benefits of individual waiting rooms vary depending on the comparative vulnerability of the people in the room.

3.1.3. Offices

Similar to the restaurant and waiting room settings, economic productivity gains accounted for the greatest

Table 1. Estimated benefits (CHF) from avoided infections in a medium-sized restaurant with far-UVC lamp installation under three scenarios in Switzerland

Category	Benefits (CHF)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Healthcare cost savings	6,000	29,000	330,000
Economic productivity gains	210,000	35,000	310,000
Monetised health benefits	130,000	440,000	23,000,000

Abbreviation: CHF: Swiss Franc.

Table 2. Estimated benefits (EUR) from avoided infections in a medium-sized restaurant with far-UVC lamp installation under three scenarios in Germany

Category	Benefits (EUR)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Healthcare cost savings	2,000	10,000	45,000
Economic productivity gains	70,000	12,000	106,000
Monetised health benefits	60,000	200,000	10,582,000

Abbreviation: EUR: Euro.

Table 3. Total estimated benefits (CHF) from avoided infections in restaurants with far-UVC lamp installation under three scenarios in Switzerland

Settings	Sum of all benefits (CHF)		
	Normal winter	COVID-19-like pandemic	severe pandemic
Pub	600,000	1,400,000	46,500,000
Large fast-food restaurant	950,000	1,600,000	67,000,000
Queue in a fast-food restaurant	52,000	87,000	3,700,000
Medium-sized restaurant	340,000	500,000	24,000,000

Abbreviation: CHF: Swiss Franc.

Table 4. Total estimated benefits (EUR) from avoided infections in restaurants with far-UVC lamp installation under three scenarios in Germany

Settings	Sum of all benefits (EUR)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Pub	231,000	614,000	20,943,000
Large fast-food restaurant	369,000	706,000	30,264,000
Queue in a fast-food restaurant	20,000	39,000	1,671,000
Medium-sized restaurant	132,000	222,000	10,733,000

Abbreviation: EUR: Euro.

Table 5. Averaged estimated benefits (CHF) from avoided infections in medical waiting rooms with far-UVC lamp installation under three scenarios in Switzerland

Category	Benefits (CHF)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Healthcare cost savings	290	1,700	17,000
Economic productivity gains	10,000	2,100	16,000
Monetised health benefits	6,500	26,000	1,200,000

Abbreviation: CHF: Swiss Franc.

Table 6. Averaged estimated benefits (EUR) from avoided infections in medical waiting rooms with far-UVC lamp installation under three scenarios in Germany.

Category	Benefits (EUR)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Healthcare cost savings	100	600	2,300
Economic productivity gains	3,500	700	5,500
Monetised health benefits	3,000	12,000	553,600

Abbreviation: EUR: Euro.

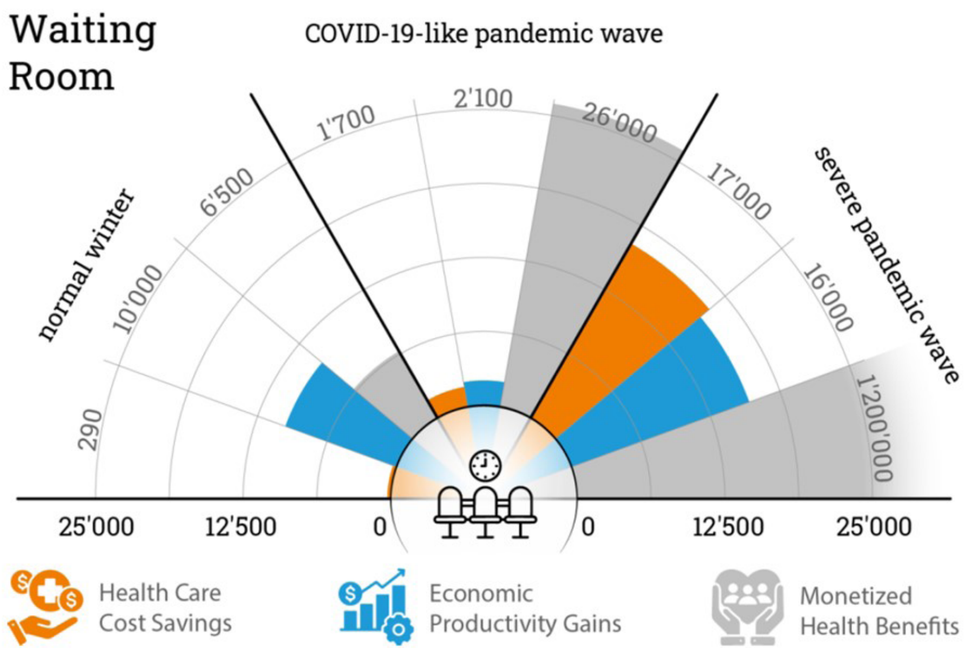

Figure 1. Overview of the averaged estimated benefits (CHF) gained through the implementation of far-UVC lamps in medical waiting rooms in Switzerland during the indicated scenarios. Healthcare cost savings are shown in orange, economic productivity gains in blue, and monetised health benefits in grey. Abbreviation: CHF: Swiss Franc.

share of benefits during a normal winter in office spaces, whereas the share of monetised health benefits increased substantially with the severity of a pandemic (Tables 7 & 8). During a normal winter, most benefits stemmed from reduced sick days, while during a pandemic, considerably more benefits stemmed from monetised health benefits (Figure 2).

Compared with restaurants and waiting rooms, the importance of far-UVC lamps in offices increased with the number of people in the office. The benefits were relatively small in a three-person office, whereas in a large office they were substantial (Table 9).

3.2. Cost–benefit ratios

The cost–benefit ratios for far-UVC lamp installation were favourable across all settings (Table 10 for Germany and Table 11 for Switzerland), even when monetised health benefits were excluded. This indicates that far-UVC lamps are a cost-saving technology for the Swiss and German societies as studied herein. These findings may be extrapolated to other Western societies with similar lifestyles, both in an average winter and in a more severe pandemic scenario.

In Switzerland, cost–benefit ratios ranged from one franc to: 30–290 CHF during a normal winter; 65–430 CHF during a COVID-like pandemic; and 2,300–20,500 CHF during a severe pandemic (ranges correspond to different settings). In Germany, cost benefit ratios ranged from 1 euro to: 7–226 EUR during a normal winter; 118–449 EUR during a COVID-like pandemic; and 659–18,946 EUR during a severe pandemic. The difference in cost–benefit ratios between the countries may be attributed to not accounting for purchasing power parity, which does not diminish the usefulness of the estimates for each country.

Another measure of the cost-effectiveness of health-related interventions is the incremental cost-effectiveness ratio (ICER). In this calculation, the status quo (ventilation at 5 ACH, no far-UVC lighting) was compared to the same condition with far-UVC lighting installed. This comprised the incurred costs of implementing far-UVC lamps in the respective setting (including electricity usage and maintenance) and the number of QALYs saved through these far-UVC lamps. As presented in Table 12, the ICER was lowest in a restaurant during a severe pandemic, at CHF 10 per QALY. It was highest in an office and a waiting room during a normal winter, at CHF 1,600 per QALY. While Switzerland does not have an official willingness-to-pay threshold, this ICER is well within the commonly cited thresholds in the United States and United Kingdom, as well as the Swiss case law ruling of CHF 100,000 per QALY reported in previous cost-effectiveness studies (Panje *et al.*, 2020; Pavic *et al.*, 2014).

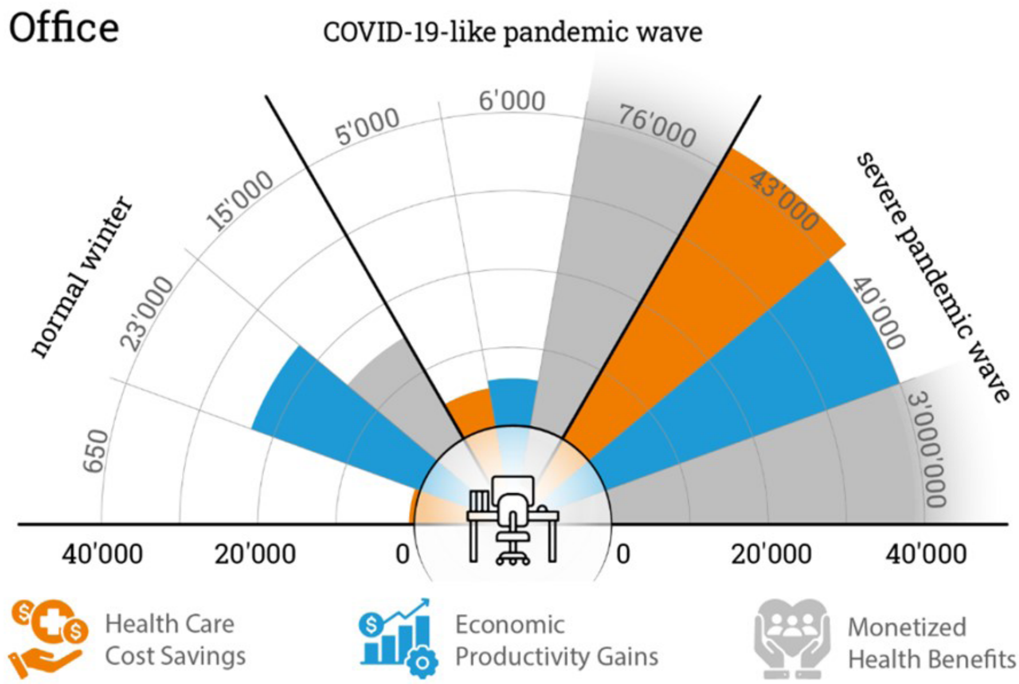

Figure 2. Overview of estimated benefits (CHF) gained through the implementation of far-UVC lamps in a large office (100 m²) in Switzerland during the indicated scenarios. Healthcare cost savings are shown in orange, economic productivity gains in blue, and monetised health benefits in grey.
Abbreviation: CHF: Swiss Franc.

Table 7. Estimated benefits (CHF) from avoided infections in a large office (100 m², 20 desks) with far-UVC lamp installation under three scenarios in Switzerland

Category	Benefits (CHF)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Healthcare cost savings	650	5,000	43,000
Economic productivity gains	23,000	6,000	40,000
Monetised health benefits	15,000	76,000	3,000,000

Abbreviation: CHF: Swiss Franc.

Table 8. Estimated benefits (EUR) from avoided infections in a large office (100 m², 20 desks) with far-UVC lamp installation under three scenarios in Germany.

Category	Benefits (EUR)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Healthcare cost savings	220	1,800	5,900
Economic productivity gains	8,000	2,100	14,000
Monetised health benefits	6,800	34,800	1,390,000

Abbreviation: EUR: Euro.

Table 9. Total estimated benefits (CHF) from avoided infections in offices of varied sizes with far-UVC lamp installation under three scenarios in Switzerland.

Office size	Benefits (CHF)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Small office	800	2,200	69,000
Medium office	9,100	20,000	870,000
Large office	39,000	87,000	3,100,000

Abbreviation: CHF: Swiss Franc.

Table 10. Cost–benefit ratios for installing far-UVC lamps in the indicated settings in Germany

Settings	Cost–benefit ratio		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Restaurant	110	190	9,000
Waiting room	35	70	3,000
Office	10	30	1,000

Note: Benefits are summed over all subtypes and divided by the annual cost of the installed lamps.
Abbreviation: EUR: Euro.

Table 11. Cost–benefit ratios for installing far-UVC lamps in the indicated settings in Switzerland

Settings	Cost–benefit ratio		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Restaurant	290	430	20,500
Waiting room	100	170	6,700
Office	30	65	2,300

Note: Benefits are summed over all subtypes and divided by the annual cost of the installed lamps.
Abbreviation: CHF: Swiss Franc.

Table 12. Incremental cost-effectiveness ratio (ICER; CHF per QALY) for installing far-UVC lamps in the indicated settings in Switzerland

Settings	ICER (CHF per QALY)		
	Normal winter	COVID-19-like pandemic	Severe pandemic
Restaurant	1,600	500	10
Waiting room	16,000	4,900	90
Office	16,000	3,100	80

Abbreviations: CHF: Swiss Franc; QALY: quality-adjusted life year.

In Germany and Switzerland, the greatest benefit was demonstrated in restaurants during a severe pandemic. As expected, the cost–benefit ratio decreased as the pandemic worsened. Nonetheless, even the smallest cost–benefit ratio—in an office during a normal winter season—demonstrated a benefit that is estimated to be seven times the cost of the far-UVC lights.

When restaurants were analysed by type across our scenarios, the greatest benefit accrued to fast-food restaurants, followed by pubs. Our modelling demonstrated that the cost–benefit ratios improved with office size, with the smallest office in Germany yielding a benefit of 2 times the cost of the lights, while the largest office yielded a benefit of 11 times the cost. There was no discernible pattern among the different waiting rooms.

3.3. Per capita benefits

We calculated societal gains, i.e., total benefits minus costs, and the number of avoided sick days per person annually when far-UVC lamps were implemented in all restaurants, medical waiting rooms, and offices in Switzerland (Table 13). This was performed based on statistics on the numbers of each location within the country and existing estimates of the number of people visiting each location during opening hours. Details can be found in the supplementary materials.

In 2022, in Switzerland, the average number of workdays missed by full-time employees amounted to 9.3 days (Federal Statistical Office, 2024). Among these absences, approximately 69% were attributable to illness or accidents. Therefore, a reduction of 2.4 days would signify a substantial decrease of about 37% in health-related absences or 26% in total work absences.

The gains per capita corresponded to country-wide gains of CHF 12 billion in a normal winter, CHF 18 billion in a COVID-like severe pandemic, and CHF 860 billion in a severe pandemic. These comparatively high numbers, especially in the severe pandemic scenario, need to be assessed with caution, as we did not account for infections occurring in settings other than restaurants, offices, and waiting rooms. In scenarios with extremely high population incidence rates, this assumption becomes increasingly distorting, leading to an overestimation of our results. Nonetheless, societal gains in a severe pandemic

Table 13. Gains per capita (total benefits minus costs) and annual avoided sick days per person from far-UVC lamp installation in all restaurants, waiting rooms, and offices in Switzerland

Societal gains	Normal winter	COVID-19-like pandemic	Severe pandemic
Gains per capita (CHF)	1,400	2,100	98,000
Avoided sick days per capita (days)	2.4	0.4	3.7

Abbreviation: CHF: Swiss Franc.

are driven by the substantial number of avoided deaths and are plausibly very high relative to, e.g., the Swiss gross domestic product.

Our findings highlight the importance and cost-effectiveness of improved indoor air quality during seasonal cold and flu waves, as well as during pandemics—particularly relevant given the threat of future pandemics and need for preparedness.

3.4. Comparison to other indoor air quality measures

The intended use of HEPA filters and far-UVC lamps is similar, making their costs and benefits readily comparable. We found that the costs of both technologies are broadly comparable. Both approaches assume a homogeneous air mixture in the room—a condition that is unlikely in practice. Far-UVC light offers an advantage by also disinfecting air in near-field zones and areas less effectively reached by HEPA filtration. Conversely, HEPA filters remove nanoparticles but do not reduce concentrations of ozone, CO_2, and other toxic chemicals (Vijayan *et al.*, 2015). Addressing these requires additional activated carbon filters or enhanced ventilation. From the end-user perspective, a large difference is the much higher noise levels generated by HEPA filtration, especially at high clean air delivery rates, compared with the silent operation of far-UVC devices. Furthermore, HEPA filtration requires considerably more energy (60 W per filter vs. 11 W per far-UVC device). Thus, far-UVC lamps could contribute to a more sustainable building footprint.

In our calculations, we assumed far-UVC's efficacy based on a study by Eadie *et al.* (2022) on *Staphylococcus aureus*. Some studies have suggested that far-UVC lamps may be 10–100 times more effective than HEPA filtration due to varying effects on different viruses and bacteria (Buonanno *et al.*, 2020; Ma *et al.*, 2021). In particular, far-UVC appears highly effective against SARS-CoV-2 and influenza-like viruses. Although further research is required, early literature has shown promising results. If the lamps are 10 times more effective than HEPA filtration, the cost-effectiveness ratio for restaurants, waiting rooms, and offices increases roughly by a factor of 2 rather than 10, due to the exponential decay of pathogens over time. In high-pathogen environments, such as fast-food queues, the cost-effectiveness of a 10-fold higher efficacy is tripled. Under the conservative assumption based on Eadie *et al.* (2022), far-UVC's cost-effectiveness is already comparable to HEPA filtration. Therefore, far-UVC is likely more cost-effective than HEPA filters, has a higher potential in settings with high pathogen loads, and plausibly achieves levels of virus inactivation that HEPA filters cannot reach.

4. Discussion

A cost–benefit analysis of far-UVC light in controlling infectious diseases is multifaceted and complex. Assumptions were used as a necessity, and some variables had limited literature to support even approximate estimates. This discussion underlines the main sources of uncertainty in the study.

The modelling of avoided infections depends on the dynamics of specific pathogens and their transmission pathways. Changes in disease transmission patterns, driven by new pathogens or changes in human behaviour, could influence the results (Park, Mistrick, & Rim, 2022). For a normal winter, we assumed far-UVC use only during the six coolest months, when respiratory illness rates are typically highest, although peaks may occur at other times. For the COVID-19-like pandemic, the model used information from a four-week peak based on Omicron infection rates in Switzerland. This assumption partly explains why benefits are significantly lower than in other scenarios, reflecting Switzerland's relative containment of COVID-19.

The study relies on plausible assumptions about the effectiveness of far-UVC lamps across varied environments, using current infection rates and lamp efficacy estimates grounded in recent research. These estimates may need to be updated as research evolves.

The analysis was based on data available at the time of the study. Pathogen inactivation and indoor air quality levels are heterogeneous, and supporting data are limited (Brouwer *et al.*, 2017). For example, ACHs are based on current European guidelines and may not accurately reflect ventilation conditions in all settings, particularly older buildings.

Benefits were categorised into healthcare cost savings, economic productivity gains, and monetised health benefits (i.e., QALY gains). These were counted separately to allow decision-makers to identify the most relevant component for their context. A limitation of this study is the lack of accounting for potential disease transmission beyond spaces equipped with far-UVC sources and the exclusion of mitigated transmission risks from individuals visiting far-UVC-equipped areas. The interplay of these effects is difficult to assess and was therefore excluded. This likely results in an underestimation of total benefits in low-incidence scenarios, as we did not account for the multiplier effect of avoided infections. Another methodological limitation is the use of CAiMIRA to model general airborne pathogen transmission, as it was developed specifically for SARS-CoV-2 (Henriques *et al.*, 2022). While the underlying Wells–Riley model is generally applicable, pathogen-specific information, such as pathogenicity and droplet size distribution, should be considered for more reliable assessments of individual pathogens. Despite this, the majority of historical pandemics involved influenza-like viruses (Piret & Boivin, 2021), which are similar in size and characteristics to SARS-CoV-2 and are therefore likely to respond similarly to far-UVC exposure.

The potential health impacts of far-UVC on humans and animals are the subject of ongoing research. Ecological costs, including electricity use and disposal of far-UVC lamps, could also be considered but were excluded from this study. Similarly, costs of potential harmful effects, as outlined in Section 1, were not included due to the theoretical nature of the risks.

Far-UVC is part of an array of approaches enhancing indoor air quality. A holistic approach that combines ventilation and filtration is likely to be more effective than the singular use of far-UVC, as demonstrated by the additive benefits of ventilation, HEPA filtration, and far-UVC lights observed in our scenarios. The effectiveness of far-UVC lamps varies depending on the type of premises where they are installed (e.g., size, ventilation, and foot traffic). The most promising environments for installation may be identified based on the results of this study, but they are not exhaustive. The effectiveness of far-UVC lamps also relies on proper installation and maintenance, although they are less prone to human error compared to masks or manual disinfection. Errors in installation could reduce expected benefits and potentially increase costs.

Public perception and acceptance of far-UVC technologies are important factors for successful implementation. Therefore, public engagement may need to be factored into costs in future studies. Measures with a lower level of personal restriction than the effect on pandemic containment were associated with higher levels of public acceptance in Germany, suggesting that a minimally restrictive measure, such as far-UVC, could become a well-accepted pandemic response (Kaltenhäuser, 2025).

Additionally, the decision about where to install far-UVC lamps raises questions of equity and access, especially in relation to resource-poor contexts.

4.1. Policy recommendations and next steps

Given the cost-efficiency of far-UVC lamps, the following recommendations are proposed to support public health and pandemic preparedness. These recommendations address the issue from different angles. They are therefore independent rather than sequential; each could be implemented immediately by different stakeholders. However, their implementation should be accompanied by ongoing evaluation and review of the published literature.

Recommendation for the private sector is to enhance infection protection through monitoring and air quality improvement. Regular air quality monitoring and the installation of systems to manage indoor air are recommended for the private sector. These measures help businesses ensure safer environments and promote the well-being of customers and employees. Far-UVC can contribute to reducing disease transmission if implemented in line with current European guidelines and in combination with ventilation.

Recommendations for public institutions:

(i) Conduct real-world and feasibility studies of far-UVC: Real-world studies are necessary to assess the applicability of far-UVC light. Such research could be commissioned by public health offices or national research programs.
(ii) Monitor indoor air quality and ensure transparency: Comprehensive data on indoor air quality is lacking in countries such as Germany and Switzerland. Surveys and public reporting can identify problem areas and define targeted improvement measures, such as ventilation.
(iii) Anchor the state's position as a role model: By setting air quality standards for public buildings, the government promotes public health and encourages other sectors.
(iv) Create incentives to improve indoor air quality: Financial incentives can help overcome implementation barriers and play a significant role in encouraging implementation of public health measures. Far-UVC may also help achieve certifications such as Leadership in Energy and Environmental Design.
(iv) Equip critical infrastructure with far-UVC technology for pandemic response: Facilities critical during pandemics, such as hospitals and government buildings, should consider long-term far-UVC installations as part of their pandemic response plans.

5. Conclusion

Far-UVC technology can offer a more reliable and less intrusive solution for mitigating indoor disease transmission across office, restaurant, and waiting rooms. Integrating far-UVC into public health strategies can enhance community resilience against infectious diseases. Far-UVC can significantly reduce healthcare costs by reducing infections, avoiding hospitalizations, and reducing the need for expensive treatments. It also provides economic benefits through productivity gains from fewer employee sickness-related absences. Initial findings are promising, and we encourage real-world trials of this technology to further evaluate and report its effectiveness.

Acknowledgments

We thank the following reviewers for their time and expertise: Dr. Nicolas Banholzer, Postdoctoral Research Fellow, Institute of Social and Preventive Medicine, University of Bern; Dr. Richard Bruns, Senior Scholar and Economist, Johns Hopkins Center for Health Security; Dr. Jasper Götting, Virologist, Convergent Research; Jakob Graabak, Foresight Director, International Center for Future Generations; Harry Koos, PhD student in Health Policy/Health Economics, Stanford School of Medicine; Dr. Michael Riediker, Director, Swiss Centre for Occupational and Environmental Health; Dr. Lisa Fischer, d-fine; Dr. Robert Görke, d-fine, Partner Pharma and Healthcare; Dr. Daniel Staudenmann, MD, Cantonal Hospital of Aarau; Prof. Dr. Ernest Weingartner, Lecturer in Sensor and Aerosol Technology, University of Applied Sciences and Arts Northwestern Switzerland; and Richard Williamson, Program Director far-UVC, Blueprint Biosecurity.

Funding

None.

Conflict of interest

Sabine Matysik, Bianca Bohmann, Stefan Kruger, Marwan El Chamaa, Markus Baumeister, and Sungmin Eu are employees of d-fine; Elina Christian and Laurent Bachler are employees of Pour Demain, Switzerland, however, they were not involved in any activities that could constitute a conflict of interest in relation to this study.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Supplementary data contain the calculations used to generate these results. For questions or further information, please contact the corresponding author.

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Appendix

Table A1. Table of assumptions

Parameter	Value	Source
COVID-19-like pandemic		
Symptomatic COVID-19 case	75%	(Chen *et al.*, 2021; El-Ghitany *et al.*, 2022; Tan *et al.*, 2022)
Long COVID	10%	(Zheng *et al.*, 2023)
Hospitalisation rate (overall)	10%	(Robert Koch Institute, 2021)
Mortality COVID-19 (overall)	4%	(Robert Koch Institute, 2023)
Cost of hospitalisation	CHF 30,250	(Zanni *et al.*, 2023)
Cost of disability case for the healthcare system	CHF 8,500	(Zanni *et al.*, 2023)
Sick days per symptomatic COVID-19 infection	5 days	(Zanni *et al.*, 2023)
Sick days per COVID-19 hospitalisation	15 days	(Al Omair *et al.*, 2023; da Costa Sousa *et al.*, 2022; Tobin *et al.*, 2023)
Sick days per long COVID case	84 days	(Gandjour, 2023)
QALYs lost per death due to COVID-19	11	(Hanson *et al.*, 2022)
Losses of QALYs associated with a symptomatic COVID-19 case	0.008	(Zafari *et al.*, 2022)
Losses of QALYs associated with a long COVID infection	0.034	(Zafari *et al.*, 2022)
Losses of QALYs associated with a COVID-19 hospitalisation	0.020	(Zafari *et al.*, 2022)
Normal winter		
Hospitalisation rate (overall)	0.30%	Calculated from Robert Koch Institute (2023)
Mortality (overall)	0.006%	(Iuliano *et al.*, 2018)
Cost of hospitalisation	CHF 10,292	(Ammann *et al.*, 2023)
Sick days per infection	3 days	(Scholz *et al.*, 2019)
Sick days per hospitalisation	17 days	Expert opinion, similar to COVID (20 sick days in total)
QALYs lost per death due to respiratory infection	3	Estimation based on Plass *et al.* (2014)
Losses of QALYs associated with a respiratory infection	0.0038	(de Boer *et al.*, 2021)
Losses of QALYs associated with hospitalisation	0.0118	(de Boer *et al.*, 2021)
Severe pandemic		
Disability rate	10%	Assumption to model a more severe pathogen than COVID-19
Hospitalization rate (overall)	30%	Assumption to model a more severe pathogen than COVID-19
Mortality (overall)	20%	Assumption to model a more severe pathogen than COVID-19
Cost of hospitalisation	CHF 30,250	As for the COVID-like pandemic
Cost of disability case for healthcare	CHF 8,500	As for the COVID-like pandemic

(*cont'd...*)

Table A1. (*Continued*)

Parameter	Value	Source
Sick days per infection	10 days	Assumption
Sick days per hospitalisation	20 days	Assumption
Sick days per case of disability	100 days	Assumption
QALYs lost per death	20	Assumption
Losses of QALYs associated with an infection	0.01	Assumption extrapolated from COVID and influenza
Losses of QALYs associated with a disability caused by infection	0.05	Assumption extrapolated from COVID and influenza
Losses of QALYs associated with hospitalisation	0.04	Assumption extrapolated from COVID and influenza
General assumptions		
Loss of productivity per sick day	CHF 360	(Zanni *et al.*, 2023)
Economic equivalent of one QALY	CHF 175,000	(Zanni *et al.*, 2023)
Cost per person per hour of exposure to an increase of 10 ppb ozone	CHF 0.006	(Morantes *et al.*, 2023; Peng *et al.*, 2023)

Abbreviations: CHF: Swiss Franc; QALY: Quality-adjusted life year.

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